UNIVERSITY OF CAPE COAST

# PREPARATION OF COMPOSITE BIOMASS BRIQUETTE FROM A MIXTURE OF DOMESTIC SOLID WASTE AND COCONUT HUSK WITH COW DUNG AS A BINDER

DOMINIC LUCKEE MILLER

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BY

DOMINIC LUCKEE MILLER

A thesis submitted to the Department of Environmental Science of the School of Biological Sciences, University of Cape Coast, in partial fulfilment of the requirement for the award of a Master of Philosophy degree in Environmental Science

OCTOBER 2023

# DECLARATION

## Candidate's Declaration

I hereby declare that this thesis is the result of my own original research and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature: ………………………………. Date: ………………….

Name: Dominic Luckee Miller

## Supervisor's Declaration

I hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of the thesis laid down by the University of Cape Coast.

Supervisor's Signature: …………………………… Date: ………………….

Name: Prof. Mohammed Augustine Takase

# ABSTRACT

The aim of the study is to determine a mixture of domestic solid waste and coconut husk for composite biomass briquette production using cow dung as a binder. A 170-litre metal drum with specified dimensions was used as a kiln during the pyrolysis of the various feedstocks and a manually fabricated cylindrical design press was employed for compaction. With the aid of Scanning Electron Microscopy (SEM), the feedstocks were subjected to characterisation. Moreover, an Oxygen Parr Bomb Calorimeter was used to calculate the composite briquette's gross calorific value. Additionally, a LECO 932 CHNS elemental analyzer was utilized to determine the elemental composition of the composite biomass briquette. Subsequently, a Water boiling test was conducted to assess the suitability of the fuel compared to traditional charcoal observing the fuel burning rate, specific fuel consumption, ignition time, and thermal efficiency. Under optimal conditions such as a feedstock ratio of 1:1 by weight 10% binder concentration and low-pressure compaction, the composite biomass briquette production yielded 14 cylindrical lumps from 4.5 kilograms of composite biochar used. The composite biomass briquettes had an optimal high heating value of 19.3 ± 0.1 MJ/kg, ash content of 7.4 ± 0.2 %, and 512.03g/ $m^3$ bulk density. The cow dung used as a binder demonstrated excellent lignin composition and adhesive properties. The composite biomass briquettes show optimal combustion properties, positioning them as efficient and suitable solid fuels for cooking and heating in homes. These properties complied with the specifications outlined by the American Society for Testing and Materials (ASTM E791-08) Standard. The outcome of the study complements the body of knowledge on composite biomass briquette technology in Sub-Saharan Africa. Also, this study addresses the growing demand for clean and cheap domestic cooking fuel while solving the widespread environmental challenges of improper municipal solid waste disposal, indoor air pollution, and deforestation in Ghana.

## KEYWORDS

Composite biomass briquette

Renewable Energy

Waste-to-energy

Proximate Analysis

Ultimate Analysis

Clean Cooking fuel

Cape Coast North Sub Metropolitan

Ghana

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# DEDICATION

To my beloved family

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| | |
|---|---|
| MSW | Municipal Solid Waste |
| CCMA | Cape Coast Metropolitan Assembly |
| GSS | Ghana Statistical Service |
| EPA | Environmental Protection Agency |
| ASTM | American Society for Testing and Materials |
| UN SDG | United Nations Sustainable Development Goal |
| PCWGR | Per capita waste generation rate |
| Hrs | Hours |
| SEM | Scanning Electron Microscope |
| WHO | World Health Organization |
| PKS | Palm Kernel Shell |
| VM | Volatile Matter |
| MC | Moisture content |
| AC | Ash Content |
| FC | Fixed Carbon |

# CHAPTER ONE

# INTRODUCTION

## Background to the Study

To sustain human life and achieve human development in all its facets (economic, social, and environmental) access to clean and affordable energy is crucial (Pandey & Asif, 2022). Exponential growth in the global human population and industrialisation have triggered a sharp increase in global energy demand. Gwenzi et al. (2020) reported that approximately 3 billion individuals, mainly residing in developing nations, depend on solid fuels like firewood, traditional charcoal, agro-forestry residues, or animal waste for cooking and heating purposes. However, the use of solid fuels adversely affects the environment and human health. Nevertheless, solid fuels remain an essential source of domestic energy in developing countries (McLean et al., 2019).

In Sub-Saharan Africa, firewood collection and charcoal production has been reported by Olorunfemi et al. (2022) as crucial forest degradation factors with commercial logging and timber exploitation accounting for more than 70% of forest degradation in Sub-Saharan Africa. Furthermore, Akolgo et al. (2018) showed that 80% of Ghanaian households primarily use forest resources as sources of energy for cooking and heating resulting in uncontrolled cutting down of forest trees. According to Acheampong et al. (2019), the growing rate of deforestation severely threatens the long-term viability of Ghana's forests and woodlands. Available research has been directed towards innovative and integrated approaches to curb the problem of deforestation. Besides deforestation from the unsustainable extraction of forest trees for firewood and traditional charcoal production, indoor air pollution is another alarming health risk associated with the use of firewood and traditional charcoal. These affect primarily, women and children in developing countries (Saini et al., 2020).

According to Ali et al. (2021), the World Health Organization in 2020 reported an estimated 4 million deaths annually from incomplete combustion using firewood and traditional charcoal for domestic cooking and heating applications in low- and middle-income countries, making indoor air pollution a public health risk that demands adequate attention.

Municipal solid waste (MSW), generally referred to as trash or garbage, encompasses the materials we use in our daily lives and subsequently dispose of. These include various objects like packaging materials, grass trimmings, furniture, bottles, textiles, food leftovers, papers, cardboard, appliances, paint, and batteries. MSW originates from residential households, educational institutions, medical facilities, and commercial establishments (Abbasi, 2018).

MSW generation rate per capita is sharply increasing in developing countries, putting more pressure on the environment. A study by Karimipour et al. (2019) predicts that by 2025, the quantity of municipal solid waste generated worldwide would have expanded to nearly 2.2 billion tonnes annually from the current 1.3 billion tonnes. As a result of this sharp increase in MSW generation, concerns are raised about the collection and disposal of municipal solid waste in underdeveloped nations. Another study by Serge Kubanza and Simatele (2020) added that improper MSW management is a widespread problem in developing countries like Ghana and these unsanitary landfill sites are considered breeding grounds for dangerous microbes and disease vectors and these pose a threat to public health. Improper MSW management remains an alarming sanitation and environmental problem in Ghana. However, various interventions, including waste-to-energy technologies can contribute to addressing the alarming environmental issues of improper MSW management specifically in developing countries.

Recently, researchers have made several efforts to address the problem of dwindling non-renewable resources by converting discarded biomass materials into green energy to meet the ever-growing energy demand. Studies indicate that biomass has high moisture content, low calorific value, and low bulk density particularly, in its raw state, hence, using it as a solid fuel presents some drawbacks. Studies, however, revealed that densification technologies such as Pelleting and briquetting can help to solve these problems. Briquetting (hereafter referred to as biomass briquetting) has proven to enhance the energy potential of raw biomass resources through densification. Biomass briquetting is a promising thermochemical waste-to-energy technology to convert solid waste and other biomass resources into clean solid fuel for cooking and heating applications in low- and middle-income countries (Obi et al., 2022). The generic steps in biomass briquetting are sourcing the feedstock, gathering the feedstock, sorting the feedstock, drying the feedstock, size reduction and compression. Various briquetting technologies have been used to produce biomass briquettes. These include Screw Press, Piston Press, Roller Press, and Manual Press. Additionally, Kpalo et al. (2020) noted that, these classifications of biomass briquetting technologies are based on the equipment used. Various feedstocks can be utilised for biomass briquetting.

Most of the feedstocks used in briquetting are produced naturally in the environment. Among them are vigorous plants, lawns that grow naturally, or organic debris generated by human activity, such as agricultural, industrial, and municipal-based residues. The optimal moisture content for good quality biomass briquette ranges from 10% to 15% (Dinesha et al., 2019). To optimize the moisture content for feedstocks intended for biomass briquetting, pretreatment by drying is required. Researchers have extensively investigated agro-based residues for biomass briquette production with a primary focus on the utilization of single feedstock (Kpalo et al., 2020). However, Obi et al. (2022) stressed that there are concerns by researchers in biomass briquette technology on the quality and sustainability of these single feedstocks used for biomass briquette production. Existing literature suggests that there is a scarcity or absence of research on the production of composite biomass briquettes using a combination of organic waste from households and coconut husks in Ghana (Doe et al., 2022; Bot et al., 2023). This study therefore aims at producing composite biomass briquette from domestic solid waste and coconut husks in Cape Coast North Sub-Metropolitan using cow dung as a binder. The outcome of the study will complement the body of knowledge on composite biomass briquette technology in Sub-Saharan Africa. Also, this study addresses the growing demand for clean and cheap domestic cooking fuel while solving the widespread environmental challenges of improper municipal solid waste disposal, indoor air pollution, and deforestation in Ghana.

## Statement of the Problem

In Europe, America, and some regions of Asia, biomass briquette is widely used for industrial purposes and home heating. The use of biomass briquette has numerous advantages such as low cost, environmental sustainability, reliable quality, and potential for product standardization. However, accepting biomass briquette as a replacement for firewood and traditional charcoal in Sub Sahara Africa is still limited. Currently, there is a growing research interest in developing countries on biomass briquette technology using agricultural, industrial, and municipal solid wastes due to some factors including the detrimental effects of forest degradation, indoor air pollution, high demand for clean, cheap, and affordable energy, depletion of fossil fuel reserves and the recent hike in fuel price because of the ongoing war between Russia and Ukraine. Previous studies have focused extensively on the use of single feedstock for biomass briquette production. However, these single feedstocks' quality and sustainability are major concerns in the scientific community, prompting researchers to investigate the mixture of different feedstocks for quality biomass briquette production.

According to the available literature, there is a lack of research or limited work on composite biomass briquette production using a blend of domestic solid waste and coconut husk, with cow dung serving as a binder. Also, the proximate and ultimate analysis of composite biomass briquette is limited in the existing literature. Hence, this study explores how to prepare composite biomass briquettes from a blend of domestic solid waste and coconut husk using cow dung as a binder.

### Main Objective

The main objective of the study is to produce and characterise composite biomass briquette from a mixture of domestic solid waste and coconut husk with cow dung as a binder.

### Specific Objectives

**The study's specific objectives include,**

i. To estimate the per capita generation rate and physical composition of domestic solid waste in Cape Coast North Sub Metropolitan.

ii. To prepare composite biomass briquette from a mixture of domestic solid waste and coconut husk using cow dung as a binder.

iii. To determine the fuel properties of the composite biomass briquette and traditional charcoal, following the American Society for Testing and Materials (ASTM E791-08) Standard.

iv. To assess the composite biomass briquette efficiency and compare with traditional charcoal following the American Society for Testing and Materials (ASTM D3172-08) Standard.

### Research Questions

i. What is the per capita generation rate and physical composition of domestic solid waste in Cape Coast North Sub Metropolitan?

ii. Can composite biomass briquette be produced from a mixture of domestic solid waste and coconut husk using cow dung as a binder?

iii. What are the fuel properties of the composite biomass briquette produced and traditional charcoal?

iv. How efficient is the composite biomass briquette produced compared to traditional charcoal in accordance with the American Standards for Testing and Materials (ASTM D-3172-08) Standard.

## Significance of the study

It is expected that the outcome from this study will contribute to an existing body of knowledge on composite biomass briquette production from a blend of different feedstocks in developing countries.

This study is also expected to contribute to providing clean and affordable cooking fuel in developing countries while solving the widespread problem of indiscriminate solid waste disposal, indoor air pollution and curbing deforestation. Additionally, the outcome of this study will contribute to achieving precisely, United Nations Sustainable Development Goal (SDG) 7 (Affordable and clean energy access for all) by preparing composite biomass briquette as alternative clean cooking fuel to firewood and traditional charcoal, SDG 11 (Sustainable cities and communities) by offering sustainable municipal solid waste treatment option, SDG 15 (Life on land) by contributing to the fight against deforestation and SDG 13 (Climate Action) by producing composite biomass briquette free of harmful greenhouse gases.

Moreover, this study will empower rural communities, youth, and women groups by providing employment opportunities through the introduction of composite biomass briquette production as a business using locally available biomass resources and cost-effective technology. The outcome of the study will be relevant for policy formulation by environmental institutions such as the Forestry Commission of Ghana, Environmental Protection Agency of Ghana, Cape Coast Metropolitan Assembly (CCMA), UNDP, USAID, Clean Cooking Alliance, and Other International Development Partners.

## Organization of the study

The study is divided into five main sections that are represented by chapters. The study's general introduction is covered in Chapter One. This Chapter consists of the study's background, problem statement, research objectives, research questions and the significance of the research. Chapter Two presents a review of related literature on the study. The materials and methods used in the study are covered in Chapter Three. The results are analyzed and discussed in Chapter Four. The recommendations and conclusions are covered in Chapter Five.

# CHAPTER TWO

# LITERATURE REVIEW

## Global Energy Crisis

All economic activities require the use of energy. Energy is critical for socio-economic activities (Bauer et al., 2017; Amjad et al., 2021). Since it is necessary for all economic activities, the significance of energy can never be underestimated. However, energy poverty affects most developing nations. Many studies have been done on energy and its sustainability (Østergaard et al., 2022; Azam et al., 2023). Energy is also essential for social stability and environmental sustainability. Clean energy is also essential for achieving the United Nations 2030 Agenda for Sustainable Development, ratified in 2015 by 133 countries and the Paris Agreement on Climate Change. Kaygusuz (2012) noted that worldwide consumption of energy is increasing on a global scale. Over the past few decades, the amount of energy consumed worldwide has significantly increased, rising from 8,588.9 Mtoe in 1995 to 13,147.3 Mtoe in 2015. In addition to that, the reduction in the abundance of natural resources and the increase in greenhouse gas emissions pose a significant threat to ecosystems. Approximately, 771 million people globally do not have access to electricity with 85% living in rural areas (Asghar et al., 2022). In contrast, Foley et al. (2015) reported that more than two out of five of the global population (2.9 billion people) uses traditional energy sources for domestic purposes. According to Ali et al. (2021), approximately 3.55 million people die annually in developing countries because of inhaling smoke and fumes from indoor cooking. Predominantly, children and women are the most affected. A study by Bryant (2019) revealed that indoor air pollution is responsible for a higher mortality rate among girls in Sub-Saharan Africa compared to diseases like malaria and malnutrition. More than half (55%) of the population without access to electricity worldwide reside in Africa followed by South Asia (34%). According to Foley et al. (2015), 87% of these regions' population without access to electricity lives in rural areas while the remaining 13% reside in urban areas. Additionally, Foley et al. (2015) found that with a percentage of 38%, South America has the highest proportion of people without access to clean energy for cooking. East Asia comes in second with 21%, followed by Sub-Saharan Africa with 26%, and other regions with 16%. To add on, 17% of the population lives in cities and 83% lack access to clean cooking energy (Foley et al., 2015).

**Status of Energy in Africa**

Modern energy is essential for any country's socioeconomic advancement and overall well-being. A study by Ahmad et al. (2022) reported that 40% of the world's population lacks access to clean cooking, making the situation worse regarding energy for cooking. Also, about 3 billion people from low- and middle-income countries still use open fires and inefficient stoves to cook using solid fuels such as firewood, crop wastes, charcoal, animal residues, municipal solid waste, and kerosene. These biomass resources have high moisture content, limited bulk density, and low heating value in their raw state. Hence, there is a need to improve the low calorific value and bulk density. Also, the moisture content should be optimized as an efficient solid fuel for domestic cooking and heating applications. It is reported that waste-to-energy technologies like briquetting can improve bulk density and the calorific value of biomass resources, making them more efficient for domestic cooking and heating in developing nations like Ghana (Antwi-Boasiako & Acheampong, 2016).

### Cooking fuel sector of Ghana

A reliable and affordable energy supply is the foundation for developing nations. According to Gyamfi et al. (2018) and Economy (2022), Ghana is experiencing a severe energy crisis. The authors indicated that the nation could no longer supply enough electricity to satisfy the growing demand of the country's population. Therefore, Ghana's energy transition is unique, implying that the energy supply must be switched to renewable sources to preserve the environment and promote the circular approach to solid waste management in Ghana. Präger et al. (2019) noted that utilizing locally available biomass is essential to boost Ghana's future energy mix. Statistical reports and empirical studies show that the dominant cooking fuel used in Ghana is firewood, which has low bulk density and calorific value in its raw state. Also, unsustainable extraction from the forest contributes to deforestation (Afele et al.,2022).

According to the Ghana Statistical Service (GSS) (2014), more than 40% of Ghanaian households used fuelwood as their primary source of cooking fuel in 2013, followed by charcoal and liquified petroleum gas (LPG). About 75% of households in rural areas cook primarily with firewood, compared to almost 44% of households in urban areas who cook using charcoal. Only 5.5% of rural households use liquefied petroleum gas (LPG) as their primary cooking fuel compared with 36% of urban households. Traditional firewood and charcoal stoves make up the majority of cookstoves in Ghana (Afrane & Ntiamoah, 2012). Considering the statistics on cooking fuel in Ghana, converting the loose biomass into a more densified form, increasing its bulk density and calorific value is essential to make the cooking fuel more efficient for domestic applications.

Also, Ghana must exploit alternative renewable energy sources to meet its recent energy supply deficits for the growing population and energy needs and reduce carbon gas emissions that combat climate change.

### Different forms of Energy

Energy is classified into two major types: non-renewable and renewable energy. Non-renewable energy refers to energy sources that cannot be easily replenished within a relatively short timeframe, considering the human lifecycle once they have been utilized. Examples of such energy sources include oil, natural gas, coal, and certain metallic minerals which may take thousands to hundreds of millions of years to form again. In contrast, the rate of replenishment for these non-renewable resources is much slower than the rate of their exploitation or consumption. These energy sources cannot be renewed within the timescale of human survival. Non-renewable energy sources primarily consist of fossil fuels such as coal, oil and natural gas which are mostly used in industries, agriculture, transportation, households, and mechanized activities. In recent years, fossil fuels consumption has experienced a notable increase, as highlighted by Refaat et al. (2008). This global trend has raised significant concerns, leading to a growing emphasis on transitioning from non-renewable energy sources to environmentally friendly alternatives, such as bioenergy, which is derived from renewable sources. Moreover, during combustion, these fossil-related fuels emit harmful greenhouse gases into the atmosphere, increasing the surface temperature and climate change (Alrikabi, 2014). According to Martins et al. (2019), the continued use of non-renewable energy sources raises concerns about availability and price instability as reserves deplete and global demand rises. Consequently, there is a pressing global concern to shift away from non-renewable energy sources and embrace environmentally friendly alternatives, including bioenergy. This transition is driven by the need to mitigate environmental impacts and promote sustainable energy practices. According to Amin et al. (2022), the renewable energy transition has the potential to mitigate the adverse effects of using non-renewable energy and ensure adequate energy security.

On the other hand, energy sources that are continuously replenished by nature are referred to as renewable energy sources. Solar, wind, hydroelectric, geothermal, and biomass energy are a few examples of renewable energy sources. These sources of energy are sustainable and have the potential to reduce reliance on finite fossil fuel resources while minimizing environmental impact. According to Alrikabi (2014) renewable energy sources have a lower environmental impact than non-renewable ones because they do not emit greenhouse gases or contribute to climate change. Rahman et al. (2022) also acknowledged that the advancement of renewable energy technology has quickened recently because of many nations setting elaborate targets to raise the share of renewable energy in their national energy mix.

According to Li et al. (2022), the advancement of renewable energy has surpassed all expectations in recent years. Noting that, the amount of renewable energy infrastructures installed worldwide has changed significantly. The bulk employment ratio from the renewable energy sector is also growing in nations like the, Germany, India, China, United States, the Member States of the European Union, and Brazil (Li et al., 2022). Although there is a lot of energy supply and jobs associated with renewable energy sources like biomass, biofuels, hydrogen, wind and solar adoption in Africa and Sub-Saharan Africa is still relatively low. Though renewable energy sources have significant potential, several challenges must be addressed before they can be used effectively. Also, another study by Viviescas et al. (2019) stressed concerns about the seasonal availability of some renewable energy sources and its sustainability. The infrastructure required for renewable energy storage and distribution is expensive and needs to be developed. However, a greater acceptance and use of renewable energy is urgently needed, though, as the negative effects of non-renewable energy, such as air pollution and greenhouse gas emissions, are becoming more obvious.

### Different Forms of Renewable Energy

Renewable energy sources have recently drawn adequate attention due to the need to combat climate change and reduce dependence on non-renewable energy sources. Some of the most popular renewable energy forms include solar, biomass, geothermal energy, hydroelectricity, and wind. Moreover, to make the transition to a lower-carbon and more sustainable energy system easier, renewable energy sources are crucial. In recent years, renewables have experienced rapid expansion, driven by both support for policy and significant reductions in cost for technologies like wind power and solar photovoltaics. These factors have contributed to the widespread adoption of renewable energy as a viable and economically feasible alternative to traditional energy sources. In recent years, the compelling growth of wind and solar photovoltaics added to hydropower's already significant contribution to the electricity sector.

According to Zhang and Chen (2022), only one-fifth of the world's energy consumption is accounted for by electricity, and the use of renewable energy for heating and transportation is still essential for the energy transition. This implies that the heating and transportation sectors are of critical focus. A study by Kota et al (2022) noted that biomass energy is a potential renewable energy source considering its cheap price and wide availability.

## Biomass Energy

All organic materials derived from living things, including plant and animal life, are referred to as biomass. It serves as a renewable energy source, with potential uses in heat, electricity, and biofuel production (Bradu et al., 2022). Amjith and Bavanish (2022) claimed that biomass is currently the most popular renewable energy source. To add on, increasing concern over the harmful effects of fossil fuel consumption, such as climate change and global warming, and their negative effects on human health has led to an increase in the use of biomass globally. Through combustion or conversion into other biofuels, the energy stored in biomass can be directly released. Additionally, biomass can be categorised based on where it comes from (Figure 1). Most biomass materials are organic waste products left over from human activity, such as industrial waste, agroforestry residue, sewage, municipal solid waste, or naturally occurring plants like grasses or energetic crops (Rawat & Kumar, 2022; Bradu et al., 2022). According to a study by Kalak (2023), solar energy produced by photosynthesis serves as biomass's main source of energy. According to the authors, animals, plants, and the waste they produce all contain or store biomass energy. The combustion of biomass fuel is used to recover this energy. The combustion of biomass results in the production of heat and carbon dioxide. And Kalak (2023) acknowledged that using biomass energy effectively reverses the photosynthesis process, making biomass energy a renewable source of energy.

According to Gnanasekaran et al. (2023), biomass can be utilized as a fuel through both direct and indirect methods. Direct methods involve burning biomass sources like fuelwood, animal waste, agro-based residues for household cooking and heating purposes. On the contrary, indirect methods include converting animal residues, agro-forestry, and industrial and municipal solid waste to solid, liquid, or gaseous fuels such as biomass briquette and pellets. Using biomass benefits the environment and the economy by providing clean energy and renewable resources (Jaiswal et al, 2023). Also, compared to fossil fuels, biomass energy emits fewer emissions and converting biomass into green energy reduces the quantity of solid waste leaving to disposal sites while reducing the reliance on imported fossil fuel. It is predicted that biomass energy will generate thousands of job opportunities and improve rural households' economic status shortly.

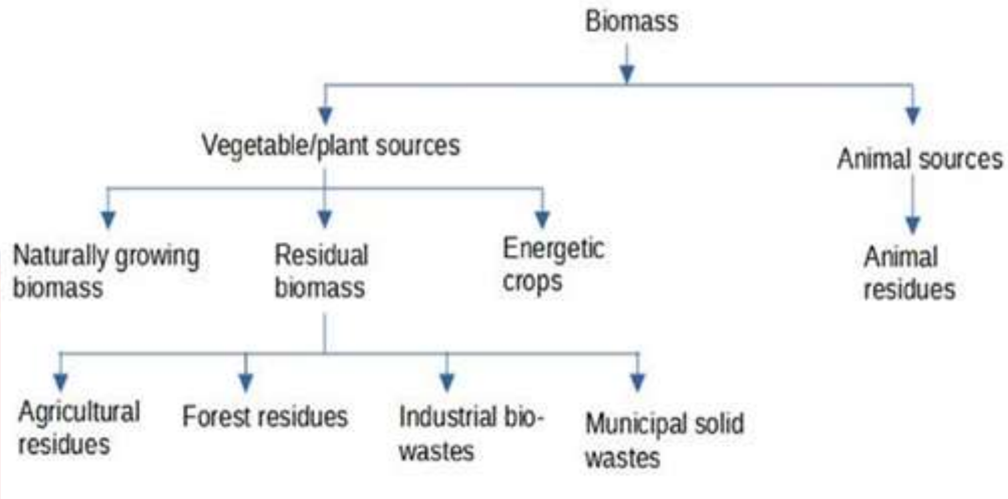

*Figure 1*: Classification of biomass based on origin
Source: Rawat and Kumar (2022)

**Biofuels**

Depending on the type, feedstock, and production technology employed to make the biofuel, different benefits may be obtained (Priya et al., 2023).

Biofuel is an energy source derived from biomass such as organic material found in plants, animals, municipal solid waste, and microorganisms. Biomass is a store of carbon that is ingested by plants during photosynthesis. Modern bioenergy is a promising fuel with close to zero emissions because when this biomass is burned to produce energy, carbon is released into the atmosphere. Biofuel can be solid, liquid, or gaseous. Bioenergy can regenerate making it a renewable and promising energy source. According to Priya et al. (2023), Biofuel is a potential substitute for fossil fuels. In a similar vein, Al-Shetwi (2022) claimed that modern biofuels make up most of the renewable energy worldwide (55%) and account for more than 6% of the world's energy supply. According to the Net Zero Emissions by 2050 Scenario, the use of bioenergy will rise quickly by 2030, replacing fossil fuels. Modern bioenergy usage is expected to grow by an average of 7% annually between 2010 and 2021, with an upward trend. More work is required to hasten the widespread adoption of modern energy from biomass to meet the Net Zero Scenario, which calls for implementation to rise by ten percent per year between 2021 and 2030 while guaranteeing that manufacturing of bioenergy has no detrimental effects on society or the environment (Al-Shetwi, 2022). Although biomass is regarded as a potential renewable energy source to replace fossil fuels, its use is constrained by a few feedstock characteristics, including low energy yield, high moisture content, and inefficient handling and storage techniques. It is advised to pretreat the raw biomass to reduce this restriction before turning it into an environmentally friendly fuel. Studies have extensively described briquetting technology as a promising densification technique that converts raw biomass into solid fuel, reducing the high moisture content, optimizing the heating value, and increasing the bulk density. This briquetting technology has been proven to make raw biomass more energy efficient for domestic heating and cooking applications (Bamisaye et al., 2022; Vaish et al, 2022; Kamal et al., 2023)

### Biomass briquette

Biomass briquettes are densified combustible biomass materials used as a solid fuel for heating or cooking in households or industries (Suryaningsih et al., 2017). Biomass briquettes are eco-friendly alternative solid fuels to traditional charcoal and firewood. Biomass Briquettes are produced from agroforestry wastes, industrial bio-waste, and municipal solid waste. Biomass Briquettes made from densified biomass (Figure 2a) can be cylinder-shaped, cubic-shaped, or rectangular and have a hole in the middle or may not have a hole in the middle (Rawat & Kumar, 2022).

Several international and national standards, including the European Standards (EN ISO 17225), the American Society for Testing and Materials (ASTM 1762-84), and others, specify specific requirements that biomass briquettes must meet. For biomass briquettes to be approved for use, they must adhere to the above-mentioned quality standards. Biomass briquettes are produced using a variety of densification techniques, including, mechanical piston, hydraulic piston presses, ram presses, screw extruders, manual presses, and roller presses. Studies have extensively classified briquetting technology based on compaction into low-pressure technology, high-pressure, and medium pressure. The process of densification also results in the production of biomass pellets (Figure 2b), though these are typically less significant than briquettes due to the intended application, feedstock composition and production process (Rawat & Kumar, 2022).

Pellets typically have cylinder shapes, with diameters ranging from 3 to 27 mm and lengths ranging from 3 to 31 mm, according to Obi and Pecenka (2023). Contrarily, cylindrical briquettes typically have lengths of 10 to 100 mm and diameters of 18 to 55 mm (Rawat & Kumar, 2022; Obi & Pecenka, 2023).

However, no standard dimensions generally distinguish biomass pellets from briquettes (Rawat & Kumar, 2022). Concerns about the quality of raw materials have also been emphasized in previous studies (Rawat & Kumar, 2022; Obi & Pecenka, 2023). To address these concerns, researchers are investigating using composite raw materials to prepare biomass briquettes

(Rawat & Kumar, 2022; Obi & Pecenka, 2023). To improve the general characteristics of the biomass briquettes and adhesive capacity, research into composite raw materials for biomass briquettes aims to take advantage of the diverse structural and chemical properties of various biomass materials. Although there is little information in the existing literature, research has been done on composite briquettes made of materials with complementary and similar properties (Rawat & Kumar, 2022; Obi & Pecenka, 2023).

More investigations are encouraged on using composite feedstock from municipal solid waste and agro-forestry residues to address the problem adequately. Therefore, this study aimed to prepare a composite biomass briquette from a mixture of municipal solid waste using cow dung as a binding agent. This will complement the knowledge of biomass briquette production in Sub Sahara Africa. The production of biomass briquettes is a multi-step process that includes a collection of the raw materials, drying, pyrolysis/carbonization for charred briquette production, particle size reduction, mixing, conditioning, briquetting, drying, and packaging.

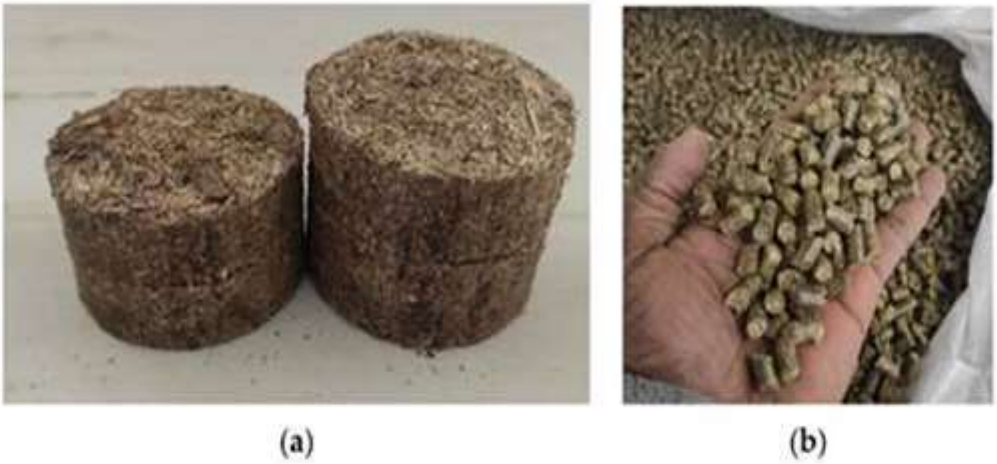
(a) (b)

*Figure 2*: Samples of biomass briquette (a) and samples of biomass pellet

Source: Lubwama et al. (2020)

## Composite Biomass Briquette

Composite biomass briquettes made from municipal based residues offer a promising solution to the growing problem of waste management and energy generation. These briquettes are produced by blending various types of biomass waste derived from MSW, like organic waste, bulky yard waste, paper, cardboard, and wood scraps. The resulting composite biomass briquettes have several advantages. Firstly, they provide a sustainable alternative to fossil fuels by utilizing organic waste that would otherwise end up in landfills, reducing environmental pollution and greenhouse gas emissions. Secondly, these briquettes possess high calorific value, enabling efficient combustion and energy production. Moreover, MSW supports the transition to greener and more sustainable energy practices by serving as a renewable and clean source of fuel for businesses, power plants, and residential heating systems (Lubwama et al., 2020). Also, the composite nature of these biomass briquettes further enhances their performance and versatility. The combination of different waste materials allows for a balanced composition that improves fuel quality and combustion efficiency. The addition of food waste to biomass briquettes is one example of using composite raw materials. This addition can lower the ash content while raising the moisture content of the briquettes. As a result, the briquettes' combustion properties can be improved, resulting in improved combustion performance. Moreover, blending different biomass sources ensures a diverse mix of organic materials, leading to a more stable combustion process and reduced emissions. The composite biomass briquette also possesses better physical properties, such as durability and higher bulk density which facilitate transportation, handling, and storage. By effectively utilizing municipal solid waste through the production of composite biomass briquettes, communities can address waste management challenges while simultaneously contributing to a sustainable energy future (Lubwama et al., 2020).

## Biomass Briquette History

Biomass energy utilization has a long history dating back thousands of years. In ancient times, people relied on biomass materials like agricultural residues, animal waste, firewood and traditional charcoal for domestic heating and cooking purposes. Also, the extensive use of biomass as a source of energy was observed when energy demand increased significantly during the Industrial Revolution in the 18th and 19th centuries. This led to new technologies and processes for utilizing biomass as a fuel source. One of the early developments was the invention of the charcoal briquette, which used charcoal made from wood as a fuel (Guo et al., 2015).

In the late 19th and early 20th centuries, several patents were filed for biomass briquetting machines. These machines were designed to produce briquettes from various biomass materials, including sawdust, agricultural residues, and peat. However, the use of biomass briquettes remained limited during this period and other fossil fuels like oil and coal, dominated the energy landscape (Guo et al., 2015).

In the late 20th century, increasing environmental concerns and the need for sustainable energy sources renewed interest in biomass briquettes. The focus shifted towards utilizing waste biomass materials and agricultural residues that were abundant and often discarded. This helped address waste management issues while promoting the use of renewable energy (Guo et al., 2015).

In recent decades, advancements in briquetting technology and an improved understanding of biomass characteristics have led to efficient biomass briquetting processes. Biomass briquettes are produced using various methods, including mechanical presses, extrusion, and binder-assisted processes. These methods involve compacting biomass materials under high pressure to form dense briquettes (Guo et al., 2015).

Biomass briquettes have applications in various sectors including domestic heating, industrial processes, and power generation. They propose numerous benefits like reduced harmful greenhouse gas emissions, efficient combustion, easy handling and storage and utilization of locally available waste materials (Toklu, 2017).

Biomass briquettes continue to gain recognition as a renewable energy source and a viable alternative to fossil fuels. Their utilization contributes to reducing reliance on non-renewable resources, mitigating climate change, and promoting sustainable development. Ongoing research and development efforts focus on improving briquetting technologies, exploring new biomass sources, and expanding the range of applications (Toklu, 2017). It's important to note that the history of biomass briquettes is an ongoing story with continuous advancements and innovations in the field. The transition to a more sustainable energy future will likely drive further biomass briquetting and utilization developments.

## Importance of Biomass Briquette

Biomass briquettes significantly address environmental, social, and economic challenges (Ambaye et al., 2021). Below are seven of the crucial importance of biomass briquettes:

1. **Renewable Energy Source**: Biomass briquettes are produced from renewable biomass resources such as wood waste, agricultural residues, and energy crops. Unlike fossil fuels, biomass is a replenishable and sustainable energy source. Using biomass briquettes can lessen dependence on finite fossil fuels and create a more sustainable energy future (Ambaye et al., 2021).
2. **Reduction of Greenhouse Gas Emissions:** Burning biomass briquettes releases carbon dioxide ($CO_2$), but the emissions are carbon-net carbon neutral since the $CO_2$ released during combustion is approximately equal to the amount absorbed by the biomass during its growth phase. We can reduce net $CO_2$ emissions and mitigate climate change by substituting fossil fuels with biomass briquettes (Ambaye et al., 2021).
3. **Waste Management and Agricultural Residue:** Biomass briquettes provide a solution for managing agricultural residues and other biomass waste materials. Rather than being burned openly or left to decompose, these waste materials can be processed into briquettes, offering a revenue stream for farmers, and reducing environmental pollution caused by open burning (Ambaye et al., 2021).
4. **Efficient Energy Conversion**: Biomass briquettes have a higher energy density than their raw biomass counterparts. They are denser

and have a lower moisture content, which enhances their combustion efficiency. This means that a smaller volume of biomass briquettes can produce the same amount of energy as a larger volume of raw biomass, making them more convenient for transportation and storage (Ambaye et al., 2021).

5. **Versatile Applications:** Biomass briquettes have diverse applications across various sectors. They can be used for heating residential and commercial spaces, providing heat for industrial processes, and even generating electricity through specialized biomass power plants. Biomass briquettes can be used in existing infrastructure and equipment for solid fuel combustion making them a flexible energy source (Ambaye et al., 2021).
6. **Rural Development and Job Creation:** The preparation of briquettes can be a source of income and employment opportunities, particularly in rural areas where biomass resources are abundant. Establishing biomass briquetting industries can contribute to rural development by creating jobs, supporting local economies, and reducing dependence on external energy sources (Ambaye et al., 2021).
7. **Energy Security:** Biomass briquettes offer an opportunity to enhance energy security by diversifying the energy mix. Countries can reduce their dependence on imported fossil fuels by utilizing locally available biomass resources and strengthening their energy independence (Ambaye et al., 2021).

Biomass briquettes are crucial in promoting sustainable development, supporting the low-carbon economy transition, and promoting environmental impacts. Their importance lies in their ability to provide a renewable, carbon-neutral, and versatile energy source while addressing waste management challenges, deforestation and contributing to rural development.

### Sources of feedstocks for biomass briquette production

### Agroforestry waste

Biomass briquettes can be produced from various agro-based waste materials including rice husk, bagasse, corn stalks, wheat straw, coconut shells, peanut shells, coffee husk and sawdust. These waste materials are abundant and pose disposal challenges. They can be utilized as valuable renewable energy sources by been converted into biomass briquettes. Agro-based waste biomass briquettes offer benefits such as waste management, renewable energy generation, reduced greenhouse gas emissions and rural development. They provide a sustainable alternative to traditional fuels and contribute to a more sustainable, low-carbon future (Deshannavar et al.,2018)

### Municipal solid waste (MSW)

MSW can be utilized as potential feedstock for biomass briquette preparation by extracting the organic fraction from the waste. Organic waste including food, yard, paper, and cardboard, undergoes pretreatment like drying to reduce the high moisture content and thorough sorting to remove impurities. The pretreated municipal solid waste is compressed under high, medium, or low pressure to produce biomass briquettes. These biomass briquettes can be utilized as a renewable energy source for heating, cooking, and industrial applications, contributing to sustainable solid waste management and reducing greenhouse gas emissions. Proper sorting, processing, and quality control measures are essential for effectively utilizing MSW in biomass briquette production. This study utilized a mixture of domestic solid waste and coconut husk to produce composite biomass briquette with cow dung as a binder.

## Municipal solid waste generation rate per capita in Ghana

Numerous metropolitan and municipal assemblies in Ghana face a significant challenge with waste management. The amount of waste produced in urban areas is continuously rising rapidly, while the corresponding infrastructure for its proper management fails to keep up. According to a study by Miezah et al. (2015), that looked at the examination of municipal solid waste in Ghana's ten regions, it was discovered that each day, on average, 0.51 kilograms per person per day, of waste was produced in the regional capitals of Ghana. In contrast, the other study areas, excluding the regional capitals, had a slightly lower rate of 0.47 kilograms per person per day. The Kumasi metropolitan area had the highest waste generation rate among the regional capitals, according to the Miezah et al. (2015) study on municipal solid waste in the ten regions of Ghana. The rate in Kumasi was 0.75 kilograms per person per day, which was slightly higher than the rate in Accra, the nation's capital, which was 0.74 kilograms per person per day. When considering four of the five metropolitan areas studied (Accra, Kumasi, Takoradi, and Cape Coast), the average waste generation rate was 0.72 kilograms per person per day. In contrast, Tamale had a lower average rate of 0.34 kilograms per person per day. Regardless of socioeconomic factors, Ghana's waste generation rates varied from 0.2 to 0.8 kilograms per person per day. This range of waste generation rates is also observed in many cities throughout Sub-Saharan Africa as reported by Friedrich and Trois (2011) and UNEP (2013).

## Physical composition of municipal solid waste in Ghana

According to Miezah et al.'s (2015) research, more than 61% of the waste produced across all regions of Ghana is organic waste. The waste stream is made up of plastics, inert materials, paper, random items, metals, glass, textiles, leather, and rubber in descending order of frequency after organic waste. Ghana's reliance on agricultural products can be attributed to the substantial presence of organic waste. Within the organic waste category, food waste was the most significant sub-category, followed by yard waste. Plastic waste is the second-largest fraction in terms of weight. This is due to the rising prevalence of plastic products, particularly in packaging. Considering these figures, recycling can be accomplished by utilizing waste-to-energy technologies.

## Binders for biomass briquette production

During the densification process of biomass as a fuel source, natural binding agents like proteins and lignin are present. These binding agents are released and activated when exposed to high temperatures and pressures.

According to Oyelaran et al. (2015), the natural binders present in biomass play a crucial role in enhancing the bonding between particles in biomass briquettes. However, there are situations where biomass may not have sufficient natural binders, or the densification process may require the inclusion of additional binders to attain the desired hardness and durability of the briquettes. Binders used for briquettes can be classified into three categories based on their composition: organic, inorganic, and composite binders (Montiano et al., 2015; Kivumbi et al., 2021).

Although binders are essential for improving particle bonding when biomass is being compressed, the precise mechanism governing this process is still unclear (Ibitoye et al., 2021). The particle bonding phenomenon in biomass densification is explained by a variety of theories in earlier research. Among the ideas covered by these theories are capillary pressure, solid bridges, mechanical interlocking bonds, adhesion, and cohesion forces, as well as attractive forces between particles (Samuelsson et al., 2012; Ibitoye et al., 2021). These theories consider mechanical as well as chemical aspects, and they shed light on how the chemical and structural properties of biomass affect the bonding procedure during densification. There are several factors to take into consideration when choosing binders for biomass briquetting. These variables include the price and accessibility of binders, the characteristics of the raw materials, the amount of moisture in the mixture, the pressure required for densification, and the desired high heating value of the biomass briquettes (Olugbade et al., 2019). The price and accessibility of binders are important factors in many developing communities when choosing the best options. To produce biomass briquettes to be viable and sustainable, these communities frequently give preference to inexpensive and easily accessible binder options. Binders can generally be categorized into two types: organic and inorganic binders. Organic binders are derived from natural substances, such as plant-based materials or waste products, while inorganic binders are typically mineral-based. However, based on their composition, binders can be further classified as organic, inorganic, and compound, depending on the materials used and their combination (Obi et al., 2022). This categorization allows a more comprehensive understanding of the different types of binders available and their suitability for specific biomass briquetting applications.

### Types of Binders for biomass briquette preparation

#### Inorganic binders

Inorganic binders offer several advantages, including strong adhesion, absence of sulfur pollution, low cost, and good hydrophilicity. However, they do have some drawbacks, such as lower combustion efficiency due to their limited calorific values and a tendency to produce higher ash content (Shu et al., 2012). Examples of inorganic binders include clay, bentonite, and ammonium nitrate. These binders can be categorized into three main types: industrial binders (such as sodium silicate, cement, magnesium chloride and bentonite clay), neutral binders (including kaolin clay and limestone), and eco-friendly binders (like calcium oxide, iron oxide and magnesium oxide which are desulfurization agents) (Zhang et al., 2018).

Recent studies focused on biomass briquetting have shown limited utilization of inorganic binders, as highlighted by Obi et al. (2022).

#### Organic binders

According to Zhang et al. (2018), organic binders commonly possess favorable binding properties such as high impact and abrasion strength, along with strong resistance to water. However, these binders tend to have limited thermal stability and reduced mechanical strength because they tend to decompose rapidly at high temperatures, as noted by Miao et al. (2019). These binders are renowned for being widely accessible, inexpensive, highly calorific, and having a low ignition temperature. There are four major types of organic binders used in biomass briquetting: lignosulfonate, tar pitch and petroleum bitumen (including coal tar pitch and tar residues), biomass binders made from agricultural waste and forestry biomass, and polymer binders like resins, polyvinyl chloride, and starch. Based on how organic binders interact with water, Miao et al. (2019) further divides them into hydrophobic binders, such as coal tar and asphalt, and hydrophilic binders, such as biomass. However, Yun et al. (2014) emphasizes that the main reason for the limited commercial use of organic binders in biomass briquetting is that they lack adequate thermal stability.

### Composite binders

In biomass briquetting, a variety of binders are combined to form compound or composite binders. By using this method, it is possible to take advantage of the unique binding benefits of each binder, producing briquettes with improved thermal stability and increased mechanical strength. Examples of composite binders include bentonite mixed starch, carbide lime, and molasses (Miao et al., 2019). Also, Zhang et al. (2018) provide a classification of different types of briquette binders, focusing on their strengths and weaknesses in biomass briquette production. Table (1) presents an overview of binder types, along with their respective strengths, weaknesses, and examples, offering a comprehensive understanding of the various binder options available.

**Table 1: Binder types and their characteristics for briquetting**

| Binder category | Examples | Advantages | Disadvantages |
|---|---|---|---|
| Inorganic | Limestone, clay, cement, bentonite, calcium oxide, and iron oxide. | Wide availability, good thermal stability, high bonding strength, sulfur retention, and hydrophilicity. | High ash content, high price, and low heat. |
| Organic | Starch, molasses, lignin, guar gum, and water hyacinth. | High heating value, high mechanical strength, widely available, and low price. | Low ignition temperature, the release of pollutants during combustion, limited thermal stability, and poor water resistance. |
| Composite | Bentonite and starch, resin and starch, pitch, and molasses. | High thermal stability, bonding strength, water resistance, and mechanical properties. | Mainly high price and high ash content. |

Source: Zhang et al. (2018)

### Cow dung as a binder

Cow dung has indeed emerged as a highly promising binder for biomass briquette production, providing an eco-friendly and cost-effective solution. Due to its abundant availability and natural adhesive properties, cow dung serves as an effective binding agent in forming briquettes. This renewable and sustainable binder option offers environmental benefits by utilizing a waste product while reducing the dependence on synthetic binders. Additionally, cow dung has been found to contribute positively to the combustion characteristics and overall quality of biomass briquettes. Moreover, this natural material is abundantly available in rural and agricultural regions and presents a sustainable alternative to synthetic binders with potential environmental drawbacks. When mixed with other biomass materials such as sawdust, agricultural residues, or paper waste, cow dung acts as a remarkable binding agent. Its inherent sticky and adhesive properties, primarily attributed to its high fibre content, facilitate the effective binding of biomass particles. This results in briquettes with enhanced cohesiveness, density, and stability, ultimately yielding a fuel source with superior combustion characteristics (Zhang et al., 2018).

The utilization of cow dung as a binding agent for low pressure briquetting brings forth numerous advantages. Firstly, it addresses waste management challenges by utilizing an abundant agricultural by-product that would otherwise be discarded or left to decompose. This conversion of cow dung into a valuable resource promotes a circular economy and reduces waste in rural areas. Moreover, the incorporation of cow dung as a binder contributes to mitigating greenhouse gas emissions as it effectively sequesters carbon during the briquette manufacturing process. Additionally, cow dung-based briquettes offer a viable substitute for traditional fuels like firewood and traditional charcoal, particularly in regions with a significant livestock population. By encouraging sustainable energy practices and reducing reliance on finite fossil fuels, these briquettes foster environmental conservation while simultaneously creating opportunities for socioeconomic development in rural communities (Zhang et al., 2018).

### Biomass briquette production process

Briquetting typically begins with gathering the residues which are then reduced in size, dried, and then compacted using an extruder or press. Briquetting can be done with or without the use of a binder. The method without a binder is more convenient, although it requires advanced and expensive presses and drying equipment.

### Collection of feedstocks

The initial stage of biomass briquette production is collecting the feedstock. The raw materials are carefully gathered and stored in specific locations such as storage rooms or silos at the pretreatment location or designated collection points (Karkania et al., 2012).

### Drying of feedstocks

Drying is a crucial step in both briquette and pellet production processes, aiming to achieve a uniformly dried feedstock regarding the high moisture content in biomass. The moisture content plays a crucial role in the binding mechanisms and has a direct impact on the quality of the biomass briquettes. It is recommended that the feedstock has an approximate moisture content of 12%, while the target for the final product is typically within the range of 6% to 8% moisture content, as stated by Karkania et al. (2012).

### Pyrolysis of feedstocks

The carbonization process involves several steps for converting biomass into char through pyrolysis. These steps are as follows: The pretreated feedstocks are collected and packed into a kiln, the primary carbonization vessel. Once the biomass is loaded into the kiln, the top is sealed using a metal cover attached to a conical chimney. This closure ensures a controlled environment for the carbonization process. In the firing process of the kiln, a small quantity of biomass is used to initiate the ignition. Once ignited, the kiln doors are tightly sealed to initiate the pyrolysis process. The kiln is designed with perforations underneath to facilitate the pyrolysis process. These perforations allow a slow and controlled airflow, allowing the fire to spread throughout the biomass gradually. As the pyrolysis process progresses, the biomass undergoes complete carbonization, resulting in the formation of char. Once the biomass has been fully carbonized, the kiln lid is removed. To ensure the stability and quality of the char, water is sprinkled over it after the lid is removed. This step helps to cool and solidify the char. The next step is to reduce the particle size of the briquette.

### Particle size reduction

Particle size reduction is crucial for biomass briquetting as it serves various purposes. Research has highlighted its ability to partially break down the lignin content in biomass, thereby enhancing inter-particle bonding due to the increased total surface area (Tumuluru et al., 2011). Reducing biomass size also leads to higher bulk density, improving flow during the densification process (Tumuluru et al., 2011). Numerous methods can be employed for size reduction, such as milling, chipping, chopping, blending, shredding, crushing, and grinding. Based on their dimensions, the size-reduced biomass can be categorized as ground to a finer consistency (<8 mm), chipped (8–50 mm), or chopped (50–250 mm) (Karkania et al., 2012).

### Mixing and addition of binder

During the mixing stage, if applicable, there is a deliberate effort to blend the processed feedstock or various combinations of feedstocks with binders like cow dung. The primary goal is to enhance the biomass briquette quality or improve efficiency. Carefully incorporating binders into the feedstock at a known ratio allows optimal biomass briquette characteristics and the production process can be optimized for better outcomes (Karkania et al., 2012).

### Conditioning

At the conditioning stage, when required, the mixture undergoes a process of conditioning and softening. This is typically accomplished by introducing superheated steam or injecting water into the mixture before densification occurs. Conditioning prepares the mixture for effective densification by making it more flexible and easier to handle. The mixture becomes appropriately softened by applying superheated steam or water injection, allowing for smoother and more efficient densification. However, the conditioning is not compulsory but optional (Karkania et al., 2012).

### Briquetting

The briquetting stage involves feeding the preconditioned and homogeneous feedstock into specialized machines where densification occurs. Utilizing hydraulic, mechanical, or roller presses, briquettes are frequently produced. When using a reciprocating ram or plunger to press the feedstock into a die to create a briquette, this process is known as piston-pressed briquetting. Either a mechanical or hydraulic gearbox is used to move the piston. As contrasted with this, according to Karkania et al. (2012), screw presses use single- or double-screw extruders with heated taper dies to extrude the product. However, the above-mentioned briquetting machine is expensive and might appear financially unfeasible in low and middle-income households. Therefore, the manual press has been introduced and seems appropriate for biomass briquette production in developing countries as a cost-effective technique to produce biomass briquettes for domestic cooking and heating applications.

**Drying/ Packaging**

After the biomass briquettes are produced, they can be sun-dried for 4 to 5 days, depending on the weather condition and later packaged for their intended application (Karkania et al., 2012).

**Analysis and Combustion Test**

To ensure quality control, biomass briquette produced must conform to International solid fuels standards such as the European Standard (EN ISO 3324), American Society for Testing and Materials (ASTM D3172-04), and other recognized international and national standards. Therefore, the biomass briquette produced is subjected to energy content analysis, ultimate analysis, proximate analysis, and combustion test to determine its suitability for domestic and industrial applications. The generic process of biomass briquette production is displayed in Figure 3.

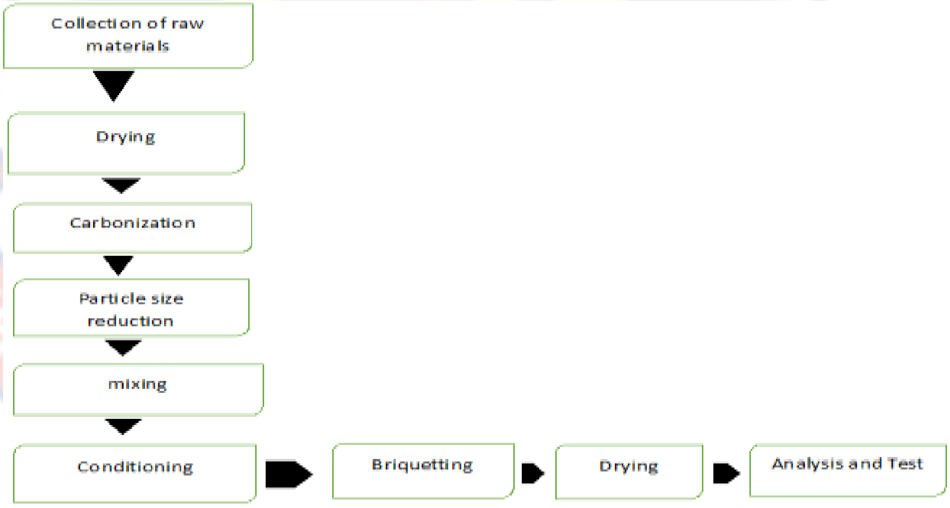

*Figure 3*: Charred biomass briquette production flow chart
Source: Christoforou (2022)

**Quality parameters of good biomass briquette**

Biomass briquettes possess favourable combustion properties making them an effective and efficient fuel source. Though there is no specific international standard for biomass briquettes, general guidelines and specifications are commonly followed in the biomass briquette industry. Below are the typical specifications for biomass briquettes.

### High Calorific Value

Gross calorific value is a critical quality parameter for biomass briquette. Biomass briquettes should have a high value representing the heat energy released during combustion. The calorific value is generally measured in British thermal units per pound (BTU/lb) or megajoules per kilogram (MJ/kg).

The typical range for gross calorific value is between 17 and 22 MJ/kg (7,300-9,500 BTU/lb) (Dinesha et al., 2019). Therefore, estimating the energy content of various raw materials before the briquette is essential to ensure a high calorific from the resulting biomass briquette.

### Low Moisture Content

Biomass briquettes are typically manufactured with low moisture content which improves their combustion efficiency. It is crucial for the raw material for biomass briquette production to have an optimal moisture content, ideally ranging from 8% to 12%. High moisture content can lead to difficulties during the grinding process. The absence of excess moisture reduces the need for additional energy to evaporate water during the burning process, allowing for more efficient and cleaner combustion (Dinesha et al., 2019).

### High Bulk Density

Biomass briquettes should have a high bulk density which contributes to their slow and controlled combustion. The dense structure leads to a longer burning duration providing a sustained heat output. It also makes them simpler to transport, store and handle. Estimating the bulk density of the raw materials for biomass briquetting is crucial to ensure that the resulting briquettes have a higher calorific value. The density is classically measured in pounds per cubic foot (lb/ft³) or kilograms per cubic meter (kg/m³) The thickness of biomass briquettes can vary depending on the materials used but it is generally 600 to 1,200 kg/m³ (37-75 lb/ft³) (Dinesha et al., 2019). Considering these factors ensures that the raw material is suitable for the briquetting process, producing high-quality briquettes with desirable combustion properties. The impact of different process variables on the bulk density of biomass briquettes can be significant. These elements include the amount of binder, particle size, moisture content, compaction temperature, and pressure (Yun et al., 2014). These elements are crucial in determining the density and compactness of the briquettes, which in turn affects their physical and combustion characteristics. To produce biomass briquettes to have the desired bulk density, these variables must be properly controlled and optimized.

### Low Ash Content

The feedstocks used for biomass briquetting should maintain a low ash content to minimize slag formation during combustion. This helps maintain the efficiency of the briquettes as a fuel source (Dinesha et al., 2019). Low ash content also implies less maintenance and improved combustion efficiency. The ash content is typically stated as a percentage of the briquette's total weight. Ideally, the ash content should be below 10% for high-quality briquettes.

### High Volatile Matter

The combustible elements in biomass briquettes are represented by the volatile matter content. It is specified as a proportion of the entire weight.

Higher volatile matter content generally indicates better combustibility. The specific requirements for volatile matter can differ depending on the intended application of the biomass briquette (Dinesha et al., 2019).

### High Carbon Content

Biomass briquettes should have a high carbon content to ensure efficient combustion and minimize emissions. Briquette carbon content is frequently stated as a fraction of the total weight of the product. Indicating a higher concentration of combustible material within the briquette, a higher carbon content denotes higher fuel quality (Dinesha et al., 2019). This factor plays a crucial role in determining the briquette's energy potential and fuel efficacy.

### Dimension

Biomass briquettes are typically cylindrical, measuring 200–300 mm in length and 50–100 mm in diameter. The dimensions may vary based on regional preferences and equipment specifications (Dinesha et al., 2019).

### Application of Briquette

Biomass briquettes are renewable energy fuels made from biomass materials. They have several applications including heating and cooking in residential and commercial settings, industrial heat and power generation, agricultural uses like crop drying and greenhouse heating, institutional and commercial heating, co-firing with coal, waste management and substituting traditional charcoal. Biomass briquettes provide a sustainable and eco-friendly alternative to fossil fuels thereby reducing emissions and promoting a circular economy.

# CHAPTER THREE

# MATERIALS AND METHOD

## Composite biomass briquette production from a mixture of domestic solid waste and coconut husk with cow dung as a binder

### Research Design

The study employed a mixed-methods design that combines qualitative and quantitative approaches and adopts a pragmatic paradigm. This methodological approach enables the collection and analysis of both qualitative and quantitative data while enabling a thorough exploration of the research main objective. The study consists of two phases. Firstly, domestic solid waste was quantified and characterized to estimate the domestic waste generation rate per capita and physical composition identifying suitable organic waste components for composite biomass briquette production across three socio-economic areas in Cape Coast North Sub Metropolitan. The second phase of the study was an experimental design and analysis to prepare composite biomass briquettes from a mixture of domestic solid waste components identified during the solid waste quantification and characterisation study.

### Description of Study Area

The municipal solid quantification and physical composition study was conducted in three stratified communities in Cape Coast North Sub Metropolitan, namely: Fourth Ridge, Akotokyir and Ansepetu in Cape Coast North Sub Metropolitan. Cape Coast North Sub Metropolitan is one of the two sub-metropolitans under the Cape Coast Metropolitan Assembly (CCMA). Cape Coast Metropolis lies within a latitude of 5°7'53.44" North and longitude

1°16'46.11" West of the Greenwich Meridian. The experimental design and laboratory analysis were conducted at the School of Agriculture Food and Nutrition Laboratory, University of Cape Coast Technology Village.

*Figure 4*: Map of the Study Area

**Instruments and Materials**

The instruments used in the domestic solid waste audit and the experiment to produce the composite biomass briquette include; Electronic Suspended Balance (KERN CH Version 3.5), Delmhorst Moisture meter (J-2000), Bomb calorimeter (Perr 6400), Electronic Digital Vernier Caliper (VINCA DCLA-0605), Laboratory Oven (YIHENG, DGH-9140A), Infrared thermometer (Lasergrip 1080), CHNS analyzer (Model Vario EL-III), Analytical Balance (Shimadzu Corporation, SHIMADZU), muffle furnace (Thermo Scientific™), Stopwatch and SEM apparatus (HITACHI (Corp.), Tokyo, Japan).

The laboratory and field equipment used in this study include; black polythene bags, black Plastic sheet (5mm thick), chopper, traditional stick broom, Tyler sieve (2mm), Charring Unit (170-litre metal drum kiln), Mortar and pestle, blender, knife, crucible, kerosene, traditional tripod stove, cooking pot, lighter, dish pan (black), stirrer, hand mould, hammer, water, mixed organic waste obtained from the solid waste audit in Cape Coast North Sub Metropolitan, and fresh cow dung obtained from the University of Cape Coast farm.

### Domestic solid waste quantification and physical composition

### Sample Size Determination

Due to the heterogeneity and variability of domestic solid waste, an established statistical technique was employed to estimate the number of waste samples to be examined. The sample size formula for continuous variables measurement as recommended by Cochran (1977) was used to estimate the required sample size to obtain accurate data on the solid waste generation rate per capita and physical composition at households in Cape Coast North Sub Metropolitan. Given a desired level of precision, a desired level of confidence, and an estimated proportion of the element present in the population, the Cochran formula was used to estimate the ideal sample size. Cochran's formula is particularly appropriate in scenarios with large populations. If the population size is relatively small, there is a "correction" that may be used to lower the sample size given by Cochran's formula. Cochran’s formula has been widely used in similar studies by Seshie et al. (2020), Miezah et al. (2015), Puopiel (2010) and Gomez et al. (2008). The equation is depicted below:

$$\boldsymbol{n} = \frac{\boldsymbol{z^2\, p * q}}{\boldsymbol{e^2}} \qquad (1)$$

Where: $\boldsymbol{n}$ is the sample size, $\boldsymbol{Z}$ is the value for the chosen alpha level from the Z table, which in this study is 1.96 since the desired confidence level is 95%, **p** is the (estimated) proportion of the population that has the attribute under question, **q** is (1 – p), **e** is the desired margin of error (± 0.05).

Therefore: $\boldsymbol{n} = \frac{(\mathbf{1.96})^2(\mathbf{0.5})^2}{(\mathbf{0.05})^2} = \mathbf{385}$

### Classification of settlements into socio-economic areas

The Cape Coast Metropolitan Assembly (CCMA) has classified all settlements into three fundamental socioeconomic groups, namely: first-, second-, and third-class residential areas. The CCMA classification, which is based on socioeconomic development factors, considers several variables, including the type of buildings, the standard of living, and the accessibility of social amenities in residential areas. Additionally, the Cape Coast Metropolitan Assembly regularly reviews and updates the settlement classification to ensure that accurate and current information is provided (CCMASSP, 2019).

### First class communities

These communities have comparatively good feeder roads, dependable access to social amenities and services like water and electricity, security, well-designed homes with fences and other social amenities. The homes are typically single- or multi-story detached structures with sizable paved or grassed yards. Despite the perception that members of this class have high incomes, there has not been any research on income stratification to accurately determine the socioeconomic standing of the settlers usually with small family sizes (CCMASSP, 2019).

### Second class communities

According to the Cape Coast Metropolitan Assembly, these residential areas comprise flats or bungalows as typical buildings. Most of the time, multiple households occupy the structures. The buildings are detached or semi-detached with paved courtyards and occasionally backyard gardens. Some societal amenities and services might have been improved.

### Third class communities

These residential areas lack some social services and amenities. They are mainly occupied by slum-dwelling households. The buildings vary from storey buildings or detached structures to squalid shacks. Other characteristics of these low-income communities include scarce resources, poorly designed housing, high crime and violence and inadequate educational opportunities.

### Household identification for sampling

Nordtest (1995) methodology used for studies on socio-economic areas was employed to determine the required number of households used in achieving the minimum sample size of between 100 to 200kg which is ideal for the solid waste characterization study. And hence thirty (30) households were randomly selected from each socioeconomic area. This methodology was also applied in similar studies by Seshie et al. (2020) and Gomez (2008). From Table 2, it is observed that the sample size used in the solid waste characterization study was higher than the statistically required sample size. However, increasing the sample size was appropriate based on the central limit theorem which states that as the number of samples to be analyzed increases, the accuracy in determining the desired parameters also increases. Though, the quantity of solid waste to be analyzed should be manageable, considering the availability of resources and time available to conduct the study.

**Table 2: Number of households selected and the samples collected for analysis at various socioeconomic levels within the study area**

| S/n | Residential Area category | Sampling communities | Number of Selected Households | Required Sample size. | Number of samples collected and analyzed |
|---|---|---|---|---|---|
| 1 | First-Class | Fourth Ridge | 30 | 385 | 1260 |
| 2 | Second Class | Akotokyir | 30 | 385 | 1260 |
| 3 | Third Class | Ansepetu | 30 | 385 | 1260 |

Source: Field Survey (2023)

The sampling process involved random selection of households within stratified socioeconomic communities. The required sample size and number of households were determined beforehand. In each socioeconomic area, households were chosen by selecting every 8th house from the first point of contact within the sampling area. The selection of households commenced from the direction of the first point of contact with any house in the study area. This approach ensured a systematic and unbiased representation of households across the socioeconomic communities.

**Stakeholders' engagement and site assessment**

After an ethical clearance with ID: (UCCIRB/CANS/2023/08) was obtained from the University of Cape Coast Institutional Review Board (UCCIRB), it was crucial to conduct site assessments at each residential area across the socio-economic zones before commencing the domestic solid waste audit. The community entry and site assessment had two objectives: 1) to seek the selected communities' leaders and residents' full support for the study and

2) to gather preliminary data to support the sampling and sorting plan for each selected socio-economic area under the study. To achieve this, the Cape Coast Metropolitan Assembly members responsible for the selected communities under the study were contacted and briefed about the primary objective of the municipal solid waste audit. As shown in figure 5, these communities' leaders were instrumental in seeking the corporation of participants from the selected households to fully support the study's objective. Also, suitable locations were identified for the on-site weighing and component-wise sorting of domestic solid waste.

*Figure 5*: Stakeholders' engagement and preliminary site assessment before the domestic solid waste audit commenced in Ansepetu

## Quantification of Domestic Solid Waste

The methodology used in this study for the solid waste quantification characterization was adapted from the American Society for Testing and Materials (ASTM D 5231-92), Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste. The selected households were visited and issued black polythene bags labeled with uniform size and asked to accumulate their daily domestic solid waste generated in the black polythene bags. The solid waste generated at selected households on the first day of the solid waste audit was discarded as the samples may contain solid waste accumulated from previous days. The actual sampling of solid waste commenced on the second day to the eighth day (Pathak et al., 2020; Donacho et al., 2023). The collected domestic solid waste samples were weighed on-site using an Electronic Suspending Balance (KERN CH Version 3.5). The data on the daily per capita waste generation rate (PCWGR) were recorded separately on a Microsoft Excel Spread sheet for each socio-economic area under the study. The domestic solid waste quantification is depicted in figure 6 (a). Also, the domestic solid waste sampling was carried out for seven (7) consecutive days across all socio-economic zones to account for the weekdays variations in the per capita waste generation rate (Nadeem et al., 2022). Additionally, the solid waste audit was repeated five (5) times during the study's period maintaining the same sample size, sampling methodology, solid waste components to be sorted and sampling communities. The rationale was to account for the seasonal variations in the per capita waste generation rate and physical composition (Adeleke et al., 2021). The study was conducted between March and May 2023. The equation for estimating the per capital waste generation rate is shown below:

$$\text{PCWGR} = \frac{\text{wieght of domestic solid waste generated at household}}{\text{Total number persons in the household x total generation days}} \qquad (2)$$

**Determination of physical composition of the domestic solid waste**

A suitable flat area was identified with proximity to the final waste disposal site in each socio-economic area. Following the ASTM D 5231-92

Standard for the determination of the composition of unprocessed municipal solid waste, 10 waste sample bags were randomly selected from the total waste sample bags collected from the households. The ten waste sample bags randomly selected were representative to achieve a minimum sample size of 200 to 300lb (91 to 130 kg) for solid waste characterization study as recommended by the American Society for Testing and Materials (ASTM D 5231-92). The ten waste sample bags were emptied onto a 5 mm thick black plastic sheet placed on the ground. Following the ASTM standard with modifications, the following seven solid waste components were considered for sorting:  organics, paper, plastic, metals, rubber and leather, inert materials and miscellaneous items were the eight solid waste components analyzed. The coning, quartering and manual sorting techniques were applied to estimate the physical composition of the domestic solid waste across the three socio-economic areas in Cape Coast North Sub Metropolitan. The Solid waste sorting is shown in figure 6 (b). The percentage composition of each waste component produced by the households was estimated by dividing the total amount of each sorted solid waste component by the total number of all mixed solid waste components collected during the six weeks (42 days) between March and May, 2023 and multiply the result by 100 to get the percentage. The procedure was followed in all socio-economic areas under the study. The equation is shown below:

*Figure 6*: Domestic solid waste component-wise sorting in Ansepetu (a) domestic solid waste quantification in Akotokyir (b)

$$\%\textbf{Composition of sorted waste} = \frac{\text{wieght of sorted waste}}{\text{The total mixed weight of sample}} \times 100 \qquad (3)$$

The component-wise weighing and sorting was conducted for seven consecutive days and repeated five times during the entire study period. The results were recorded separately on a Microsoft Excel spreadsheet for each socio-economic area in the study. Moreover, during the component-wise weighing and sorting exercise suitable solid waste components were identified, collected, and stored for composite biomass briquette production. However, plantain peels, cassava peels, sugar cane bagasse and empty fruit bunch (EFB) were the solid waste components collected for composite biomass briquette production and this was the primary rationale for the solid waste audit. The domestic solid waste components collected as feedstocks for composite biomass briquette production were sun-dried, milled and characterized.

## Characterisation of feedstocks for composite biomass briquette production

### Proximate analysis of feedstocks

The proximate analysis of feedstock consists of the composition of the feedstock in moisture, volatile matter, ash, fixed carbon, and their calorific value. The proximate analysis was done according to the American Society for Testing and Materials (ASTM D-3173).

### Moisture content Determination

Crucibles made of porcelain were cleaned, dried, and weighed. The samples were weighed in spotless, oven-dried crucibles at a weight of about 10–12g. To ensure even heating, the sample-containing crucibles were positioned all around the oven's base. For 48 hours, they were kept in a thermostatically controlled oven at 105 $^0$C. The samples were taken out at the end of the time, cooled in a desiccator, and then weighed. This was done in triplicates. The sample's percentage of water loss was then used to calculate the moisture content. The composite biomass briquette's moisture content was calculated using the formula below:

$$\%\ \mathrm{MC} = \frac{initial\ weight\ (w1) - final\ weight\ (w2)}{initial\ weight\ (w1)} \times 100 \qquad (4)$$

### Determination of Volatile Matter

The percentage of the volatile matter was first calculated by placing 3 g of the solid waste sample using a clean crucible and placed in an oven at 110 $^0$C for two (2) hours to maintain a stable weight. The sample was subsequently removed from the oven and cooled in a desiccator. Once the sample had cooled, the sample was placed in a crucible with an oven dry weight (w2) and heated for 10 minutes at the temperature of 550 $^0$C to obtain weight (w3)

(ASTM D3175). The formula below was used to estimate the percentage of volatile matter:

$$\%VC = \frac{oven\ dry\ weight\ (w2) - weight\ of\ broken\ briquette\ (w3)}{oven\ dry\ weight\ (w2)} \times 100 \qquad (5)$$

## Ash Content Determination

The dried composite biomass briquette samples were heated under carefully controlled conditions. They were initially slowly heated in an oven at 105°C for about sixty minutes. The samples were then placed in a furnace for an overnight exposure to a temperature of 550°C. The heating cycle was repeated until all the carbon was completely burned off. After cooling in a desiccator and being weighed, the resulting ash in the dish was taken out of the furnace. By calculating the proportion of the ash content to the original sample, the percentage of ash content was estimated. The formula used to estimate the ash content is depicted below:

$$\%\ Ash\ Content = \frac{weight\ of\ ash\ (w4)}{dry\ weight\ (w2)} \times 100 \qquad (6)$$

## Determination of Fixed Carbon

The percentage of fixed carbon was estimated by subtracting the summation of the %volatile matter and % ash content from 100.

$$\%\ FC = 100 - (\%VM + \%\ Ash\ content) \qquad (7)$$

## SEM Analysis of feedstocks for composite biomass briquette

To assess the morphological characteristics of the feedstocks used for composite biomass briquette production, scanning electron microscope (SEM) analysis was conducted. The SEM analysis utilized a specific model equipped with an EDAX (Energy-Dispersive X-ray Spectroscopy) system. The EDAX model employed in this study was the Nano Xflash detector from Bruker, a German manufacturer known for its high-quality instruments. The SEM analysis was carried out at the Chemical Engineering Laboratory, Kwame Nkrumah University of Science and Technology (KNUST) in accordance with the DIN EN ISO 9001:2008 standards, ensuring adherence to established quality management protocols. The SEM imaging provided detailed visual information about the surface morphology and microstructure of the feedstocks (plantain peels, cassava peels, sugar cane bagasse, coconut husk and empty fruit bunch) used for the composite biomass briquetting, enabling a comprehensive understanding of their physical characteristics at the microscopic level.

The SEM analysis helps the researcher to gain valuable insights into the structural properties of the raw materials. This information is essential for evaluating the quality, performance, and potential applications of suitable raw materials for biomass briquette production.

### Preparation of composite biomass briquettes

Biomass briquette preparation required several steps including feedstock collection, pretreatment pyrolysis, particle size reduction, briquette sample preparation and synthesis, briquette analysis and test.

### Collection of feedstocks

Cassava peels, empty fruit bunch, sugar cane bagasse, and plantain peels, were collected from Fourth Ridge, Akotokyir and Ansepetu between March and May 2023. Dried coconut husks were collected from a random coconut seller at Abura Market in Cape Coast North Sub Metropolitan. The Choice of feedstock is primarily based on availability, low cost, and individual characteristics. A mixture of organic solid waste was chosen based on their availability and optimal combustion characteristics. Moreover, solid wastes are indiscriminately disposed of in the environment, posing serious environmental problems. Therefore, adding value to these locally available wastes by producing clean and cheap alternative cooking fuel is appropriate for this study.

**Drying of feedstocks**

The raw materials underwent a pre-treatment process that involved sun-drying them for four days in an environment with ambient temperatures between 24 °C and 32.2 °C to reduce their moisture content. By allowing for the natural evaporation of moisture from the raw materials, this pre-treatment method reduced the moisture content of the materials and improved their suitability to produce biomass briquettes. The dried feedstocks were thoroughly sorted to remove unwanted materials like metals and plastics. The particle size of feedstocks was subsequently reduced before carbonization.

**Pyrolysis of feedstock**

The pyrolysis process was carried out based on previous experiments conducted by Bonsu et al. (2020) using a mixture of solid waste components. This mixture consisted of plantain peels, cassava peels, sugarcane bagasse, empty fruit bunch, and coconut husk. Before the experiment, these feedstocks were dried under the sun for four days at an ambient temperature of 24 °C and 32.2 °C. The total weight of the dried feedstocks was 28.5 kilograms which were divided into five sections each weighing 5.7 kilograms. Each section representing a specific feedstock was pyrolyzed separately using a 170-litre metallic drum as a kiln. The pyrolysis process occurred within the metallic drum, and various observations such as the initial quantity of feedstocks, the final quantity after the pyrolysis, duration, and biochar yield (refer to Table 3).

A metallic drum with dimensions of 50.4 cm in height and 30.2 cm in width at the top and bottom was used for controlled burning. The metallic drum's bottom was perforated with steel that had a diameter of 5 mm and a length of 21.25 mm to allow for controlled airflow. Because of the restricted oxygen supply and slower burning caused by these perforations, the biomass was able to distribute heat more evenly. On the drum's cover, a hole with a diameter of 15 cm was also made. A two-way open cylindrical pipe with a chimney that was 15.4 mm in diameter and 21.2 cm long was inserted through this hole to help release the gas and smoke during the burning process. To initiate the ignition of the feedstocks inside the metallic drum, a small amount of biomass in the form of dried leaves was used. Once the ignition took place, the initial smoke was allowed to disperse. The sides of the metallic drum were covered to enclose the environment. After loading the biomass into the drum, the top was closed using the cover and the chimney was attached. With these preparations, both the metallic combustion drum and the feedstocks were ready for the pyrolysis process. During the initial stage of combustion, the smoke emitted from the pyrolysis of the feedstocks exhibited a creamy brown colour.

During the carbonization process, the lid on the top of the kiln was initially left open for approximately 10 minutes to allow volatile gases to escape. Afterwards, the lid was properly sealed to prevent the entry of air. The pyrolysis process proceeded slowly at an average temperature of 400 °C which was monitored using a thermometer in a low-oxygen environment. The duration of the pyrolysis varied for each feedstock, with coconut husk taking 14 minutes, sugar cane bagasse taking 6 minutes, plantain peels using 11 minutes and cassava peels taking 11 minutes. The variation in resident time could be attributed to the composition of each feedstock.

After the pyrolysis, water was sprinkled on the charred feedstocks to extinguish the fire and then they were allowed to cool for 1 hour. Subsequently, the charred feedstocks were sun-dried for 6 hours to reduce moisture content and facilitate easier crushing. The biochar yield after pyrolysis varied among the feedstocks, based on the recorded initial and final weights. The final weight of the coconut husk was 3.2 kg, sugar cane bagasse was 2.85 kg, cassava peels were 2.34 kg, empty fruit bunch was 3.04 kg, and plantain peels were 2.41 kg (as shown in Table 3). The mentioned values were employed in determining the percentage recovery of biochar for each specific feedstock. This calculation allows for the evaluation of the efficiency of the biochar production process and the amount of biochar obtained relative to the initial feedstock used. The highest biochar yield was obtained from coconut husk at 53.3%, followed by empty fruit bunch at 50.0%, sugar cane bagasse at 42.3%, and cassava peels at 41.1%. These results demonstrate the efficiency of the metallic drum used as a kiln. The results of the pyrolysis are depicted in Table 3 below.

**Table 3: Results of Pyrolysis of various feedstocks for composite biomass briquette production**

| Description of feedstocks | Initial weight (kg) | Final weight (kg) |
|---|---|---|
| Coconut Husk | 5.7 | 3.2 |
| Sugar Cane Bagasse | 5.7 | 2.85 |
| Cassava Peels | 5.7 | 2.34 |
| Empty Fruit Bunch | 5.7 | 3.04 |
| Plantain Peels | 5.7 | 2.41 |
| Biochar yield for various feedstocks (%) | | |
| Coconut Husk | 56.1 | |
| Sugar Cane bagasse | 50.0 | |
| Cassava peels | 41.1 | |
| Empty Fruit Bunch | 53.3 | |
| Plantain Peels | 42.3 | |
| Quantity of composite biochar used for biomass briquette production (kg) | 4.5 | |
| Number of Biomass briquettes produced from composite biochar (lump) | 14 | |

*Figure 7*: Composite biomass preparation stages, (a) dried feedstocks before pyrolysis (b) pyrolysis (c) particle size reduction (d) Screening and (e) Composite biomass briquettes
Source: Field Experiment (2023)

### Particle size reduction

The charred feedstocks weighing a total of 13.84 kilograms from the initial 28.4 kilograms were collected for crushing. The charred feedstocks were then pulverized using a mortar and pestle into powder form and screened using a 2mm Tyler sieve (figure 7d) to obtain a suitable particle size. It is important to note that particle size is a vital process variable for good-quality mixing and briquette compaction. According to the (ASTM-04) Standard 2mm is an acceptable particle size for low-pressure technology briquette production which was appropriate for this study.

### Preparation of composite biomass briquette samples and Compaction

The composite biochar powder with a uniform particle size of 2mm was mixed with a binder and water in a known ratio**.** 1kg of cow dung powder of particle size 1.5mm was dissolved in a pan containing 50 ml of water and stirred for 45 minutes to get a thick black paste. The thick black paste formed was gradually mixed with 4.5kg of the pulverized biochar at the biochar powder to binder ratios of 90:10 %wt and stirred thoroughly for 45 minutes with a stirring stick until a homogenous paste was formed.

Subsequently, biomass briquette compaction was done manually using a hammer and a hand mould. A total of 4.5 composite biochar powder was used to produce a total of 14 lumps of briquettes (shown in figure 7e), respectively. The biomass briquettes produced were sun-dried for one week in an ambient atmosphere (24-32.2 $^{0}$C). Bonsu et al. (2020) reported that sun drying increases the compactness of the briquette and lowers its moisture content. After seven days of sun drying, the biomass briquette was subjected to proximate, ultimate and combustion analysis. The rationale behind utilizing a low-pressure technology and locally available waste for preparing biomass briquettes is to demonstrate a cost-effective approach to biomass briquette production. This method is particularly beneficial for individuals residing in rural areas where access to expensive briquette machines may be limited. By utilizing simple and affordable techniques, such as low-pressure technology and locally sourced waste materials with the intention to provide a practical and accessible solution for biomass briquette production in resource-constrained settings. This approach enables communities in rural areas to utilize their readily available biomass resources and transform them into valuable fuel sources, promoting sustainable energy practices and reducing dependence on traditional fuels. The composite biomass briquettes produced in this study are intended for domestic cooking and heating applications.

### Determination of physical, chemical and combustion properties of composite biomass briquette

To assess the suitability of the selected solid waste components for producing composite biomass briquettes, a series of tests were conducted in accordance with the American Society for Testing and Materials (ASTM D-3173) guidelines. These tests included proximate analysis, ultimate analysis, ignition test, and combustion test. The proximate analysis provided information about the moisture content, volatile matter, fixed carbon, and ash content of the solid waste components. The ultimate analysis determined the percentage of carbon, hydrogen, nitrogen, sulfur, and oxygen present in the samples. The ignition test examined the ease of igniting the biomass briquettes, while the combustion test evaluated their combustion characteristics. These standardized tests helped evaluate the feasibility and quality of the solid waste components for composite biomass briquette production. The experiment was carried out in triplicates using a sample size of 1g and the mean values and standard deviations were recorded (ASTM D-3173).

### Proximate Analysis

The proximate analysis of fuels consists of the composition of fuels in moisture, volatile matter, ash, fixed carbon, and their calorific value. The proximate analysis was done according to the American Standard Test Method (ASTM D-3173).

### Determination of Moisture Content

Firstly, porcelain crucibles were washed, dried, and their weights were recorded. Next, approximately 10-12g of the composite biomass briquette samples were accurately weighed and placed into the clean, oven-dried crucibles. To ensure even heat distribution, the crucibles containing the samples were spread evenly over the base of a thermostatically controlled oven. The samples were then kept in the oven at a temperature of 105°C for a duration of 48 hours. After the allotted time, the crucibles containing the samples were removed from the oven, allowed to cool in a desiccator, and re-weighed. This process was repeated three times for each sample. The moisture content of the samples was then determined by calculating the percentage of water loss from the initial weight. The equation below was used to estimate the moisture content of the biomass briquette:

$$\%\ \mathrm{MC} = \frac{initial\ weight\ (w1) - final\ weight\ (w2)}{initial\ weight\ (\ w1)} \times 100 \qquad (8)$$

### Determination of Volatile Matter

The percentage of volatile matter in the composite biomass briquette was determined in accordance with ASTM D3175-77. Approximately 2g of the composite biomass briquette with particle size 2mm was placed in a porcelain crucible weight (w2). Each sample was first oven dried and then kept in an electric furnace at a temperature of 550ºC for 10 minutes and weighed (w3) after cooling in a desiccator (Emerhi, 2011). The equation below was used to estimate the percentage of volatile matter:

$$\%VM = \frac{oven\ dry\ weight\ (w2) - weight\ of\ broken\ briquette\ (w3)}{oven\ dry\ weight\ (\ w2)} \times 100 \qquad (9)$$

### Determination of Ash Content

The composite biomass briquette samples were carefully dried and subsequently subjected to controlled heating. Initially, they were gently heated in an oven at a temperature of 105°C for approximately one hour. Afterward, the samples were transferred to a furnace and exposed to a higher temperature of 550°C overnight. This prolonged heating process ensured complete combustion of all carbon particles within the samples. The resulting ash was carefully collected from the dish, allowed to cool in a desiccator to prevent moisture absorption, and then accurately weighed. The percentage of ash content was then determined by calculating the weight of the ash relative to the original sample. The equation below used to estimate the ash content is depicted below:

$$\%\ AC = \frac{weight\ of\ ash\ (w4)}{dry\ weight\ (\ w2)} \times 100 \qquad (10)$$

### Determination of Fixed Carbon

This percentage of fixed carbon in the composite biomass briquette was estimated by subtracting the summation of the %volatile matter and % ash content from 100. The equation is shown below:

$$\% FC = 100 - (\%VM + \% \text{Ash content}) \quad (10)$$

*Figure 8:* Researcher conducting Proximate Analysis on Biomass Briquette

### Determination of Gross Calorific Value

The Perr 6400 Bomb Calorimeter with Benzoic Acid -1.00g, calibrated at (26.454 MJ/Kg) as Standard was used to estimate the gross calorific value (GCV) or high heating value (HHV) of the composite biomass briquette (Wirabuana & Alwi, 2021).

*Figure 9*: Parr 6400 Bomb Calorimeter used to estimate the gross calorific value of composite biomass briquette.

### Ultimate Analysis

The ultimate analysis of the composite biomass briquette involves determining the concentration of carbon, hydrogen, nitrogen, sulphur, and oxygen present in the sample. To conduct this analysis, the LECO 932 CHNS Elemental analyzer was utilized. This instrument enables accurate measurement of the elemental composition of the biomass briquette, providing valuable information about its chemical makeup. The percentage of oxygen was estimated by difference: %Oxygen = [100-(C+H+N+S)] (11)

### Determination of Bulk density

The bulk density of the composite biomass briquette was determined following the experiment by Zhang (2018). An empty container was weighed using a digital balance with an accuracy of 0.0001 grams. Subsequently, the empty container was filled with the composite biomass briquette sample, and care was taken to compact the material slightly to eliminate any significant empty spaces within it. The combined weight of the container and the sample was then measured. This procedure was repeated three times to ensure accurate results. The wet bulk density of the composite biomass briquette sample was determined using the following equation:

The bulk density of the composite biomass briquettes was estimated using the ASTM E873-82 Standard Test Method for densified biomass fuel. The bulk density (dry mass) of the biomass briquette was determined using the mass of the briquettes placed in a container with the formula below.

$$\rho b = \frac{W2-W1}{V} \qquad (12)$$

In the given equation above, the symbols represent the following variables: **ρb** denotes the bulk density of the sample, measured in grams per cubic centimetre (g/cm$^3$). **$W_2$** represents the combined weight of the container and the sample, measured in grams (g). **$W_1$** indicates the weight of the container alone, measured in grams (g). **V** represents the volume of the container, measured in cubic centimetres (cm$^3$).

### Combustion test on the composite biomass briquette produced and traditional charcoal in line with ASTM E791-08 standard.

A water boiling test was done to conduct the combustion test using a cooking pot and conventional tripod stoves in a rural household setting. In this test, 100 ml of water that had been preheated to 30 °C was measured and added to the cooking pot. Then, seven biomass briquettes were placed on the conventional tripod stove and lit with matches. The purpose of this test was to mimic typical cooking conditions and evaluate how well the biomass briquettes performed in terms of their capacity to bring the water to a boil. The temperature of the water was recorded at four-minute intervals until it reached 100 $^{0}$C using an Infrared thermometer (Lasergrip 1080). The procedure was also followed for traditional charcoal to compare with the biomass briquette produced. The experiment was repeated three (3) times, and the mean value was noted. The following parameters were measured and observed during the fuel combustion test.

### Rate of Fuel Burning

The fuel burning rate refers to the rate at which a specific mass of fuel is consumed when burnt in the air. In this study, the fuel-burning rate was estimated following the method described by Bonsu et al. (2020). The biomass briquettes were loaded in a traditional cook stove. To estimate the fuel burning rate, exactly 100 grams of the briquette was placed in the traditional cook stove and the burner ignited. These weight measurements were taken continuously until the briquette was completely burnt, and a constant weight was achieved. The weight loss at a specific time interval was calculated using the following equation:

$$\text{FBR} = \frac{M1-M2}{Time\ taken} \qquad (13)$$

Where:

- FBR is the fuel burning rate (in grams per minute).
- $M_1$ is the initial mass of fuel prior to burning (grams).
- $M_2$ is the final mass of fuel after burning (grams).
- T is the total burning time (in minutes).

By substituting the appropriate values into the equation, the fuel burning rate (FBR) of the biomass briquette and traditional charcoal was calculated. Yes

### Specific Fuel Consumption

The data obtained from the fuel burning rate test helped in estimating the specific fuel consumption (SFC) using the equation below:

$$\text{SFC} = \frac{M1 - M2\ (g)}{W1 - W2\ (ml)} \qquad (14)$$

### Ignition Time

The ignition time refers to the time it takes for a known mass of fuel to ignite. In this study, the ignition time was determined following a procedure like the one described by Bonsu et al. (2020). The equation below was used to determine the ignition time:

$$\text{Ignition time} = T_1 - T_0, \qquad (15)$$

### Thermal Efficiency

The Thermal Efficiency (TE) test involved several steps. Firstly, a steel pot was filled with 100 litres of water at an initial temperature of 30 $^0$ C and sealed properly to minimize evaporation losses. The pot was then placed on a tripod cookstove. To measure the initial temperature of the water, a thermometer was used. Next, 4.0 kg of composite biomass briquettes were measured and divided into four equal parts for testing. The briquettes were ignited, and the water in the pot was heated until it reached boiling point. The heating process continued until all the water evaporated and the briquettes were completely burned. After the boiling, the final temperature of the water was measured. Following that, the lid of the pot was removed, and evaporation was allowed to continue for an additional 15 minutes. The pot was then taken off the tripod cookstove and left to cool for 1.5 hours. The final volume of water was measured at this point. To determine the thermal fuel efficiency, the time between the initial temperature measurement ($T_0$) and the boiling temperature (Tb) was recorded using a stopwatch. This testing procedure was like the one conducted by Aboagye (2017). The thermal fuel efficiency was determined using the obtained data and calculations specific to the test setup. The equation below was applied to estimate the thermal efficiency of the biomass briquette produced.

$$\eta\ (\%) = \frac{Mw\ x\ cp\ x\ \Delta T}{Mf\ x\ CV} \times 100 \qquad (16)$$

Where:

$\eta$= Thermal efficiency, %

M w = Initial mass of water taken, kg

Cp=Specific heat of water, kJ/kg K

$\Delta$T= Rise in temperature of water (K)

Mf= quantity of fuel used, kg

C.V= calorific value, kJ/kg

### Data Management and Statistical Analysis

The dependent relationship between waste generation rates per capita and household income levels as well as the waste generation rate and household size were determined by linear regression model using the IBM Statistical Package for Social Sciences (SPSS) version 22.0. The significant difference in solid waste generation rate per capita among the socioeconomic areas and material composition was also analysed using one-way ANOVA.

Data from the analytical tests were keyed into Microsoft Excel version 2016 and cleaned. Data was later exported to IBM SPSS version 22.0 for statistical analysis. A descriptive analysis was carried out to determine the measures of central tendency, dispersion, and distribution of the data set.

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## Physical Composition of Domestic Solid Waste in Cape Coast North

Table 4 provides an analysis of domestic waste generated in Cape Coast North Sub Metropolitan, categorized into 8 major components. The data were collected and averaged for the three socio-economic areas in the study. This detailed categorization of 8 major components allowed for the identification of specific waste fractions that could be targeted for energy recovery and recycling purposes. The major components identified in the study include organics, plastics, papers, metals, leather and rubber, textile, inert materials, and miscellaneous items.

The household waste component analysis reveals the following results: Fourth Ridge consisted of 71.1% organic waste, 8.7% paper, 10 % plastics, 5.8 % metals, 1.5% textile, 0.9% rubber and leather, 0.8% inert materials, and 1.2% miscellaneous items. Also, Akotokyir had 63.3% organic waste, 7.9 % paper and cardboard, 14.3% plastics, 3.8% metals, 5.0% textile, 2.3% leather, 1.5% inert materials, and 2.0% miscellaneous items while Asepetu exhibited 45.8% organic waste, 5.0 % paper and Cardboard, 10.2% Plastics, 2.3% Metal, 2.2% Textile, 0.9% Leather, 22.1% inert materials and 11.4 % Miscellaneous items.

A total of 11,497.6 kg of waste was analyzed during the solid waste audit for six weeks in three socio-economic areas within Cape Coast North Sub- Metropolitan. The third-class income area contributed 3,349 kg, the second-class area provided 3,832.6 kg, and the first-class area yield 4,3168.1 kg (Table 3). The analysis reveals the average composition of municipal solid waste across all three socioeconomic areas indicating that organic waste fractions account for 60%, paper for 7.2%, plastics for 11.5%, metals for 4.0%, textiles for 2.9%, miscellaneous items for 4.9%, rubber and leather for 1.3 %, and inert materials for 8.2 %. Notably, Organic waste fractions constituted the largest proportion in all socio-economic areas, while inert materials were the least household solid waste fraction in Fourth Ridge. On the other hand, the least prevalent solid waste fraction observed in Akotokyir and Asepetu was rubber and leather. The significant presence of organic waste in the study area can be attributed to Ghana's heavy reliance on agricultural products. Ghana's economy is heavily dependent on agriculture with a large portion of the population engaged in farming and related activities. As a result, there is a higher proportion of organic waste generated including agricultural residues, food waste, and other biodegradable materials.

Also, the trend of domestic solid waste physical composition observed in this study aligns with the physical composition of household waste in many developing countries where the preparation of unprocessed food generates a significant amount of organic waste fractions. In contrast, developed countries rely more on processed and ready-to-eat foods, resulting in a lower percentage of organic waste but a higher percentage of packaging materials. It is important to note that numerous studies, such as those by Gomez et al. (2009), Miezah et al., (2015) and Seshie et al. (2020) have emphasized the significant contribution of food and garden waste to the total organic waste streams in several developing nations, corresponding to about 65.1%. The findings of this study, which indicate an average organic waste fraction of 60%, are consistent with earlier studies carried out in Ghana by Miezah et al. (2015) and Seshie et al. (2020). Similar patterns have been seen in other Sub-Saharan African nations, including Ibadan (56%) organic waste in household solid waste, Kampala (75%), Accra (85%), Kigali (94%), and Nairobi (51%).

The organic waste fraction exhibited the highest proportion in Fourth Ridge. This could be attributed to local restaurants (Chop bars) within homes in the second-class income area where some leftovers from these establishments find their way into household bins. On the other hand, the third-class area had the lowest fraction of organic waste, as most of this organic waste was used as animal feed. Also, in the second and third-class income areas, peels of some local food products such as cassava, yam, and plantain was prevalent. This could be attributed to the preparation of gari and fufu in these communities. Moreover, in the first-class area, yard trimmings constituted most of the organic waste fraction in the first-class income area which could be attributed to the presence of lawns and gardens on residents' compounds.

Plastic waste, predominantly composed of LDPE and HDPE (pure water sachets), constituted the next highest fraction after organic waste. The highest plastics generation was recorded in the second-class income area (14.3%) and the lowest (10.0%) was observed in the first-class income area. Paper waste primarily consisted of cardboard, newsprint, disposable tissues, and diapers across all socioeconomic areas. Comparatively, the component of paper waste was lower in the study areas of the Cape Coast North Sub-Metropolitan than in developed cities/countries. Most paper waste generated in households of the Sub-metropolitan, such as newspapers and magazines, is waste sold by offices and institutions to food vendors who use them for wrapping food items.

The first-class income area generated a higher total percentage of packaging waste (paper, metals, and plastics) than the second-class. In contrast, the third-class income area generated the least amount of paper and metals. The higher percentage of packaging waste the high-income population generates reflects their greater purchasing power and consumption capacity. A study by Jagun et al. (2022) reported a direct relationship between the components of packaging waste in domestic waste and household income level with wealthier households producing significantly higher percentages of paper, plastic, and metal waste for packaging items. The composition of packaging materials from the first-class income areas in this study confirms this finding. The third-class income area exhibited the least production of packaging waste. The second-class income area had the highest proportion of textile waste (5.0 %) while the textile waste fraction in the third-class and first-class income areas were 2.2 % and 1.5%, respectively. The lower fraction of textile waste in the first-class income area may be attributed to donating used clothing to the neighbourhood.

**Table 4: Physical Composition of the domestic solid waste across the three Socio-economic areas**

| Material composition of waste | Socio-economic Areas | | | | | | |
|---|---|---|---|---|---|---|---|
| | 4th Ridge - First Class | | Akotokyir-Second Class | | Ansepetu-Third Class | | Overall Average |
| | Wt (kg) | Wt (%) | Wt. kg | Wt % | Wt. kg | Wt % | |
| Organics | $3068.4^{bd}$ | 71.1 | $2425.2^{ab}$ | 63.3 | $1532.5^{cd}$ | 45.8 | 60.0 |
| Paper | $376.6^{ef}$ | 8.7 | $302.7^{ef}$ | 7.9 | $168.6^{ac}$ | 5.0 | 7.2 |
| Plastics | $432.4^{ab}$ | 10.0 | $546.4^{ab}$ | 14.3 | $342.3^{mn}$ | 10.2 | 11.5 |
| Metals | $252.0^{gh}$ | 5.8 | $144.6^{ef}$ | 3.8 | 78.4 ij | 2.3 | 4.0 |
| Textiles | $64.6^{jk}$ | 1.5 | $192.3^{ab}$ | 5.0 | $72.4^{jk}$ | 2.2 | 2.9 |
| Leather | $37.3^{mn}$ | 0.9 | $86.3^{ed}$ | 2.3 | $31.8^{qn}$ | 0.9 | 1.3 |
| Inert materials | $32.4^{ab}$ | 0.8 | $58.6^{cd}$ | 1.5 | $740.3^{ef}$ | 22.1 | 8.2 |
| Miscellaneous | $52.4^{qr}$ | 1.2 | $76.4^{cp}$ | 2.0 | $382.6^{vn}$ | 11.4 | 4.9 |
| Total | 4316.1 | 100 | 3832.6 | 100 | 3349.0 | 100 | |

Means for total weight in rows with the same letter superscripts are not significantly different ($p > 0.05$), whereas means for total weight in rows with different letter superscripts are significantly different ($p < 0.05$).

### Physical Composition Across Income Groups for Solid Waste Fractions

To investigate the statistically significant difference in material composition among waste fractions generated across first class, second class, and third-class areas, a one-way analysis of variance (ANOVA) was conducted on the mean values of different waste materials, as presented in Table 4. The findings revealed that there were statistically significant differences ($p > 0.05$) in the weights of domestic solid waste components among the three socio-economic group. This implies that, all solid waste categories, including organic, paper, plastic, metal, rubber, textiles, inerts and miscellaneous, displayed statistically significant differences ($p > 0.05$) across the three socio-economic groups.

### Per capita waste generation rate in Cape Coast North Sub Metropolitan

Table 5 displays the per capita waste generation rates (PCWGR) across the three socioeconomic income areas within the Cape Coast North Sub-Metropolitan. The first-class income area recorded the highest per capita waste generation rate at 0.72 kg/capita/day, followed by the third-class and second-class areas with rates of 0.63 kg/capita/day and 0.66 kg/capita/day, respectively. On average, the three socio-economic income areas had a per capita waste generation rate of 0. 67 kg/capita/day. Importantly, there were no statistically significant differences in the waste generation rates per capita among the three income areas as determined at a 5% significance level.

The average per capita waste generation rate of 0.67 kg/capita/day reported in this study is slightly lower than the per capita generation rate of 0.72 kg/capita/day reported by Miezah et al. (2015) for most metropolitan cities in Ghana, except Tamale. However, it is above the estimated average waste per capita waste generation rate of 0.5 kg/capita/day as reported by Ezeudu et al. (2019) in Nigeria. Also, this result aligns with the global trend of waste generation rates for developing countries which typically fall within the range of 0.5-0.9 kg/capita/day, as reported by Gomez et al. (2009).

The per capita waste generation rates in Ghana, regardless of socioeconomic factors varied between 0.2 and 0.8 kg/person/day. This range is also observed in most cities across Sub-Saharan Africa, as noted in studies conducted by the United Nations Environment Programme (UNEP, 2013).

Table 5: Per Capita Waste Generation Rate Across Socio-economic Areas

| S/N | Socio-economic Areas | Kg /capita/day |
|---|---|---|
| 1 | Fourth Ridge | 0.72 |
| 2 | Akotokyir | 0.63 |
| 3 | Ansepetu | 0.66 |
| | Average | 0.67 |

**Per Capital Waste Generation at different Socio- economic Levels**

To assess the statistically significant differences in Per Capita Waste Generation Rates (PCWGR) among three income levels (high, middle, and low), a post-hoc examination was conducted after a one-way analysis of variance (ANOVA) utilizing data obtained from the solid waste audit in Cape Coast North Sub Metropolitan. A confirmatory Tukey's Post Hoc test (Nyankson, 2020) was executed.

Table 6 reveals that during weeks 1-4, there was statistically significant difference in PCWGR between the socio- economic levels. This pattern remained consistent for the subsequent weeks (weeks 5-6), where a statistically significant difference in PCWGR was evident among first-, second-, and third class-income groups. Overall, the first-class residents produced the highest total waste quantity (6459.89 kg/capita), followed by the third-class areas (4524.93 kg/capita), while the second – class area generated the least amount of waste (3613.82 kg/capita).

The variation in per capita waste generation rate (PCWGR) can be associated with the consumption habits and lifestyle choices of individuals within their respective income groups. The overall dynamics of PCWGR may be influenced by the affluent lifestyle of the first- class group, characterise by increased purchases and the disposal of items that are no longer useful, often in the form of donations to the less privileged. This phenomenon contributes to a higher accumulation of waste in the low-income group compared to the middle-income level.

**Table 6: Per Capital Waste Generation at Different Socio- economic Levels**

| Period | First Class kg/capita/week | Second Class kg/capita/week | Third Class kg/capita/week |
|---|---|---|---|
| Week 1 | 785.36$^{ob}$ | 489.36$^{ck}$ | 606.7 $^{rk}$ |
| Week 2 | 689.43$^{cf}$ | 432.9 $^{ek}$ | 513.59$^{sk}$ |
| Week 3 | 859.32$^{bd}$ | 304.16$^{zn}$ | 726.5$^{ze}$ |
| Week 4 | 679.04$^{em}$ | 457.2$^{cv}$ | 499.9 $^{cv}$ |
| Week 5 | 642.34$^{df}$ | 398.28$^{wn}$ | 447.09$^{um}$ |
| Week 6 | 582.82$^{ec}$ | 313.8$^{ko}$ | 522.06$^{bn}$ |
| Total | 6459.89 | 3613.82 | 4524.93 |

Means for Per Capita Waste Generation in rows with the same letter superscripts are not significantly different ($p > 0.05$), whereas means for Per Capita Waste Generation in rows with different letter superscripts were significantly different ($p < 0.05$).

### Relationship between domestic solid waste generation rate and both income level and household size

Although previous research by Qdais et al. (1997) found a positive correlation between waste generation and higher income levels, this study did not observe any such correlation between household income and waste generation. The findings in this study align with studies conducted in Ghana by Miezah et al. (2015), and in Mexico by Gomez et al. (2008). It is worth noting that some high-income individuals may reside in lower-class areas, which, along with other factors, might explain the absence of a correlation between household income and waste generation in this study.

Furthermore, this study found that individuals living in larger households produced less waste compared to those in smaller households. This trend could be attributed to larger households frequently purchasing items in bulk or larger packages, which are then shared among all household members. Consequently, the amount of waste generated is limited compared to if each person were to individually purchase smaller packages, as observed in a study by Grover and Singh (2014) in India.

## Feedstocks characterization with proximate analysis and SEM analysis

### Proximate analysis of feedstocks

### Moisture Content

The proximate analysis of the solid waste components used as feedstocks in the study including coconut husk, sugar cane bagasse, cassava peels, plantain peels and empty fruit bunch, revealed significant differences in their chemical composition (Table 7). Specifically, plantain peels exhibited the lowest moisture content (6.6 ± 0.02) followed by empty fruit bunch (6.9 ± 0.24), cassava peels (8.0 ± 0.05) and sugar cane bagasse (10.3 ± 0.2) while coconut husk recorded the highest moisture content (12.8 ± 0.04).

However, the moisture contents recorded for all these feedstocks analyzed were below the average moisture content of 29% for agricultural waste and 12% for forestry waste as reported by Mkini and Bakari (2015) in Tanzania. However, the results fell within the optimal range of 10% to 15% according to the ASTM D2216 standard and agree with a study by Bonsu et al. (2021) on feedstocks used in biomass briquetting. Notably, the moisture content is an integral proximate parameter to consider when assessing the quality of raw materials for biomass briquetting. Mkini and Bakari (2015) found that the percentage of moisture content of the feedstock influences the quality of the biomass briquette. Therefore, the raw materials selected were suitable based on the acceptable moisture content values recorded from the analysis. Also, blending these different feedstocks takes advantage of individual characteristics which could optimize the moisture content of the composite biomass briquette produced in this study.

### Volatile Matter

Table 7 showed that sugar cane bagasse reported the highest percentage of volatile matter which was 96 ± 0.3, followed by coconut husk at 92.4 ± 0.3. Empty Fruit Bunch at 91 ± 0.3 and 90.1 ± 0.2. However, the lowest percentage of the volatile matter was observed in plantain peels at 80 ± 0.5. These results indicate that a significant portion of sugar cane bagasse is composed of combustible components that can be released as gas or vapour when subjected to heat followed by coconut husk. On the other hand, empty fruit bunch was slightly lower than coconut husk but still relatively high in terms of combustible content. The high percentages of volatile observed in this study correspond to a study by Bonsu et al. (2020) on palm kernel briquette and this clearly indicates that high volatile matter enables the biomass material to ignite quickly. The results offer insights into the composition of the biomass materials in terms of their combustible content which is valuable for biomass briquette production.

### Ash Content

The ash content refers to the inorganic residue that remains after the combustion of a substance. According to table 7, sugar cane bagasse had the lowest ash content at 4.1 ± 0.3, which indicates that sugar cane bagasse contains a relatively low amount of inorganic residue after combustion. This is followed by Cassava Peels at 5.6 ± 0.2 and empty fruit bunch at 7.1 ± 0.3

which contains a slightly higher amount of inorganic residue compared to sugar cane bagasse but still maintains a relatively low ash content. Also, the ash content for coconut husk was 4.6 ± 0.3 while Plantain Peels recorded the highest value of ash content at 10.2 ± 0.5. This suggests that plantain peels contain a relatively large amount of inorganic residue after combustion. Notably, the ash content is crucial for various applications including biomass briquette production. However, higher ash content could impact the efficiency and performance of the Biomass briquette. The knowledge of the ash content of various biomass materials was valuable to assess the suitability of various feedstocks used for biomass production and it is recommended that the ash content should be less than 10% (Bonsu et al., 2020).

### Fixed Carbon

Fixed carbon refers to the solid combustible components remaining in a substance after volatile matter and moisture have been driven off. According to Table 7, sugar cane bagasse had the highest fixed carbon content at 55.7 ± 0.2, followed by coconut husk at 53.6 ± 0.2, empty fruit bunch at 52.7 ± 0.2 and cassava peels at 52.2 ± 0.1, while plantain peels recorded the lowest fixed carbon content at 46.4 ± 0.3. These results were higher than the results of raw materials reported by Bonsu et al. (2020) on palm kernel. To add on, sugar cane bagasse contains a relatively high amount of solid combustible components, while plantain peels contain a relatively lower amount of solid combustible components compared to the other feedstocks mentioned. Understanding the fixed carbon content of various raw materials is essential for applications such as biomass briquetting, as it represents the solid combustible components that contribute to the energy released during combustion. Knowledge of the fixed carbon content is valuable for assessing the potential energy value and utilization of different feedstocks for biomass briquette production (Bonsu et al., 2020).

**Table 7: Proximate analysis of feedstocks used for composite biomass briquette production**

| Sample Description | Moisture Content (%) | Ash Content (%) | Volatile Matter (%) | Fixed Carbon (%) |
|---|---|---|---|---|
| Plantain Peels | 6.6 ± 0.02 | 10.2± 0.5 | 80 ± 0.5 | 46.4 ± 0.3 |
| Cassava Peels | 8.0 ± 0.05 | 5.6 ± 0.2 | 90.1 ± 0.2 | 52.2 ± 0.1 |
| Sugarcane Bagasse | 10.3 ± 0.2 | 4.1 ± 0.3 | 96 ± 0.3 | 55.7 ± 0.2 |
| Empty Fruit Bunch | 6.9 ± 0.24 | 7.1 ± 0.3 | 91 ± 0.3 | 52.7 ± 0.2 |
| Coconut Husk | 12.8 ± 0.04 | 4.6 ± 0.3 | 92.4 ± 0.3 | 53.6 ± 0.2 |

Source: Laboratory Analysis (2023)

### SEM Analysis of raw materials

The feedstocks used to produce biomass briquettes were characterised using scanning electron microscopy (SEM). This analytical method was selected because it provides thorough insights into the feedstocks' morphology, microstructure, and surface properties. Using SEM, a thorough understanding of the feedstocks' physical characteristics and surface features was attained, assisting in the evaluation and optimization of their suitability to produce biomass briquettes. The SEM images presented in Figures (11,12,13,14 & 15) illustrate the microstructure and surface morphology of the various feedstocks used in this study. The result showed that the samples of cassava peels, empty fruit bunch and sugar cane bagasse particles appeared tightly packed without significant voids, indicating a well-distributed structure. On the other hand, the Plantain peel and Coconut husk samples exhibited slightly packed together and arranged horizontally. The particle sizes of feedstocks observed in the images range from 1.64 μm to 39.73 μm in diameter. Although the feedstocks were tightly packed and had fewer voids, some longitudinal cracks were present.

It is worth noting that the information provided lacks some clarity and specific context so the interpretation and understanding of the details may be limited. Comparing different waste samples, the surface area of plantain peel, sugar cane bagasse and empty fruit bunch appears to be finer than coconut husk, while empty fruit bunch exhibited a coarser texture.

Tumuluru and Wright (2010) found that the particle size of feedstock plays a crucial role in the compaction process during densification and finer particles tend to result in high-quality biomass briquettes. This is because fine particles offer a larger surface area for bonding. Bazargan et al. (2014) however, recommended that particle size should be less than 25% of the densified product. SEM analysis is particularly important for biomass briquette production because the surface characteristics of the raw materials can significantly impact the briquetting process, including factors such as adhesion, compaction, and binding. Moreover, SEM helps identify the texture, porosity, and surface irregularities of the solid wastes which aided in the findings are consistent with previous studies conducted by Zhang and Guo (2014) and Stelte et al. (2011), which explored the morphology of raw material for biomass briquette production.

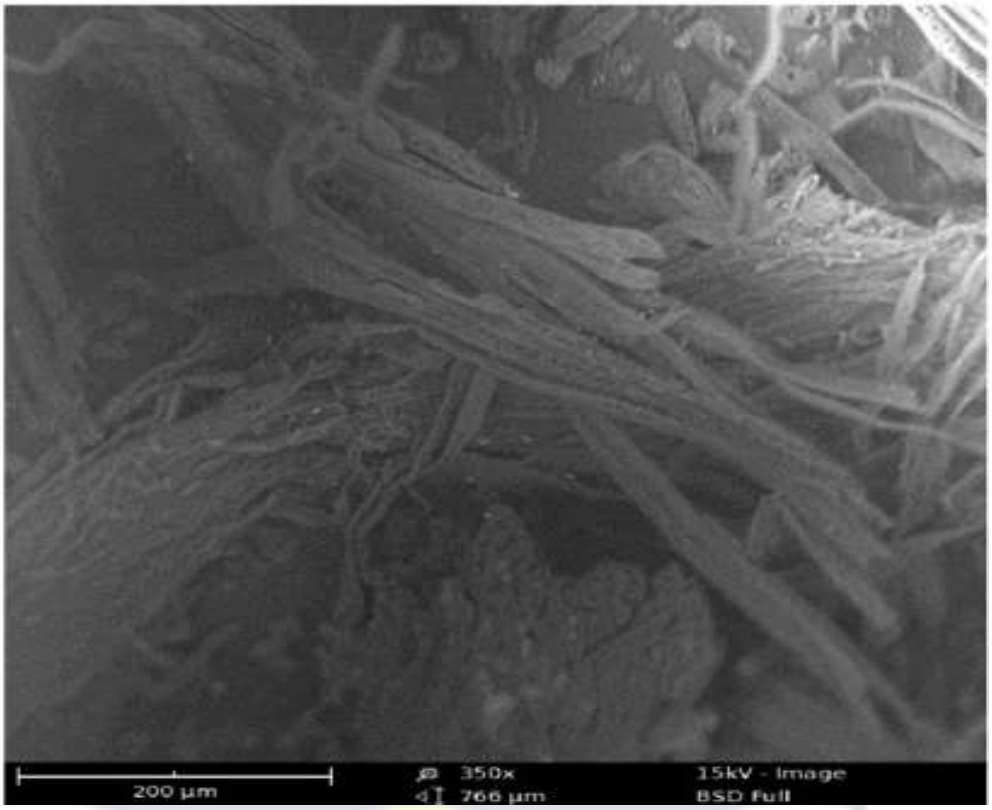

*Figure 10:* SEM Image of Plantain Peels at 15kV X 10,000 Magnification
Sources: Laboratory Analysis (2023)

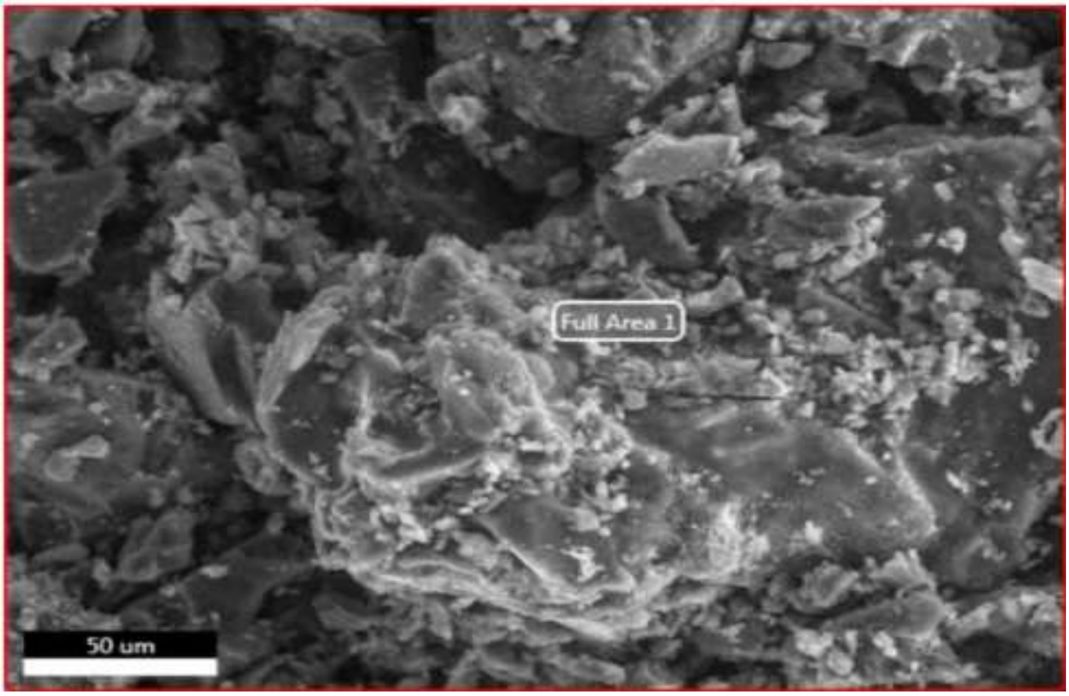

Figure 12: SEM Image of Cassava Peels at 15kV X 10,000 Magnification
Source: Laboratory Analysis (2023)

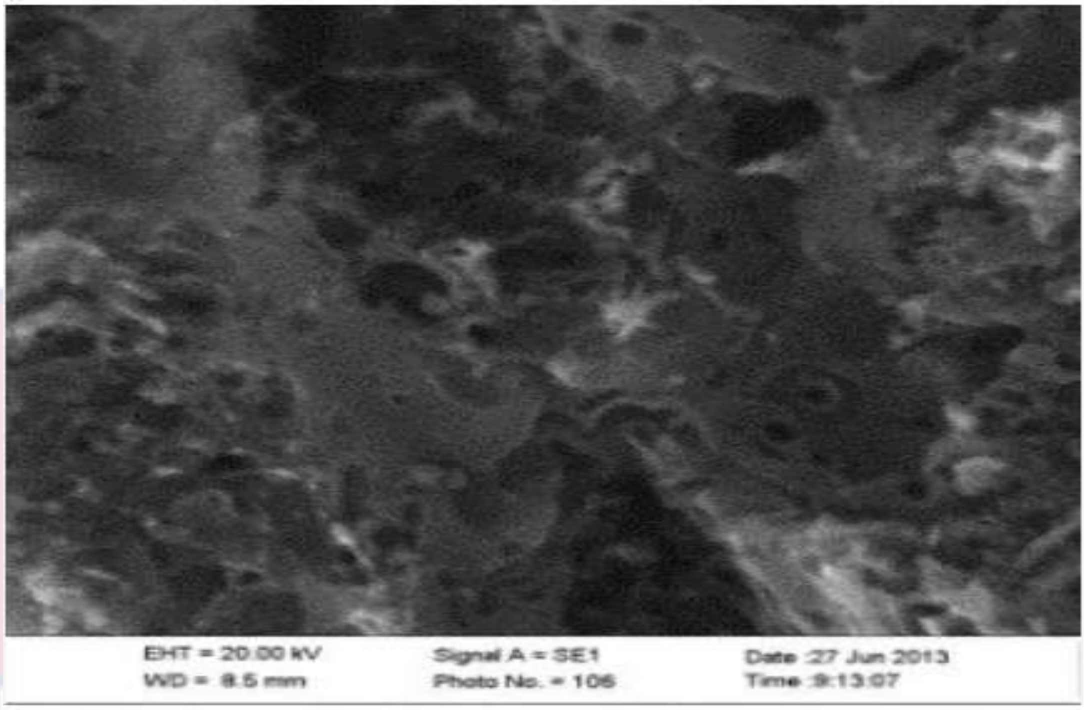

*Figure 13*: SEM Image of Empty Fruit Bunch (EFB) at 15kV X 10,000 Magnification

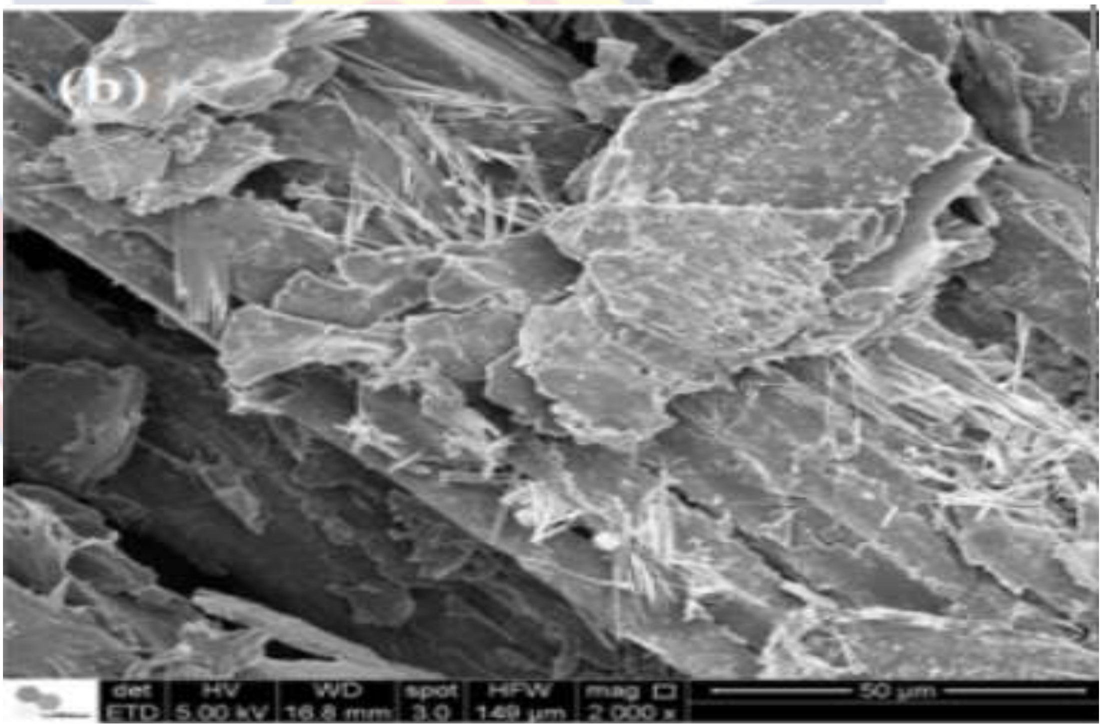

*Figure 14*: SEM Image of Sugarcane Bagasse at 15kV X 10,000 Magnification

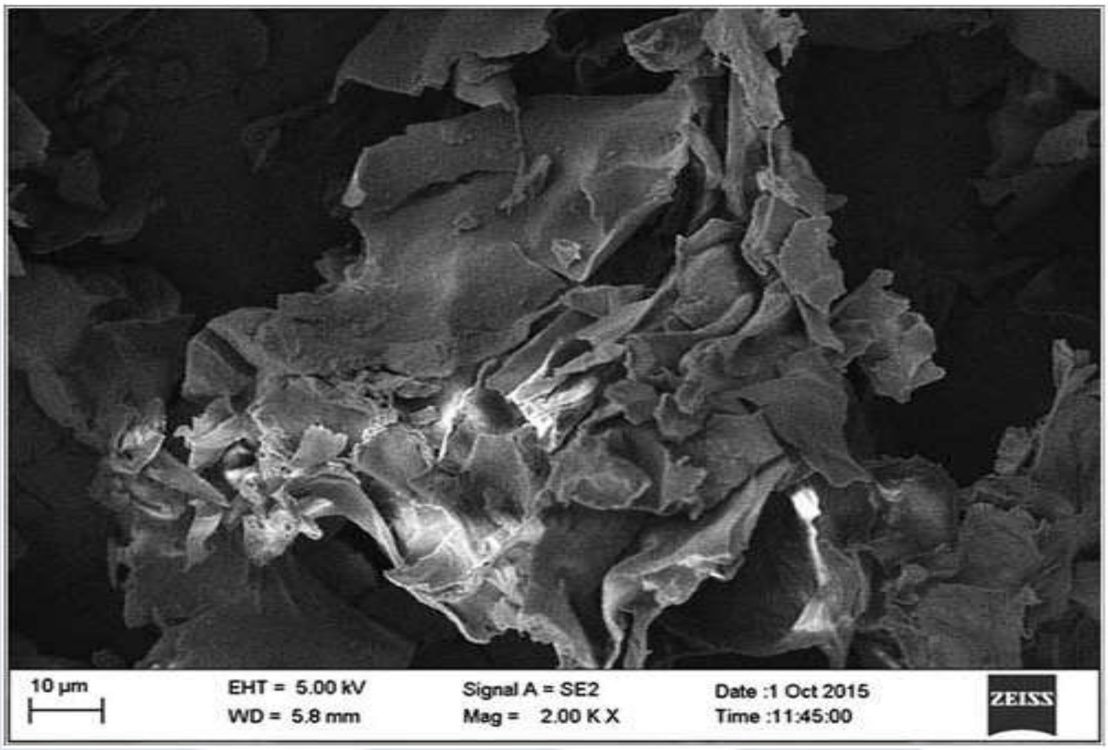

*Figure 15*: SEM Image of Coconut Husk at 15kV X 10,000 Magnification

### Physical Characteristics of Composite Biomass Briquette

The physical properties of the biomass briquette were analyzed according to ASTM standards. The study focused on parameters including diameter, thickness, mass, volume, bulk density, and length. The values obtained for these properties are presented in Table 7.

### Dimension of the composite biomass briquette

The average diameter of the composite biomass briquette was estimated using a Digital Vernier calliper and found to be 60.3 mm which is in line with the acceptable range of 25-100 mm as recommended by Kpalo et al. (2020). Also, the average thickness of the biomass briquette measured 46.3 mm and the average mass of 48.85g is consistent with a study by Borowski (2011). Borowski (2011) reported a range of 25-280 mm for biomass briquette thickness and noted that the mass of biomass briquettes can vary significantly based on the design of the machine used and the intended purpose of the fuel.

Also, the average length recorded for the composite biomass briquette was 60.8mm. There is, however, no globally recognized standard for these physical parameters. In terms of volume, the average volume recorded was 175.93 $m^3$. Also, the compacting pressure during the briquette production process played a significant role in influencing the bulk density. However, this study utilizes low-pressure briquette technology. The particle size for the biochar used in preparing the biomass briquette was 2mm. Particle size is another very important factor affecting bulk density with smaller particle sizes leading to good-quality biomass briquette (Dogra et al., 2023). All these physical characteristics determined in this study fell within the ASTM standard on solid fuel which highlight the suitability of the composite biomass briquettes for domestic applications.

**Bulk Density**

Table 8 presents the bulk density of the composite biomass briquette which was estimated at 512.03 kg/ $m^3$. This value is consistent with the recommendations of the Food and Agricultural Organization (FAO) as reported by Akowuah et al. (2012) which suggest a bulk density range of 500 to 800 kg/$m^3$ for biomass briquette. Branca et al. (2014) stressed that the bulk density of a briquette can vary depending on the specific feedstock used, the binder content, the pressure applied during compaction and the moisture content of the briquette. Also, the particle size of 2mm could have contributed to the high bulk density observed for composite biomass briquette. It is important to note that a higher bulk density generally indicates a denser and more energy-dense briquette which can have advantages in terms of storage, transportation, and combustion efficiency. This is consistent with a study by

Holdich (2020) which reported that finer particles tend to result in denser biomass briquettes due to lower void space. Holdich (2020) also noted that the porosity index of fine particles of raw material is generally lower than that of medium and larger particles which was confirmed in another study by Bonsu et al. (2020) on Palm Kernel briquette.

**Table 8: Physical Characteristics of Composite Biomass Briquette**

| | **Diameter (mm)** | **Thickness (mm)** | **Mass (g)** | **Volume ($m^3$)** | **Bulk Density (kg/ $m^{3)}$** | **Length (mm)** |
|---|---|---|---|---|---|---|
| **Biomass Briquette** | 60.3 | 46.3 | 48.85 | 175.93 | 512.03 | 60.8 |

Source: Laboratory analysis (2023)

### Proximate analysis of Composite biomass briquette and traditional charcoal (Acacia)

#### Moisture content

According to the data presented in Table 8, the moisture content of the composite biomass briquette was 5.4 ± 0.1%. This fell below the optimal range of 8- 12% according to the ASTM D 3173-87 standard. Bonsu et al. (2020) reported that an ideal moisture content for cooking fuels is typically between 8-12% or lower since this promotes efficient and sustainable combustion, ultimately affecting the energy value of the fuels. This was also confirmed by Pandey and Dhakal (2013). However, the moisture content for the composite biomass briquette reported in this study aligns with previous studies by Onochie et al. and Pandey and Dhakal (2013). The optimal moisture content in this study could be attributed to the sun drying and pyrolysis of the feedstocks as well as the individual characteristics of the feedstocks.

Comparing the moisture content of the composite biomass briquette to that of the feedstocks (Plantain Peels, Cassava Peels, Sugar Bagasse, Empty Fruit bunch and Coconut husk) obtained before pyrolysis, the composite biomass briquette exhibited significant, optimal moisture content (5.4 ± 0.01) which was still consistent with the raw materials' values of 6.6 ± 0.02%, 8.0 ± 0.05, 10.3 ± 0.2, 6.9 ± 0.24 and 12.8 ± 0.04 respectively. Conventionally, coconut husk and empty fruit bunch are used in their raw form for cooking and heating applications, but they are considered suboptimal due to the excessive smoke emitted by their organic constituents (Bonsu et al., 2020). The reduction in moisture content achieved through the pyrolysis process indicates that the composite biomass briquette is a more efficient and sustainable alternative to raw residues, traditional charcoal, and firewood as a source of solid fuel for domestic cooking and heating purposes.

Traditional charcoal (Acacia) however, displayed a moisture content of 12.1±0.3, which is relatively higher than the moisture content of the composite biomass briquette produced. The slightly higher moisture content is associated with less efficient burning and increased smoke emissions during the combustion (Zhao et al., 2021). This clearly explains the excessive smoke emission observed during the combustion of traditional charcoal. In contrast, composite biomass briquette offers significant advantages as it serves as an efficient fuel source without any emissions during combustion (Bonsu et al., 2020). The moisture content value obtained for composite biomass briquette in this study is consistent with the findings by Pallavi et al. (2013), who suggested moisture content values of between 8% and 12% for solid fuel.

### Volatile Matter

The presence of volatile matter in traditional charcoal as indicated by its high percentage of 46.2±0.2% in Table 8 correlates with the observations made during the combustion test. It was noted that traditional charcoal with its high volatile matter content exhibited a greater ease of ignition compared to the composite biomass briquette which had a lower volatile matter percentage of 45.3 ± 0.2 % (Table 9). This divergence in volatile matter content directly influenced the ignition process, resulting in longer ignition times and a higher demand for kerosene when using composite biomass briquettes for cooking and heating purposes.

These findings agree with a study conducted by Bonsu et al. (2020) who reported that traditional charcoal with a higher volatile matter content tends to possess superior ignitability and combustion characteristics. The higher volatile matter content in traditional charcoal allows it to readily release combustible gases, facilitating easier ignition and a more efficient combustion process.

In contrast, composite biomass briquette with its lower volatile matter content, exhibited relatively slower ignition and necessitated the use of additional aids such as kerosene to support the ignition process. This difference highlights the influence of volatile matter content on the ignition behaviour and overall combustion performance of different solid fuel types.

Traditional charcoal, known for its high volatile matter content ignites and burns out at a faster rate compared to other solid fuels. The raw materials (Plantain Peels, Cassava Peels, Sugar cane Bagasse, Empty Fruit Bunch and Coconut Husk) used for the preparation of composite biomass briquettes were found to have high volatile content with respective percentages. According to the results, it is expected that the charred feedstocks' volatile matter content would fall within the range of 75-89% after pyrolysis. However, the charred feedstocks when combined for biomass briquetting exhibited a percentage volatile matter of 45.3 ± 0.2. This optimal volatile matter content observed could be attributed to the mixing of the raw residues during the experiment which took advantage of individual characteristics. While traditional charcoal ignites quickly and burns out rapidly, the composite biomass briquette offers advantages in terms of more even heating and maintaining a consistent temperature for a longer duration during use. This was observed in the combustion test and is in line with a study by Bonsu et al. (2020).

### Ash Content

The ash content in biomass is a complex issue influenced by various factors such as organic and inorganic matter present as well as potential impurities. In the case of biomass briquette, the ash content is affected by factors such as impurities and contaminants' presence, higher moisture content can lead to incomplete combustion and higher ash content. Therefore, it is important to properly dry the raw materials before briquetting to achieve the desired ash content and the type and quality of the biomass feedstock used to produce the biomass briquettes and this plays a significant role in determining the ash content (Bakari et al., 2023; Onochie et al., 2017). The estimated ash content in the composite biomass briquette was recorded as 7.4 ± 0.2, which is lower than the ash content values of traditional charcoal (5.1±0.1). The lower ash content in the biomass briquette may be attributed to its fewer organic constituents after pyrolysis.

During the combustion test, biomass briquette produced less ash compared to traditional charcoal, which burned faster and incompletely, resulting in a higher ash residue. The low ash content of the composite biomass briquette agrees with the findings reported by Bonsu et al. (2020), who stated that higher ash values can have detrimental effects on boiler operations and domestic cooking.

The raw residues (plantain peels, cassava peels, sugar cane bagasse, empty fruit bunch and coconut husk) had slight differences in ash percentage, with values of 20 ± 0.5, 9.7 ± 0.2, 4.1 ± 0.3, 9.1± 0.3 and 7.6 ± 0.3 respectively. After charring these feedstocks, the ash percentage of the composite biomass briquette produced remained 7.4 ± 0.2. The value recorded suggests that composite biomass briquette maintains a relatively low ash content which makes it a suitable solid fuel for domestic cooking and heating purposes.

According to Huang et al. (2022), many industries view biomass briquettes as an advantageous solid fuel for boilers. This is attributed to their low ash content and reduced levels of potassium and chlorine, which help minimize ash agglomeration during usage. Additionally, biomass briquettes generate minimal ash during prolonged combustion, and this ash does not contain toxic heavy metals or other harmful pollutants. In contrast, traditional charcoal with higher ash content not only contributes significantly to air pollution but can also potentially contaminate food during preparation (Jelonek et al., 2020; Onochie et al., 2017). Thus, biomass briquettes offer a cleaner and more environmentally friendly alternative, making them an appealing choice for various industries.

The ash content value observed for biomass briquette was acceptable and did not adversely affect the combustion process. According to the United Nations Environmental Programme (2014) energy efficiency guide, the acceptable range of ash content in briquettes is between 5% and 40%.

### Fixed Carbon

Fixed carbon plays a crucial role as the primary heat generator during combustion. In this study, the composite biomass briquette exhibited the highest percentage of fixed carbon at 41.9 ± 0.1. Comparatively, the percentage of fixed carbon in traditional charcoal was 36.6 ± 0.3. The differences observed between traditional charcoal and Biomass briquette can be attributed to the carbonization process where fuelwood is converted into traditional charcoal, resulting in higher carbon content in traditional charcoal.

Significant variations were observed in the values obtained for the raw residues (plantain peels, cassava peels, sugar cane bagasse, empty fruit bunch and coconut husk) with percentages of 46.4 ± 0.3, 52 ± 0.1, 55.7 ± 0.2, 52.7 ± 0.2 and 53.6 ± 0.2 respectively. These variations can be attributed to the chemical composition of individual raw materials used. Each biomass feedstock has a unique chemical composition which can vary based on factors such as species, maturity, and growth conditions. Differences in the composition of cellulose, lignin, hemicellulose, and other organic compounds can impact the carbon content. A similar study by Bonsu et al. (2020) on Palm Kernel Shell briquette, noted that PKS (Dura) has thicker shells compared to PKS (Tenera), which has thinner shells. This property likely increased the carbon content thereby contributing to the final charred fixed carbon percentage for the briquette produced.

Fixed carbon refers to the solid carbonaceous material that remains after volatile matter has been driven off during combustion. It represents the portion of the briquette that can be converted into heat energy. A higher fixed carbon content indicates a higher proportion of carbon available for combustion. Biomass briquettes with higher fixed carbon content tend to burn more efficiently and produce more heat. This indicates that the fixed carbon content recorded for biomass briquette in this study was optimal, making biomass briquette a potential alternative solid fuel to traditional charcoal and fuelwood.

**Table 9: Proximate analysis of biomass briquette and Traditional Charcoal (Acacia)**

| Parameters | M C (%) | A C (%) | V M (%) | FC (%) |
|---|---|---|---|---|
| Biomass Briquette | 5.4 ± 0.1 | 7.4 ± 0.2 | 45.3 ± 0.2 | 41.9 ± 0.1 |
| Traditional Charcoal | 12.1±0.3 | 5.1±0.1 | 46.2±0.2 | 36.6±0.3 |

Source: Laboratory Analysis (2023)

### Ultimate Analysis of the Biomass Briquette

Table 10 provides details on the elemental composition of the composite biomass briquette indicating the percentages of carbon, hydrogen, nitrogen, oxygen, and sulfur, as 49.8 ± 0.55, 8.7 ± 0.53, 1.5 ± 0.11, 38.82 and 0.1 ± 0.01, and respectively. These values, however, fall within a range and exhibit slight differences compared to the values of carbon: 46.28%, Hydrogen: 5.59%, Nitrogen: 0.90%, Sulfur: 0.10%, and Oxygen: 46.44% reported by Onochie et al. (2017). Moreover, the variations in percentages may be attributed to various factors such as differences in moisture content, briquette preparation methods, weather conditions, chemical composition of the feedstocks and other factors (Onochie et al., 2017). Furthermore, these results indicate that carbon constitutes approximately 49.8% of the total composition of the biomass briquette. Also, the result showed that hydrogen makes up approximately 8.7% of the total composition of the biomass briquette. The ultimate analysis provides crucial information about the elemental composition of biomass briquettes. Elements such as carbon, hydrogen, nitrogen, oxygen, and sulfur content play a significant role in determining the energy content, combustion characteristics and environmental impact of the biomass briquettes.

Carbon and hydrogen are the main combustible elements in biomass, contributing to the energy released during combustion. The nitrogen content is important for understanding the potential for nitrogen oxide (NOx) emissions during combustion. Important to note is the percentage of nitrogen of 1.5 ± 0.11 recorded in this study which indicates that burning of composite biomass briquette would result in modest emissions of nitrogen dioxide and nitrogen trioxide (CHEMIK, 2013).

Also, oxygen is an essential component that is typically present in biomass due to its high moisture content. The sulfur content is crucial for assessing the potential for sulfur dioxide ($SO_2$) emissions during combustion, particularly if the biomass briquettes contain sulfur-rich feedstocks. The ultimate analysis results are valuable for evaluating the quality and performance of the biomass briquettes as well as for comparing the biomass briquette to specific regulatory or technical standards.

The carbon content is also a crucial parameter as it determines the energy content and combustion characteristics of the briquettes. The optimal range for carbon content in biomass briquettes can vary depending on the intended use and the specific requirements of the application. However, in general, higher carbon content is desirable as it leads to higher calorific value and improved combustion efficiency. A higher carbon content means that more of the biomass material is converted into carbon, resulting in increased energy density. If the carbon content is too low, the briquettes may have a lower energy value and may be less effective as a fuel source. On the other hand, if the carbon content is too high, it may lead to excessive ash production and poor combustion characteristics. Also, the obtained sulfur content value of 0.1 ± 0.01 in the composite biomass briquette is consistent with the low sulfur content typically found by Bonsu et al. (2020) on Palm Kernel Shell (PKS) briquette. This value falls below the range of sulfur content for fuels which is typically between 0.5% and 0.8% (CHEMIK, 2013). Moreover, the low sulfur content in the composite biomass briquette suggests a slower corrosion rate when used in coal pots. The results from the ultimate analysis reveal that composite biomass briquette does not emit harmful greenhouse gases into the atmosphere and therefore is considered an eco-friendly alternative fuel source for cooking.

**Table 10 : Ultimate analysis of composite biomass briquette**

| Parameter | C (%) | H (%) | O (%) | N (%) | S ( %) |
|---|---|---|---|---|---|
| Briquette | 49.8 ± 0.55 | 8.7 ± 0.53 | 38.82 | 1.5 ± 0.11 | 0.1 ± 0.01 |

Source: Laboratory Analysis, (2023)

### Gross Calorific Value

The Gross calorific value of a solid fuel determines the amount of heat energy it contains. According to Figure 16, composite biomass briquette exhibits the highest gross calorific value of 19.3 ± 0.1 MJ/kg while traditional charcoal value of 16.2±0.5 MJ/kg was lower than that of the composite biomass briquette. Importantly, the high gross calorific value observed in the composite biomass briquette could be attributed to the high carbon content and relatively low ash content recorded in the feedstocks used. Also, the particle size of 2mm of pulverized biochar and the uniform formulation contribute to better attrition and a high degree of conditioning, allowing for efficient moisture absorption. It is important to note that production conditions such as temperature and pressure can also influence the gross calorific value of the composite biomass briquette.

In addition, the calorific values of the composite biomass briquettes are influenced by factors such as carbon content, optimal ash content, manufacturing conditions and the combustion properties of the cow dung used. Composite biomass briquettes can compete with traditional charcoal and fuelwood as an alternative energy source and the properties of the binder such as cow dung also play an important role in determining the overall characteristics of the composite biomass briquettes. The high calorific value recorded in this study highlights composite biomass briquette as a favourable solid fuel for combustion. Additionally, the calorific value falls within the range specified by the ASTM E711-23e1 standard for Refused-Derived Fuel by Bomb Calorimeter which is typically between 18 MJ/kg to 23 MJ/kg.

Hence, the observation made in the study reveals that the process of biomass briquetting resulted in an increase in the calorific value of raw biomass materials. This increase in calorific value can be attributed to the higher carbon content in the briquettes which is consistent with findings reported by Bonsu et al. (2020) and Otieno et al. (2019). Overall, the biomass briquetting process improved the energy potential of municipal based residues by increasing its gross calorific value and bulk density making composite biomass briquettes a more efficient and valuable alternative fuel source for domestic cooking and heating purposes in low- and middle-income households.

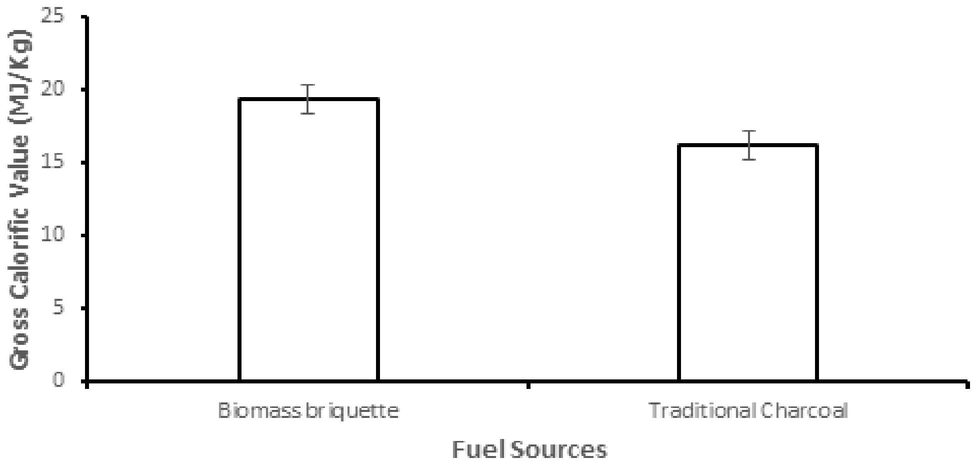

*Figure 16:* Gross Calorific value for Composite biomass briquette and Traditional charcoal

**Combustion Test**

Water boiling tests were conducted to evaluate the suitability of the composite biomass briquettes as an alternative source of cooking fuel in homes (Bonsu et al., 2020). Based on the ignition test results presented in Table 10, the biomass briquettes did not willingly ignite until additional quantities of kerosene were added. This observation could be attributed to the composition of the various feedstocks used. Initially, the same quantity of kerosene (4.06 g) was added for ignition and neither solid fuel did not ignite readily at the spot. Hence, composite biomass briquette required significantly larger amount of kerosene (16.02g) compared to traditional charcoal (Acacia) to achieve ignition. Therefore, this indicates that the composite biomass briquette required four times the amount of kerosene needed for traditional charcoal (Acacia) to initiate ignition.

**Ignition time**

As shown in Table 10, the observed ignition time for the composite biomass briquette (8 minutes) and traditional charcoal (2 minutes) correspond with similar value of 8 minutes reported by Bonsu (2020) for PKS briquette. However, the prolonged ignition time of the composite biomass briquette might be attributed to the nature of mixed characteristic of different feedstocks used and the binder concentration in the fuel. Unlike traditional charcoal with shorter ignition time (2 minutes). However, once the composite biomass briquette is ignited it could sustain combustion effectively.

These findings highlight the specific ignition characteristics and requirements of composite biomass briquette compared to traditional charcoal. It is important to consider these factors when evaluating the suitability and practicality of biomass briquettes for domestic cooking and heating purposes. The varying volumes of kerosene used for both fuels had minimal impact on the boiling time of water as the high calorific value of composite biomass briquettes contributed to a higher combustion rate (Bonsu et al., 2020; Ugwu & Agbo, 2011). During ignition, a slight emission of smoke was observed from the composite biomass briquette which is likely due to the presence of the binder (cow dung) and the use of kerosene for ignition. Moreover, the absence of excessive smoke emission from the composite biomass briquette highlights the significant advantage of using composite biomass briquettes over traditional charcoal and firewood for domestic cooking and heating purposes. The detrimental effects of incomplete combustion could have led to excess smoke on human health and the environment as documented in previous studies by Bonsu et al. (2020), Mbamala (2019) and Chin and Aris (2013).

**Specific Fuel Consumption**

According to Table 10, composite biomass briquette reported a specific fuel consumption of 14.58g/ml while the SFC recorded for traditional charcoal was 3.04g/ml. The specific fuel consumption value obtained indicates that it requires 14.58 g of composite biomass briquette fuel to boil 1.0 ml of water. This higher consumption can be attributed to the traditional cookstove efficiency specifically, the presence of large holes in the cookstove. Also, the disintegration of the composite biomass briquette during combustion could be another factor. It is noteworthy that even after 30 minutes of burning, the composite biomass briquette retains its black form without leaving behind any visible ash residue unlike traditional charcoal, which turns to ashes within the same duration.

The time taken for water to boil in the pot using a composite biomass briquette was 11 minutes which is shorter than the 14 minutes recorded for traditional charcoal. This highlights the advantage of composite biomass briquettes in terms of faster combustion. These results are, however, higher than the values reported by Bonsu (2020) and Holdich (2020).

## Rate of Fuel Burning

The rates of fuel burning of the composite biomass briquettes and traditional charcoal are presented in Table 10. From the table 2.34g of composite biomass briquette is burnt per minute during combustion while traditional charcoal shows that 0.44g of fuel is burnt per minute. The fuel burning rate obtained for composite biomass briquette in this study was seen to be lower than 2.84g/min obtained by Bonsu et al. (2020). This could be attributed to the varying calorific values of each fuel even though the burning rates of the various fuel sources observed in this study were within the acceptable limit of ASTM D3172-06 Standard.

**Table 11: Combustion Test on Composite Biomass Briquette and Traditional Charcoal (Acacia)**

| Test | Data on Traditional Charcoal | Data on Biomass Briquette |
|---|---|---|
| Total weight of fuel at the start of the test (g) | 154.2 g | 745.56 g |
| Total number of fuels at the start of the test | 8.00 lumps | 6.00 lumps |
| The average weight of each fuel | 19.275 g | 124.26 g |
| Total weight of the fuel after water boiled | 81.53 g | 542.52 g |
| The initial volume of water in pot/ temperature | 100 ml / 30 $^0$C | 100 ml/ 30 $^0$C |
| Final Volume of water in the pot after boiling/ Temperature | 76.08 ml/ 100 $^0$C | 86.07 ml / 100 $^0$C |
| Physical Appearance | The colour of the charcoal was black at the initial start-up | The Color of the biomass briquette was black, it was brittle to the touch and took the cylindrical shape of the manual mould |
| Density (g/ml) | 24.52g/10 ml = 2.45 g/ml | 140 g/ 110.2 ml = 1.27 g/ ml |
| Time for water to boil (minutes) | 14.00 min | 11.00 min |
| Ignition | The kerosene burnt out in 2 min and several lumps turned | The kerosene burnt out in 6 min and several briquette |

| | | |
|---|---|---|
| | reddish, and then there was ash formation | lumps turned reddish.<br>with no ash formation |
| Odour | The combustion produced a smoky odour | The combustion produced no odour |
| Sparks | The charcoal burnt with lots of sparks | The briquette burnt with no sparks |
| Cleanliness | The cooking pot's outer cover turned black from the emission of black smoke | The cooking pot remained very neat all through the cooking |
| Moisture content | 12.1% | 5.4 % |
| Specific fuel consumption | 3.04 g/ ml | 14.58 g/ml |
| Fuel Burning rate | The initial mass of the charcoal lump =19.275g<br>Final mass = 13.18g<br>Mass of burnt matter = 6.095 g<br>0.44 g/min | The initial mass of the biomass briquette lump = 124.26 g<br>Final mass = 98.46g<br>Mass of burnt matter = 25.794 g<br>2.34 g/min |
| Smoke | It burnt with the emission of smoke | It burnt with no emission of smoke |
| The mass of kerosene used | 4.06 g | 16.4 g |

Source: Field Experiment (2023)

**Thermal Efficiency**

The thermal efficiency of fuel indicates how efficiently the energy in the fuel is converted into heat energy for optimal combustion. Figure 17 shows that composite biomass briquette achieved the highest thermal efficiency which was 36% while traditional charcoal was 28%. These findings indicate that composite biomass briquettes exhibited the highest thermal efficiency making it suitable alternative cooking fuel to traditional charcoal and fuelwood.

However, the values obtained in this study are lower compared to values obtained in a study by Asad et al. (2022) on briquettes produced from coconut pith, sawdust, and sugarcane. Asad et al. (2022) reported thermal efficiencies of 63.63% for coconut pith briquettes, 61.62% for sawdust briquettes and 53.85% for sugarcane briquettes. However, value obtained for composite biomass briquette fell within the thermal efficiency optimal range for solid fuel in line with the ASTM D3172-06 standard on briquette thermal analysis.

These outcomes highlight the potential of composite biomass briquettes as a highly efficient and sustainable fuel source with excellent thermal efficiency. Further research and development in this field can explore ways to optimize and enhance the thermal efficiency of biomass briquettes thereby ensuring their continued contribution to energy efficiency and environmental sustainability.

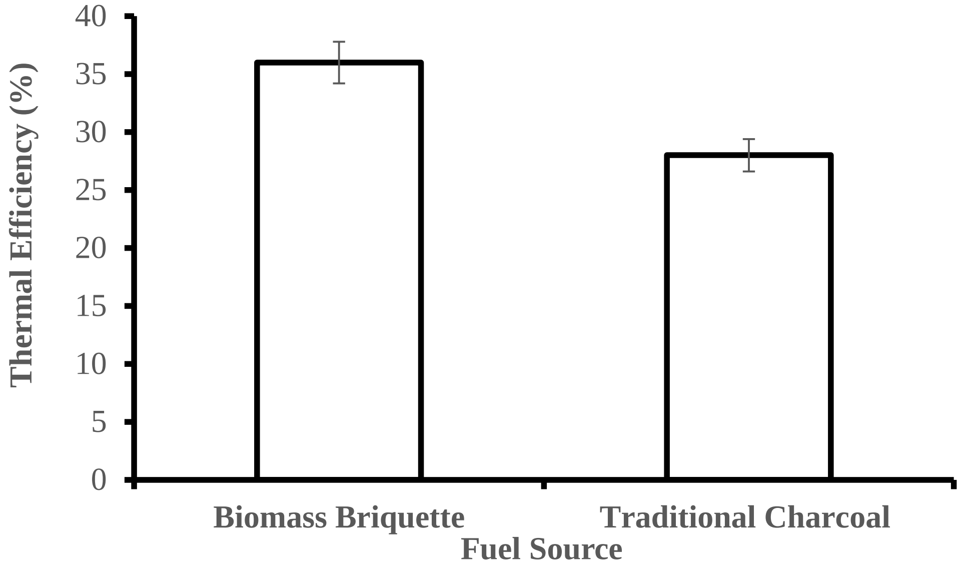

*Figure 17*: Thermal efficiency of Composite biomass briquette and Traditional Charcoal (Acacia)
Source: Laboratory Analysis (2023)

# CHAPTER FIVE

# CONCLUSION AND RECOMMENDATIONS

## Conclusion

This study explored the quantification and characterization of domestic solid waste across three socio-economic areas within Cape Coast North Sub Metropolitan. The findings revealed an average per capital waste generation rate of 0.67 kg/capita/day. Also, organic waste was the predominate waste fraction reporting an average of 60% by weight of the domestic solid waste across the three socio- economic areas. The preparation of composite biomass briquettes from a mixture of plantain peels, cassava peels, sugar cane bagasse, empty fruit bunch and coconut husk obtained from the solid waste audit was achieved with cow dung as a binder. The composite biomass briquettes produced in this study exhibited several favourable characteristics making them environmentally, sustainable fuel sources. The comprehensive proximate analysis conducted after the production of the fuel confirmed that the moisture content, ash content, volatile matter and fixed carbon of the composite biomass briquettes met established standards by ASTM D3172-04 standard. The ultimate analysis of the composite biomass briquette sample depicts the elemental composition of carbon, hydrogen, oxygen, nitrogen, and sulfur. The high heating value or gross calorific value of the composite biomass briquette was estimated and found to be higher when compared to traditional charcoal following the ASTM D3172-04 standard.

The combustion tests conducted provided valuable insights regarding the ignition, fuel burning rate, specific fuel consumption and thermal efficiency of the fuel. However, composite biomass briquettes prolonged to initiate ignition and required a more amount of kerosene for ignition compared to traditional charcoal, but once ignited composite biomass briquettes could sustain steady combustion. Also, the composite biomass briquettes exhibited a higher thermal efficiency than traditional charcoal making it a suitable alternative solid fuel. Unlike traditional charcoal which emitted significant smoke and formed sufficient ash residue, the composite biomass briquettes burned with minimal smoke emissions and produced no noticeable ash.

The findings of the research suggest that composite biomass briquettes possess desirable combustion properties making them suitable for various household applications such as cooking, heating water, smoking fish, and ironing clothes. The cost-effectiveness of the production process and the use of locally available materials make the adoption of biomass briquetting easily adaptable within local communities in Ghana and Sub Sahara Africa.

The study revealed that the production and utilization of biomass briquettes do not require specialized expertise or extensive training, making it a practical and accessible solution for sustainable fuel needs. It was also revealed that there is no need to modify available cookstoves for biomass briquette usage since briquette can be utilized in existing cooking stoves with no modification.

## Recommendations

The following are recommended in this research:

1. Research and development on composite feedstocks for biomass briquette production should prioritize the implementation of cost-effective emission reduction strategies with a specific focus on improving cook stove designs. By designing and optimizing more

efficient and improved cook stoves, the combustion efficiency of composite biomass briquettes can be enhanced thereby resulting in reduced emissions of harmful pollutants. These strategies should aim to achieve a balance between improved fuel combustion and affordability, ensuring widespread adoption and sustainable use of composite biomass briquettes as clean cooking fuel.

2. Recognizing the significant potential of municipal solid waste as a renewable energy source, further research should explore other fractions of municipal waste to produce high-quality biomass briquettes. Investigating different biomass feedstocks such as agricultural residues, wood waste, sewage sludge or other suitable biomass sources can expand the range of available biomass briquette options. This study should encompass comprehensive studies on the characteristics, availability, and sustainability of these biomass sources to ensure the development of briquettes that contribute to both energy access and effective environmental management and sustainability.
3. To address concerns regarding particulate matter emissions during briquette combustion, it is crucial to emphasize the importance of proper carbonization processes. Biomass briquettes should undergo thorough carbonization to reduce volatile matter content and increase carbon content, resulting in cleaner and more efficient combustion. This step ensures the production of biomass briquettes with lower emissions and higher combustion efficiency. For industrial applications, additional measures such as the use of centrifugal collectors or fabric filters should be explored to further mitigate

particulate matter emissions. These technologies can effectively capture and remove particulate matter and help contribute to improved air quality and reduced environmental impact.

4. Further research and development in the field of biomass briquettes on composite raw materials should focus on a detailed analysis of the elemental composition of the feedstocks and ways to reduce the ash content and volatile matter of the biomass briquette. The optimization of existing coal pots and cookstoves could be another research direction. These advancements should aim to incorporate smaller holes in the design and thereby promote efficient combustion and enhancing the overall performance of the biomass briquettes. By continually refining the briquetting technology and design aspects, biomass briquettes can offer even greater combustion efficiency, reduced greenhouse gas emissions and improved usability as well as reinforcing their position as a viable and environmentally friendly alternative solid fuel in developing.

By expanding research efforts based on these recommendations, the field of biomass briquettes can be advanced significantly. This research can lead to the development of more efficient, cost-effective, and environmentally friendly biomass briquette technologies which are suitable for various applications ranging from domestic cooking and heating to industrial processes. These will contribute to achieving the United Nations Sustainable Development Goal (SDG) 7 (Affordable and clean energy access for all) by preparing composite biomass briquette as alternative clean cooking fuel to firewood and traditional charcoal, SDG 11 (Sustainable cities and communities) by offering sustainable municipal solid waste treatment option, SDG 15 (Life on land) by contributing to the fight against deforestation and SDG 13 (Climate Action) by producing composite biomass briquette free of harmful greenhouse gases.

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# APPENDICES

## APPENDIX A: Images from Field Work and Laboratory Analysis

Hand Mould used for compaction

Researcher using Digital Vanier Caliper

Images of the combustion test

## APPENDIX B: Data Recording Sheet For Per Capita Waste Generation Rate

| **Household Code** | **Household size** | **Week 1** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **Day 1** | **Day 2** | **Day 3** | **Day 4** | **Day 5** | **Day 6** | **Day 7** | **Total (Kg)** |
| R001 | | | | | | | | | |
| R002 | | | | | | | | | |
| R003 | | | | | | | | | |
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| R030 | | | | | | | | | |
| **Total** | | | | | | | | | |

## APPENDIX C: Data Collection Form for Domestic Solid Waste Physical Composition

| Physical Composition of Domestic Solid Waste - 4th Ridge | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Week 1 | | | | | | | |
| **Components** | **Day 1** | **Day 2** | **Day 3** | **Day 4** | **Day 5** | **Day 6** | **Day 7** | **Total** |
| Organics | | | | | | | | |
| Paper & cardboard | | | | | | | | |
| Plastics | | | | | | | | |
| Metals | | | | | | | | |
| Inert materials | | | | | | | | |
| Textiles | | | | | | | | |
| Rubber & Leather | | | | | | | | |
| Miscellaneous | | | | | | | | |
| **Total** | | | | | | | | |