KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

KUMASI

COLLEGE OF ENGINEERING

DEPARTMENT OF AGRICULTURAL AND BIOSYSTEMS ENGINEERING

ASSESSMENT OF THE PHYSICAL AND COMBUSTION PROPERTIES OF BRIQUETTES PRODUCED FROM DRIED COCONUT HUSK

THIS DISSERTATION IS BEING SUBMITTED TO THE DEPARTMENT OF AGRICULTURAL AND BIOSYSTEMS ENGINEERING, KNUST IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF BSC. (HONS) DEGREE IN AGRICULTURAL ENGINEERING

BY ABOAGYE GLORIA BAABA

MAY, 2017

DECLARATION

"I hereby declare that I have completely undertaken the study reported herein under the supervision

of Prof. Ebenezer Mensah and Dr. George Yaw Obeng, and except portions where references

have been duly cited, this dissertation is the outcome of my research".

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(SUPERVISOR) SIGNATURE DATE

ABSTRACT

Ghana has in abundance of biomass resources whose potentials are yet to be fully tapped for energy generation. The over dependence on these resources, its negative impacts on the environment and the ever rising prices of energy supply could be curbed by switching to alternative technologies and one such promising technologies is briquetting. This study was undertaken to investigate the potentials of briquettes produced from dried coconut husk at 5 %, 10 % and 15 % level of starch binder. The briquettes were produced with the aid of a hand mould at an average pressure of 344.82 kNm^{-2}. The physical and combustion properties of the briquettes that were determined included; moisture content, compressed and relaxed densities, ash content, volatile matter, fixed carbon, water and shatter resistances, water boiling test (comparison of briquettes with charcoal), calorific value and heat capacity (with the aid of a bomb calorimeter), gas emission analysis (with the aid of an indoor pollution meter) and thermal efficiency. The calorific values for charred briquette (P>2 mm) with 5 %, 10 %, 15 % binding ratios were 23452.51 kJ/kg, 24989.50 kJ/kg, 20758.57 kJ/kg respectively. The calorific values for (P<2 mm) with 5 %, 10 %, 15 % binding ratios were 8450 kJ/kg, 17895 kJ/kg and 13610 kJ/kg respectively. The calorific values of uncharred briquette with 5 %, 10 % and 15 % binding ratio were 15747 kJ/kg, 16806 kJ/kg and 16075 kJ/kg. Also the calorific value of charcoal produced from sweet acacia was 19,200 kJ/kg. Thermal efficiency of the briquettes produced competed favourably with charcoal. Hence, the thermal efficiency of the charred briquette (92.42%) was the highest followed closely by the uncharred briquette (88.03%) and charcoal (77.1%). Charcoal emitted the highest carbon monoxide (561.1ppm), followed by the uncharred briquette (519.7 ppm) and the charred briquette (340.6 ppm).

DEDICATION

I dedicate this project to my parents, Mr. Frederick Aboagye and Mrs. Mercy Aboagye and to all my loved ones

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Study

Coconut, scientifically called *Cocos nucifera* is one of the most important and useful palms in the world. Coconuts grow abundantly in tropical regions, and they thrive in sandy, saline soil. Globally, coconut is grown in more than 92 countries all over the world (FAOSTAT, 2008). Indonesia and Philippines are the major producers of coconut in the world producing 19,500,000 metric tonnes and 18,300,000 metric tonnes respectively. The total world coconut growing area is estimated at 12 million hectares (Omont, 2001).

Papua New Guinea is the leading producer in the South Pacific. In Africa, Tanzania is the largest producer while in Latin America Brazil accounts for more than one half of the total coconut growing area of that region (Punchihewa and Arancon, 1999).

In Africa, the major coconut producing countries include Tanzania (530,000 metric tonnes), Ivory Coast (195,000 metric tonnes), Mozambique (260,000 metric tonnes), Nigeria (265,000 metric tonnes) and Ghana which produces about 366,183 metric tonnes annually (Muyengi et al., 2015). Below is a graph indicating the quantity of coconuts produced in Africa, Ghana and the World at large.

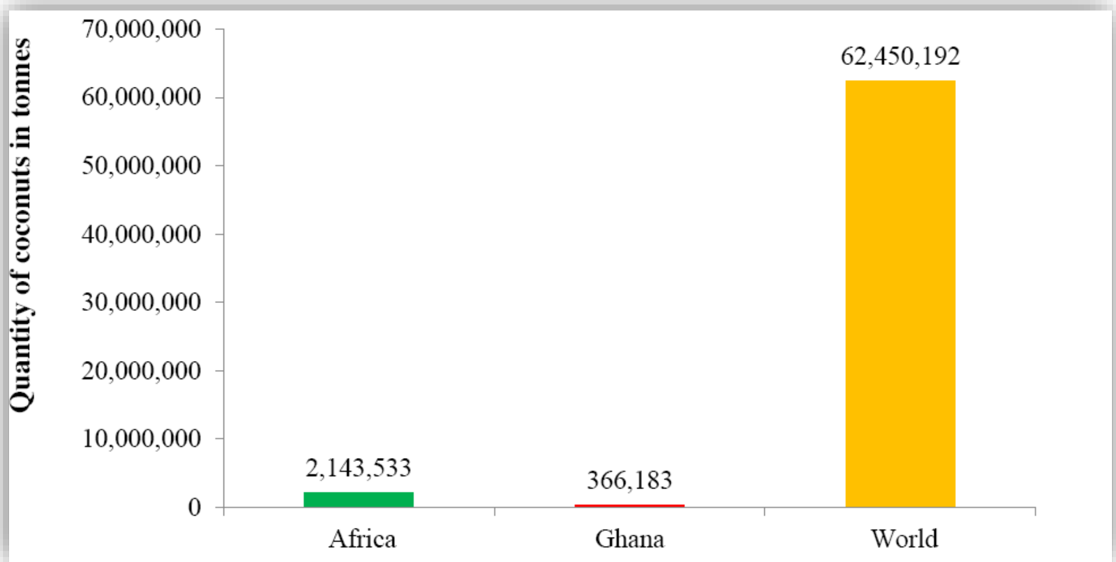

Figure 1.1: Coconut Production (tonnes), source: FAOSTATS 2013

According to the Ghana Investment Promotion Centre 2016 (G.I.P.C), coconut is produced on a very small scale between 0.5-5.0 ha. Small holders produce about eighty percent of the nuts from an area of 36,000 hectares.

Many Ghanaians have not fully discovered the enormous economic potential and uses of coconut.

Coconut husk is the rough exterior shells of the coconut. The husks are not edible like the white meat and liquid found within the exterior shell, but it can be used in several ways including being used in a biomass convertor to produce combustible gases which in turn can be used in a gas turbine to produce electricity and heat. It can also be used for fuel as well.

The outer husk of a coconut consists of long, rough fibres which are made into variety of products such as floor mats and roofing materials. Studies have shown that a healthy coconut tree will produce approximately one hundred and twenty watermelon sized husks annually (Bradley et al., 2006).

Briquetting is the process of converting agricultural waste into a uniformly shaped block of coal that are easy to use, convey and store (Raju et al., 2014).

Coconut husk can be transformed into briquettes an advanced fuel because of its clean burning nature and long storability without deterioration.

Briquetting can be done with or without a binder (also known as a fastening agent). The binding material may be an organic material and this material must be decomposed partially so as to release the fibres necessary to hold the briquette together.

Preparing coconut husk without a binder is more convenient but it requires sophisticated machines and equipments (Janczak, 1980).

Coconut husk briquette can be made locally and inexpensively and it is very efficient, burns cleanly reducing exposure to the smoke that causes respiratory diseases. By providing an alternative to wood burning, coconut husk briquette can help reduce the rate of deforestation.

Globally, more than two billion people utilise wood, charcoal, agricultural residues as the primary fuel for their cooking and heating needs leading to significant health, economic and environmental consequences.

In the year 2000, indoor air pollution from solid fuel use was responsible for more than 1.6 million annual deaths and 2.7 % of the global burden of disease (World Health Organization, 2000). About 80 percent of Ghanaian households depend on energy in the form of firewood, twigs and charcoal and it is used in the domestic sector for cooking and other domestic activities.

1.2 Problem Statement

Conversion of coconut husk into briquette have not been successful in the developing countries especially Ghana due to lack of awareness of the importance of coconut waste. Coconut farmers and many individuals have limited knowledge of different ways of utilising coconut products especially the husk and they all go to waste always making the environment unclean.

It is extremely difficult to control the disposal of coconut husk in Ghana. They are littered everywhere and sometimes used in filling potholes. They are also burnt in open environments causing pollution. Coconut sellers cannot afford the huge sums of money to burn the waste in incinerators so they always plead with food vendors to take the husk and use it as fuel, disposing off coconut waste improperly causes environmental hazards such as air pollution and it can also choke gutters creating breeding sites for mosquitoes causing malaria and other diseases.

People who utilise the raw coconut husk as firewood end up inhaling smoke which emanates from the burning of the husk causing eye and respiratory diseases.

Over exploitation of wood due to high rise in population are the major drivers of deforestation and environmental pollution.

Coconut waste generated annually in cities and towns of southern Ghana is estimated to be 200,000-300,000 metric tonnes (Greening The Savannah Project, 2012). People who utilise the raw coconut husk as firewood end up inhaling smoke which emanates from burning of the husk, which if inhaled continuously can result in eye and respiratory diseases. Therefore, there is the need to biochar the waste husk and convert to briquettes that burn clean with relatively less smoke.

1.3 Justification

When coconuts are harvested the husks are removed, and they are considered as waste materials and are dumped. But these husks have numerous advantages which have not yet been exploited. Ghana produces 366,183 metric tonnes of coconuts, and if it could be developed both technically and commercially into high value products, it would help improve the quality of life of Ghanaians. Coconut husk is of great importance and if serious attention is paid to it, the problems associated with its waste will be dealt with effectively.

Attention should be focused on converting waste coconut husk into briquette because it addresses the environmental consequences and health hazards associated with the use of solid fuels (wood, charcoal). It also gives better combustion properties and helps to reduce gas emissions more as compared to solid fuels. It helps preserve the forest resources by serving as an alternative to wood and charcoal and thereby slowing the process of deforestation.

Over the years there has been a high demand for fuel wood, which has led to its drastic shortage and this is due to high population. With successful production of coconut husk briquettes, fuel wood users especially people in the urban and peri-urban areas can have an alternative to fuel wood.

In terms of waste management, coconut husk which are basically considered as unwanted by-product at some parts of the world can be used for so many useful things that can help create employment.

1.4 Main Objective

To assess the physical and combustion properties of briquette produced from dried coconut husk.

1.5 Specific Objectives

The specific objectives of this study are:

1. To determine the energy content of charred and uncharred briquettes
2. To compare the thermal efficiencies of charcoal, charred and uncharred coconut husk briquette
3. To compare the emissions of charcoal, charred and uncharred coconut husk briquettes

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Biomass Briquetting: An Alternative Source of Energy

Globally, energy supply is highly dependent on fossil fuels (crude oil, coal, natural gas). The highly esteemed fossil fuels resources were formed from decayed plants and animals buried inside the earth crust.

In these recent times there is rapid depletion rate of fossil fuels and a double up of prices. About 140 million of biomass is generated annually (Tembe et al., 2014), a huge amount of energy is derived. Renewable energy sources are being sought after because prices of the non-renewable energy such as kerosene and LPG are relatively expensive. There is a growing interest in renewable energy source which will serve as an alternative to fossil fuel sources in some few years to come.

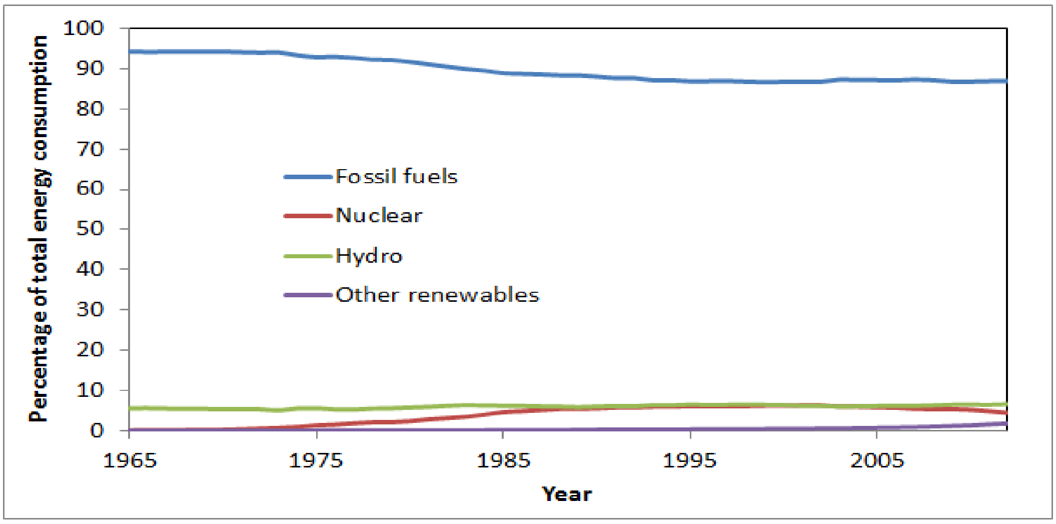

Figure 2.1: The total energy consumed from 1965-2005

From figure 2.1, it is a clear indication that fossil fuels are overused in the system and it will get exhausted in some years to come.

Biomass refers to all organic matter derived from living or recently living organisms, plant and animal-based (Shreya and Sevita, 2015).

Burning raw biomass usually has a high content of volatile matter and ash and lower density and energy values (source:www.cleancookstoves.org).

Processing the biomass into compact, evenly sized pieces such as briquettes or pellets allows the biomass to burn more efficiently and evenly, increasing their energy density and transportability.

In many parts of the world, one basic source of energy for important activities such as cooking and space heating is burning wood and other agricultural products.

With population on the increase every day, resource of combustible biomass materials is gradually diminishing and will eventually result in shortage of these materials unless certain measures are taken to reserve them. One method of making more efficient and effective use of existing resources is through the use of briquetting. It has been proposed that the conversion of dried coconut husk through the process of briquetting will go a long way to solve problems of deforestation and also problems associated with pollution.

Each year, millions of tons of agricultural wastes are generated which are either destroyed or burnt inefficiently in loose form causing air pollution which in turn causes lung and respiratory diseases killing people each year (Sriram et al., 2014). These wastes can be recycled and can provide a renewable source of energy (Maninder et al., 2012).

In Ghana for instance a large number of agricultural waste especially coconut waste is produced each day and briquetting of these wastes could mitigate these pollution problems.

Plate 2.1-Plate 2.3 indicate pollution problems with regards to coconut waste.

Plate 2.1: Burning of Coconut Waste Causes Eye and Respiratory Diseases

Plate 2.2: Improper disposable of Coconut Waste leading to Environmental Pollution

Plate 2.3: Pollution of Water Bodies

Many countries are resulting to the development of a clean, pollution free sustainable energy resources. Among the various potential sources of renewable energy, briquettes are of most interest and it is expected to play a key role in the global energy infrastructure in the future (Sriram et al., 2014).

Briquetting Technology is one of the promising solution to the problem at hand.

2.2 Coconut Production in Ghana

Agriculture in Ghana is done on a smaller holder basis (MOFA, 2011). Ninety percent of farms in Ghana are less than 2 hectares in size although there are some large farms and plantations particularly rubber, oil palm and coconut (MOFA, 2010).

2.3 Energy Potential of the Components of Coconut

The coconut is very special in that, the components of the nut have equally large energy sources. The amount of energy associated with the coconut husk is so large as to merit the large expense and serious effort is needed by studies to fully exploit these energy sources (Banzon, 1980).

Table 2.4 shows the energy content of the various part of coconut as analysed by Julian A. Banzon

Table 2.4: Energy Values of the various parts of Coconut

Component	Kg	Energy Kcal	Percent of Total Energy
Coconut oil	0.12	1080	27.7
Shell	0.18	990	25.4
Husk	0.4	1600	41.1

Observations from Table 2.4 show that energy content in the coconut husk is higher as compared to the shell and the oil and this is good for briquetting.

2.4 Waste Management of Coconut Husk

Solid waste management is the supervised handling of waste material from generation at the source through the recovery processes to disposal (source: Glossary of Environmental Statistics in Methods, 1997). Management of solid waste eliminates adverse impacts on the environmental and human health and supports economic development and it also improves the quality of life. Coconut husk which is considered as waste in Ghana is extremely difficult to manage. They are littered everywhere causing pollution to the environment. According to Ogawa (2005), challenges facing Ghana with respect to coconut husk management are; low collection coverages, inadequate waste infrastructure and irregular collection services. Proper waste collection and proper disposal of refuse are big issues facing Ghanaians (Puopiel, 2010). Coconut husk is very loose and friable a material that much attention has not been paid to it in terms of the conversion of coconut husk into briquette.

2.4.1 Uses of Coconut Husk

The coconut husk has become a very useful substance in today's environmental and economic concerns. Coconut husk could be effectively managed and utilised by supplying it to the local manufacturers for the manufacturing of carpets, egg crates, crop manure and compost, yarn and ropes and this can be achieved through the process of recycling (Amoah, 2016).

2.5 Briquetting

Briquetting is the process of compaction of residues into a product of higher density, it is also known as densification (Kaliyan and Morey,2008). If produced at a low cost and made conveniently accessible to consumers, briquettes could serve as compliments to firewood and charcoal for domestic cooking and agro-industrial operations, thereby reducing the high demand for both (Wilaipon, 2008). The briquetting of biomass improves its handling characteristics, increases the volumetric calorific value, reduces transportation costs and makes it available for a variety of application.

2.5.1 Briquetting Technology

Biomass densification represents a set of technologies for the conversion of biomass residues into a convenient fuel. The technology is also known as briquetting or agglomeration (Maninder et al., 2012). Depending on the types of equipment used, it could be categorized into five main types:

- Piston press densification

- Screw press densification
- Roll press densification
- Pelletizing
- Low pressure or manual presses

On the basis of compaction, briquetting technologies can be divided into;

High pressure compaction, medium pressure compaction with a heating device and low pressure compaction with a binder (Grover and Mishra, 1996).

2.5.1.1 High and Medium Pressure Compaction

High and medium pressure compaction normally do not use any additional binder. If fine materials which deform under high pressure are pressed, no binders are required. The strength of such compacts is caused by van der Waals' forces, valence forces, or interlocking. Natural components of the material may be activated by the prevailing high pressure forces to become binders (Grover and Mishra, 1996).

In high pressure compaction, biomass residues are compressed under high temperature and pressure (Chaney, 2010). These residues contain lignin that is a non-crystallized aromatic polymer with no fixed melting point, but at 200–300°C, lignin starts to become soft, melted and liquefied.

2.5.1.2 Low Pressure Compaction

Low pressure briquetting needs a binding agent to assist the formation of bonds between the biomass particles.

Binding agents can be divided into two main groups: organic and inorganic binders.

- Organic binders
  1. Molasses
  2. Coal tar
  3. Bitumen
  4. Starch
  5. Resin
- Inorganic binders
  1. Clay
  2. Cement
  3. Lime
  4. Sulphite liquor
  5. Waste paper

Binding Agents can also be subdivided into combustible and non-combustible binders.

- Combustible binders
    1. Natural or synthetic resins
    2. Tar
    3. Animal manure
    4. Sewage Mud
    5. Fish waste
    6. Algae
    7. Starch

- Non Combustible binders
    1. Slime
    2. Clay
    3. Mud
    4. Cement

Although the non-combustible binder lowers the heating value of the briquette and increases the ash content, it does not make possible the use of the materials which otherwise would be valueless as fuel.

2.5.2 Ram/Piston and Screw Press Technologies

Currently, there are two high pressure technologies; ram/piston press and screw press which are both used for briquetting. Briquettes produced by a piston press are completely solid whiles screw press briquettes have a concentric hole which gives it better combustion characteristics due to a larger specific area. In screw press and piston press technology, binding material is not needed and high pressure is applied which increases the temperature of biomass. The compaction ratio of screw presses ranges from 2.5:1 to 6:1 or even more. In this process, the biomass is extruded continuously by one or more screws through a taper die which is heated externally to reduce the friction (Maninder et al.,2012). In the screw press technology due to the application of high pressures, the temperature rises fluidizing the lignin present in the biomass which acts as a binder. The outer surface of the briquettes obtained through this process is carbonized and has a hole in the centre which promotes better combustion and the standard size of the briquette is 60 mm in diameter (Maninder et al., 2012). The screw press briquettes do not break easily and they have a high rate of combustion (Grover and Mishra 1996).

Table 2.5 shows a comparison between a screw extruder and a piston press.

Table 2.5 Comparison of a screw extruder and a piston press

	Piston Press	Screw Extruder
Optimum moisture content of raw material	10-15%	8-9%
Wear of contact parts	Low in case of ram and die	High in case of screw
Output from the machine	In strokes	Continuous
Power consumption	50 kWh/ton	60 kWh/ton
Density of briquette	1-1.2 gm/cm^3	1-1.4 gm/cm^3
Maintenance	High	Low
Combustion performance of briquettes	Not so good	Very good
Carbonisation to charcoal	Not possible	Makes good charcoal
Suitability in gasifiers	Not suitable	Suitable
Homogeneity of briquettes	Non-homogenous	Homogenous

(Eriksson, 1990)

Briquetting is yet to gain grounds in many developing countries like Ghana because of the technical constraints involved and also the lack of knowledge necessary in adapting the briquetting technology. According to Grover and Mishra, overcoming the many operational problems associated with the briquetting technology and ensuring the quality of the raw material used are important factors in determining its economic success.

2.5.3 Other Briquetting Technologies

- **Roller Press**

In the roller press technology, the feedstock falls in between two rollers, rotating in opposite directions and is compacted into pillow-shaped briquettes. Briquetting biomass usually requires a binder. This type of machine is used for briquetting carbonized biomass to produce charcoal briquettes (Maninder et al., 2012).

- **Pelletizing**

This is closely related to briquetting except that it uses smaller dies (approximately 30 mm) so that the smaller products are called pellets. The pelletizer has a number of dies arranged as holes bored on a thick steel disk or ring and the material is forced into the dies by means of two or three rollers. The two main types of pellet presses are: flat/disk and ring types. Other types of pelletizing machines include the Punch press and the Cog-Wheel pelletizer. Pelletizers produce cylindrical briquettes between 5 mm and 30 mm in diameter and of variable length. They have good mechanical strength and combustion characteristics. Pellets are suitable as a fuel for industrial applications where automatic feeding is required (Maninder et al., 2012).

- **Manual Presses and Low Pressure Briquetting**

There are different types of manual presses used for briquetting biomass feed stocks. They are specifically designed for the purpose or adapted from existing implements used for other purposes. Manual clay brick making presses are a good example. They are used both for raw biomass feedstock or charcoal. The main advantages of low-pressure briquetting are low capital costs, low operating costs and low levels of skill required to operate the technology. Low-pressure techniques are particularly suitable for briquetting green plant waste such as coir or bagasse (sugar-cane residue). The wet material is shaped under low pressure in simple block presses or extrusion presses. The resulting briquette has a higher density than the original material but still requires drying before it can be used. The dried briquette has little mechanical strength and crumbles easily and the use of a binder is imperative.

2.5.4 Types of Briquettes

Briquettes can be charred, acting as a substitute for charcoal, or non-carbonized, often replacing firewood and raw biomass fuel. Carbonized fuel briquettes are made from waste materials that have undergone carbonization (the conversion of organic substances into carbon in the absence of oxygen) (Source: www.cleancookstoves.org). Non-carbonized briquettes are produced from waste materials that are partially decomposed and then dried and can be made manually by hand, with presses, or with a mechanized mould or extruder, and by mixing the feedstock with water and a binder and drying them (Source: www.cleancookstoves.org).

2.5.4.1 Charred and Uncharred Processes

Charred process

In this process, the feedstock is first partially burned in an environment where fresh air is controlled. The process is known as charring or carbonisation. Once carbonised, a binding material is added and then the materials are then compacted using a briquette press. The advantage with carbonised briquettes is that they are virtually smokeless and this is a key consideration for household users (Grover and Mishra, 1996).

Uncharred process

This is the process of making briquettes without first carbonising them. The biomass materials are simply prepared and compacted to produce briquettes.

This is simpler (and cheaper) process for a micro and small scale enterprises than carbonising but only suited to applications where smoke is not an issue. For industrial applications however, it requires sophisticated machines to achieve the level of compactness (Grover and Mishra, 1996).

2.5.5 Characteristics of a Good Briquette

Generally, a good briquette should have the following characteristics;

- Hardness and Toughness

  The briquette should be sufficiently hard, but not too hard to cause it to be less coherent when subjected to rough handling.
- Weathering

  The briquette should stand long exposure to the weather with little deterioration.

  A dense briquette will stand the weather better than a porous one.

  In the process of briquette manufacturing, they are liable to crack if they lack the proper proportion of binder, or if the mixture has been improperly mixed.
- Burning Qualities

  The ease with which a briquette will ignite depends largely on the slack used, but can be regulated to some extent. Large briquettes ignite less readily than small ones.

2.5.6 Applications of Briquettes

Briquettes have many numerous uses which include both domestic and small industrial applications (Ahmed et al., 2008). They are often used as an intervention to replace firewood, charcoal, or other solid fuels. This is due to the current fuel shortage and its ever rising prices, consumers are therefore looking for affordable alternative fuels and briquettes fill this gap.

Briquettes can be applied in;

- Cooking and water heating in households
- Heating productive processes, fruits drying, poultry rearing etc.
- Firing ceramics and clay wares such as improved cook stoves, pottery, bricks etc.
- Fuel for gasifiers to generate electricity
- Powering boilers to generate steam.

2.5.7 Advantages of Briquettes

- Briquettes are easy, light in weight and cheap in transportation as compared to firewood.
- The use of briquette does not contribute to deforestation and land degradation like firewood. Various research on briquettes indicate that briquettes used in an advanced stove decrease emission.
- In terms of affordability, raw materials for briquetting are abundant in many developing countries like Ghana, and productive use of them could save on the cost of waste disposal.
- Briquettes are clean and smokeless other than firewood which emits smoke to cause eye and respiratory diseases.
- Helps improve the management of waste thereby creating employment.

2.5.7.1 Advantages of Using Briquettes Compared to other Solid Fuels

- Briquettes are cheaper than coal.
- There is no sulphur in briquettes, thus does not pollute the environment.
- Biomass briquettes have a higher practical thermal value**.**
- Briquettes have much lower ash content (2 % to 10 % as compared to 20% to 40% in coal).
- Combustion is more uniform compared to coal
- Briquettes give much higher boiler efficiency because of low moisture and higher density.
- There is no fly ash when burning briquettes.

(Manoj et al., 2015)

2.5.8 Conventional Fuels that Briquettes Can Replace

- Diesel
- Kerosene
- Furnace oil
- Lignite
- Coal
- Firewood

(Manoj et al., 2015)

2.5.9 Limitations of the Briquetting Process

As many advantages the briquetting process appears to have, it has the following drawbacks.

- Briquettes can only be used as solid fuels, it cannot be used as liquid fuel such as the one used in internal combustion engine (Grover and Mishra ,1996).
- Another setback identified with the briquetting process is with the lifespan of the screw. Usually the screw wears out within work 3-4hrs and it becomes unusable. Repairing of the screw takes time, it delays work and the screws cannot be repaired more than 10 times (Mishra, 1996).
- High investment cost and energy consumption input to the process
- Sometimes undesirable combustion characteristics are often observed e.g., poor ignitability, smoking, etc.
- Tendency of briquettes to loosen when exposed to water or even high humidity weather

2.6 Factors Affecting Densification/ Briquetting

The factors that greatly influence the densification process and determine briquette quality are:

- **Temperature and Pressure**

  - Thorough observations indicated that compression strength of densified biomass depended on the temperature at which densification was carried out.

  - Maximum strength was achieved at a temperature around 220°C.

  - It was also found that at a given applied pressure, higher density of the product was obtained at higher temperature.

- **Moisture Content**

  - Moisture content has an important role to play as it facilitates heat transfer.

  - Too high moisture causes steam formation and could result into an explosion.

  - Suitable moisture content could be of 8 % to 12 % (Maninder et al., 2012).

- **Drying**

  - Depends on factors like initial moisture content, particle size, types of densifier, throughout the process.

- **Particle Size and Size reduction**

  - The finer the particle size, the easier is the compaction process.

  - Fine particles give a larger surface area for bonding.

  - It should be less than 25 % of the densified product.

  - Could be done by means of a hammer mill.

  - Wood or straw may require chopping before hammer mill

2.6.1 Quality of Biomass Residues for Briquetting

Factors to be considered before an agricultural residue goes through briquetting process, it should have the following characteristics;

- Low moisture content. The moisture content should be as low as possible, ranging from 10-15 % (Grover and Mishra, 1996). High moisture content poses grinding problems.
- Low ash content. The ash content should be low so as to reduce the slagging behaviour of the biomass.
- A higher density is required to give the briquette a higher calorific value and makes the briquette burn more slowly as compared to the raw materials from which the briquettes are made (Kaliyan and Morey, 2009).

2.6.2 Physical and Combustion Properties of Briquettes

The physical properties include;

- Density
- Shatter Index: This is also known as friability. This factor is a measurement of the briquette's ability to resist mechanical action that will affect them when handled and transported. The shatter index also has to with the durability of the briquettes. This involves dropping the briquette samples repeatedly from a specific height onto a solid base.
- Water Resistance
- Moisture content
- Average length
- Average diameter
- Colour

The combustion properties include;

- Volatile Matter: This refers to the part of the biomass that is released when the biomass is heated up to 400-500ºC.
- Ash Content: The ash content is an organic component/matter left out after complete combustion of the biomass. Generally, it contains mainly Calcium, Potassium, Magnesium and Phosphorus elements that affect ash fusion.
- Water Boiling Test
- Energy Content: This expresses the amount of potential energy contained in the briquette.
    - ✓ Calorific value: This is the amount of energy per kg it gives off when burned.
    - ✓ Heat capacity: The amount of heat needed to raise the system's temperature by one degree.
- Fixed Carbon: This is the solid combustible residue that remains after a coal particle is heated and the volatile matter is expelled.
- Gas Emission Analysis
    - ✓ Particulate Matter: A widespread air pollutant, consisting of a mixture of solid and liquid particles suspended in the air (WHO,2013).
    - ✓ Carbon Monoxide: A colourless, odourless gas that is formed when the carbon fuels do not completely burn.

2.6.3 Binding Material for Briquetting

Briquetting can be done with or without a binder. Doing without the binder is more convenient but it requires sophisticated and costly presses and drying equipment which makes such processes unsuitable in a developing country like Ghana (Janczak,1980). Observations made by Wamukonya and Jenkins (1995), indicate that for the briquetting industry to be successful in the less industrialized countries, the equipment should consist of locally designed simple, low-cost machines. Some binders include; ash, cow dung, starch etc. The cost of the binding material can be critical to the economic success of the project, so the smallest amount of binder necessary for an acceptable briquette should be used.

2.6.4 Qualities desired in Binders

A good binder necessary to make a good briquette include;

- It should be sufficiently cheap to make the production of briquette profitable.

- It must bind strongly, producing a hard but not too brittle briquette.
- It should be able to hold the briquette together satisfactorily in the fire.
- It should not cause smoke or emit corrosive gases

2.6.5 Analysis made by Emerhi E.A on the Proximate Composition of Briquettes According to Different Binders

Table 2.6 indicates the combustion properties of different binders.

Binders	% Volatile Matter	% Ash Content	Heating Values
Ash	60.39 ± 1.41	28.13 ± 0.37	24,160.67 ± 136.63
Cow dung	75.67 ± 2.83	14.89 ± 0.05	28,578.33 ± 53.77
Starch	89.47 ± 0.22	16.94 ± 2.55	33,078.67 ± 133.52

It can be deduced from the table above that cassava starch is a good organic binder and it has a high efficiency in briquette production. Also cassava starch has the best physical and combustion properties with other binders.

2.6.6 Advantages of Starch as a Binding Material over other Binding Materials

Starch possesses the advantages of;

- It does not add a smoke producing material to the briquette
- It is non-volatile
- It is widely available
- It holds the briquette together

2.6.7 Step By Step Production of Charred and Uncharred Briquettes

The briquetting process usually starts with the collection of the residues followed by size reduction, drying and compaction by extruder or press. Briquetting can be carried out with or without a binder. The one without a binder is more convenient, but it requires sophisticated and costly presses and drying equipment (Tabil, 1997).

Listed in sections 2.6.7.1-2.6.7.6 are procedural steps for uncharred briquette production.

2.6.7.1 Sorting

This is also referred to as sieving. Usually, all unwanted materials or large biomass wastes are removed.All the unwanted pieces within the feedstock can be sieved out with a wire mesh.

2.6.7.2 Size Reduction

The raw material is first reduced in size by chopping, crushing,breaking, rolling, hammering, milling, grinding, cutting, etc.,until it can pass through a screen or reaches a suitably small and uniform size. Under this process, the size of the biomass material is reduced so as to enhance their workability and compactness.

2.6.7.3 Mixing

This is normally required in situations where different range of biomass feed stocks is to be used primarily to optimize the burning characteristics of the final fuel. This process is done in situations where ones wants to use a range of different feedstock to optimise the burning characteristics of the final fuel. For example, biomass materials with high ash content could be mixed with biomass material of low ash content. Biomass with low energy content such as papers can be appropriately mixed with those of high energy content. This helps to attain the right quality (long burning period, non-smoking and odour free) that will make briquettes competitive in the market.

2.6.7.4 Application of a Binder

A binder is used for strengthening the briquettes. The application of binder depends on the technique of briquetting employed. In addition to biomass mixing, an appropriate binder is added and mixed with the biomass thoroughly, especially if a low pressure technique is to be employed. This enhances the compactness of the biomass materials and prevents them from disintegrating apart. According to Tabil (1997), typical examples of such binders include film binders (tar, petroleum asphalt and portland cement), matrix binders (coal, and sodium silicate) and chemical binders (pitch water, sodium silicate and lingosulfonates).

2.6.7.5 Addition of Water

Water is usually added to the feedstock to make them loose and easy to work on. Some biomass materials require to be soaked in water for a number of days to ensure that they are soft enough to work on (Musa, 2007).

2.6.7.6 Compaction and Drying

Finally, the feedstock is ready for compaction, either by machine or by hand. This will be followed by ejection from the mould after some dwell time has been observed (Oladeji, 2011 Ph.D).

2.6.8 Production of Carbonized Briquettes

2.6.8.1 Carbonisation Process

- The collected biomass is packed into a kiln.
- After loading the biomass into the kiln, the top of the kiln is closed with a metal attached to a conical chimney.
- A small amount of biomass is used in the firing portion to ignite in the kiln and the doors are shut tightly for the pyrolysis process to start.
- Without air,burning is very slow so the kiln has perforations underneath so that the fire can slowly spread to the biomass.
- After the biomass is fully carbonised,the lid is removed and water is sprinkled oer the char.
- A binding material is then added to the resultant char and it undergoes briquetting.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Materials/Equipment Used

- Moisture meter
- Bomb Calorimeter
- Infrared thermometer
- Oven
- Furnace
- Hand mould
- Hammer mill
- Electronic Weighing Balance
- Tyler Sieves
- Vernier Calliper
- Charring Unit

The analysis of samples was undertaken at the Cookstove Testing and Expertise Laboratory (C-LAB, KNUST), the Food Science Technology Laboratory, KNUST and the Food Processing Lab (F-Lab, KNUST).

3.2 Collection of Dried Coconut Husk

Dried waste coconut husks were collected from Ayigya market in Kumasi, where heap of coconut husks were thrown away.

3.3 Determination of the Moisture Content

The moisture content of the dried coconut husk was measured using Delmhorst Moisture meter (J-2000) and the values obtained indicated they would be good for converting into briquettes.

3.4 Charring of the Dried Coconut Husk

The charring experiment was carried out at the Food Processing Lab (F-Lab) of Technology Consultancy Centre (T.C.C), KNUST. The charring kiln is a cylindrical metallic drum with the top cut out to place the chimney. The drum has holes punched beneath to allow for a limited amount of oxygen. Brick stones were mounted to act as a support for the charring kiln and also to allow limited amount of oxygen to get into the kiln.

Five kilograms of the dried coconut husk was weighed with the aid of an electronic balance. The dried coconut husk was put into the drum, a match was lighted and charring began. The lid was fitted unto the kiln to stop more oxygen from entering the kiln and also to serve as a passage way for the smoke to escape.

PLATE 3.1: DRIED COCONUT HUSK READY TO UNDERGO CHARRING

PLATE 3.2: SET UP FOR CHARRING PROCESS

PLATE 3.3: THE INITIAL CHARRING PROCESS

PLATE 3.4: THICK FUMES AS CHARRING WAS ON GOING

PLATE 3.5: BURNING RATE OF THE HUSK BEING OBSERVED

PLATE 3.6 A SAMPLE OF THE CHARRED COCONUT HUSK

After 5 minutes of burning, an infrared thermometer was used to check the degree of hotness and a temperature of 132.5 ^{0}C was recorded. Charring was done in batches to ensure accurate results. From the beginning of the charring process to its end took about 45 minutes for every batch. The chimney was half opened in between time to check the burning rate of the coconut husk. The brick stones were carefully removed for the charring drum to sit on the bare floor to disallow oxygen from further entering the drum for about 10 minutes. The temperature was checked using the infrared thermometer and it was observed that the temperature was gradually decreasing. The temperature decreased to about 52 ^{0}C. The burnt coconut husk was carefully poured out of the drum into a collector and water was sprinkled on it for it to cool and then it was collected, labelled and stored.

3.5 Size Reduction of the Charred Coconut Husk

The charred coconut husk was reduced in size by crushing with the aid of a thick wood after which it was sieved with the aid of Tyler sieves. The sieved charred husk was divided into two particle sizes that is, particle size greater than 2 mm and particle size less than 2 mm.

PLATE 3.7: CRUSHING OF THE CHARRED HUSK

PLATE 3.8: SIEVING OF THE CRUSHED COCONUT HUSK

PLATE 3.9: SAMPLE OF THE GROUND CHARRED COCONUT HUSK

3.6 Size Reduction of the uncharred Dried Coconut Husk

The dried coconut husk was chopped into smaller pieces and crashed using a hammer mill. The ground coconut husk was then sieved to get rid of the chaff. The particle size of the powdered coconut husk was determined using sieves. The ground coconut husk was sieved to a uniform size of 1.2 mm, labelled and stored for briquetting.

PLATE 3.10: FRONT VIEW OF HAMMER MILL

PLATE 3.11: FEEDING OF CHOPPED COCONUT HUSK INTO HAMMER MILL

PLATE 3.12: A SAMPLE OF THE UNCHARRED, GROUND COCONUT HUSK

3.7 Preparation of a Binding Material

Cassava starch was used as a binding material for the briquetting. The reason for using cassava as a binding material is its relative availability and ease of preparation (Oyelaran et al., 2014) Cassava starch possesses the advantage of not adding smoke producing material to the briquette, it is non-volatile and it binds the briquette particles together. The cassava starch was prepared by mixing 100 g of it with 800 ml of water and was boiled until it became sticky. Three binding ratios, 5 %,10 % and 15 % by weight of sample were used to determine the effect of binder on the physical and combustion characteristics of the briquettes produced.

3.8 Briquette Production

The experimental process of briquette production was done at the Cookstove and Testing Lab(C-Lab). Fifty grams of ground and uniformly sieved sample of the dried coconut husk (both charred and uncharred samples) were thoroughly mixed with cassava starch until a uniform mixture was obtained. Water was added to the mixture for easy compaction of the briquettes.

The proportions of sample: binder ratios were 50:2.5, 50:5.0 and 50:7.5. The sample-binder mixture was then hand fed gradually into a hand mould and compacted at a pressure of 344.82 kNm^{-2} with the aid of a plunger. The plunger was then hammered to make the briquette compact after which the briquette was removed from the mould. At each level of the binder, 7 replicates were produced.

The diameter of the briquettes was taken at two different points with the aid of a digital calliper, the thickness and the weight were also recorded.

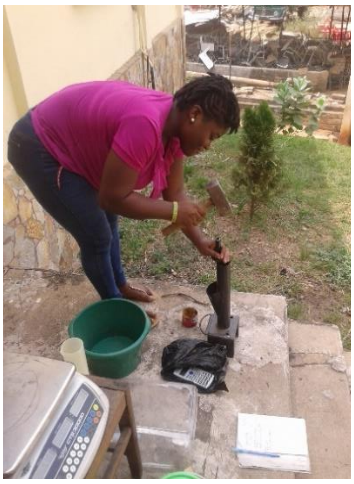

Plate 3.13: Hammering Of The Plunger To Make The Briquette Compact

Plate 3.14: Samples Of Freshly Produced Charred And Uncharred Briquettes

Plate 3.15: Weighing Of Uncharred Briquette

Plate 3.16: Drying Of The Briquettes In The Solar Drier

Plate 3.17: Determining The Length Of Uncharred Briquette Using A Digital Vernier Calliper

Plate 3.18: Pictorial View Of The Hand Mould

3.9 Determination of Physical Properties

3.9.1 Density

Three briquettes (both charred and uncharred) each were selected randomly from each production batch for evaluation of physical properties. The mean compressed density was determined immediately after removal from the mould as a ratio of measured weight to calculated volume (Olorunnisola, 2007). Relaxed density (density determined after drying) and compaction ratio (i.e. ratio of compressed density to relaxed density) of the briquette were determined after keeping the briquettes in a solar dryer within a period of four days to a constant weight at an ambient temperature. The weights of the produced briquettes were determined using an electronic weighing balance, while the average diameter, thickness and height of the briquettes were taken using the digital calliper and the volume was recorded for density determination.

Density=weight of briquette/volume of briquette

Briquette stability was measured in terms of its dimensional changes when exposed to the atmosphere (Sotannde et.al, 2010). In determining the dimensional stability, the length of three representative briquettes from each production batch (from both charred and uncharred samples) were measured at 0,30,60,1440 and 10,080 minutes' intervals.

3.9.2 Shatter Resistance Test

The durability of the briquettes was determined using the shatter index which involved dropping the briquette samples repeatedly from a specific height of 1.5 m unto a solid base.

The percentage weight loss of briquette was expressed as the percentage of the initial mass of the material remaining on the solid base whiles the shatter resistance was obtained by subtracting the percentage weight loss from 100 (Ghorpade, 2006 and Sengar et al., 2012).

Percentage weight loss= $\frac{initial\ weight\ before\ shatter - weight\ of\ briquette\ after\ shattering}{initial\ weight\ of\ briquette\ before\ shattering} x100$

Shatter resistance=100-percentage weight loss

3.9.3 Water Resistance

At each binder level for both charred and uncharred briquettes, one briquette was immersed in a clear container of tap water at 27°C for 120 sec. The percentage of water gain was calculated using the formula by Davies et al., 2013:

Percentage of water gained by briquette= $\frac{w_2 - w_1}{w_1} x100$

Water Resistance Capacity=100-% water gained

where, w_1= initial weight of briquette and w_2= final weight of briquette

3.9.4 Percentage Moisture Content

The percentage moisture content was determined by drying the briquettes in a solar dryer and taking their corresponding decrease in weight daily until constant weight was achieved.

The moisture content was calculated using the formula:

%M.C= $\frac{initial\ weight(w1) - dry\ weight(w2)}{initial\ weight(w1)} x100$ (Tembe et al., 2014)

3.10 Determination of Combustion Properties

The following combustion properties were used to determine the suitability of briquettes as cooking fuels.

3.10.1 Percentage Volatile Matter

The percentage volatile matter was first determined by keeping 2 g of fragmented briquettes (both charred and uncharred) in an oven for a period of two hours at a temperature of 110 °C to obtain a constant weight, after the fragmented briquettes were cooled, it was then kept in a crucible with an oven dry weight(w2) in a furnace for 10 mins at 550°C to obtain weight (w3) (Emerhi, 2011).

%V.M= $\frac{oven\ dry\ weight(w2) - weight\ of\ fragmented\ briquettes(w3)}{oven\ dry\ weight(w2)} x100\%$

Plate 3.19: Transferring Of Fragmented Briquettes Into The Oven

Plate 3.20: Researcher Transferring Samples Into The Furnace

Plate 3.21: Samples Of The Fragmented Briquettes After Removal From The Furnace

3.10.2 Percentage Ash Content

In determining the ash content, 2 g of oven dried fragmented briquettes was weighed in a crucible(w2). This was placed in a furnace for 3 hrs at 600 ^{o}C to obtain the ash weight (w4) (Tembe,2014).

Percentage ash content was calculated using the formula;

%Ash Content=$\frac{weight\ of\ ash(w4)}{dry\ weight(w2)}x100\%$

3.10.3 Percentage Fixed Carbon

This was calculated by subtracting the summation of %volatile matter and %ash content from 100.

Hence, %F.C=100- (%VM+%Ash Content)

3.10.4 Energy Content Determination

The energy content (calorific value and heat capacity) of both charred and uncharred briquettes was determined using the bomb calorimeter interfaced with a computer at the Cook Stove and Expertise Laboratory (C-Lab), KNUST.

One gram (1g) of the pulverised briquette (both charred and uncharred) was measured into a crucible by using a pair of tweezers and it was weighed on an analytical balance. The crucible was then placed on the crucible support of the bomb. The firing wire was connected to the two electrode rods, touching the sample in the crucible.

Ten millilitres of distilled water was poured into the oxygen bomb, the sample was placed into it and the lid was closed tightly. The oxygen bomb was filled with oxygen at pressure range of 2.5-4.0MPa for about 10 seconds after which the pressure valve was released. The bomb was then placed in a bowl of water to determine if there were some leakages. It was then transferred into the bomb calorimeter, the necessary data on the briquette (weight and type of briquette) was keyed in on the computer and the lid was closed to automatically engage the process. It took about fifteen minutes to complete the combustion after which the bomb was removed. The heat capacity and calorific values were displayed on the screen of the computer. The test was repeated three times after which the average heat capacity and calorific values were computed. By knowing the calorific value and the burning rate of the briquette (both charred and uncharred), the heat released was calculated using the formula;
Heat Released= Calorific value x Burning Rate (Faizal et al., 2009).

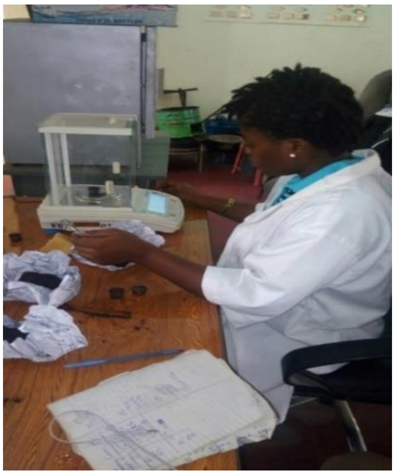

Plate 3.22: Weighing of Pulverised Briquettes Using an Analytical Balance

Plate 3.23: Winding of The Firing Wire On the Electrode Rods

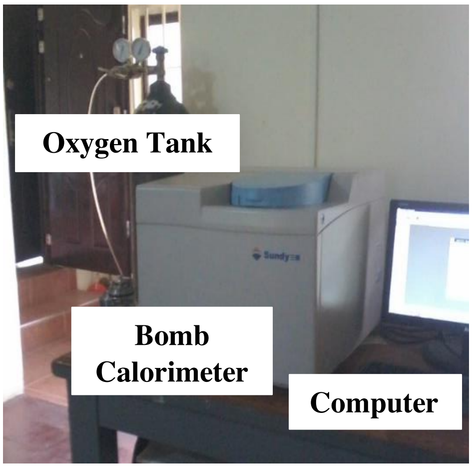

Plate 3.24: Calorimeter System at T.C.C, C-Lab

3.10.5 Water Boiling Test

The water boiling test was carried out to compare the efficiencies of the briquettes and charcoal (sweet acacia variety). The water boiling test measured the time taken for each set of briquette and the charcoal to boil an equal volume of water under similar conditions.
Briquettes (both charred and uncharred) and charcoal weighing 387.5 g were used to boil 2500 g of water using a stainless steel pot. The initial temperature of the water was measured using a thermocouple thermometer before the pot was placed on the stove. The briquette was sprinkled with a little amount of kerosene and it was then ignited. The smoke emitted was measured with the aid of an air pollution meter.

At boiling temperature, the pot was removed from the stove and weighed. The fire was quickly put out and the remaining fuel was weighed.

This procedure was followed when using charcoal to determine the water boiling test.

During this test, other fuel properties like the burning rate and specific fuel consumption were also determined (Jean and R. Owsianowksi, 2009) and the level of smoke was also observed.

Burning rate is the ratio of the mass of the fuel burnt(g) to the total time taken (mins).

The specific fuel consumption indicates the ratio of the mass of fuel consumed (g) to the quantity of boiling water (litres) (Onuegbu et al., 2011).

Burning Rate= $\frac{mass\ of\ fuel\ consumed(g)}{total\ time\ taken(\text{min})}$

Specific fuel consumption= $\frac{mass\ of\ fuel\ consumed(g)}{total\ mass\ of\ boiling\ water(l)}$

The water boiling test is an essential test required to determine the thermal efficiency of the briquettes.

The thermal efficiency of the briquettes was determined using the formula;

$\eta\ (\%)=\frac{M_w x C_p x \Delta T}{F x CV}\text{x}100\%$

Where,

η= Thermal efficiency, %
M_w= Initial mass of water taken, kg
C_p=Specific heat of water, kJ/kgK
ΔT= Rise in temperature of water
F= quantity of fuel used, kg
C.V= calorific value, kJ/kg

The following parameters were determined;

For uncharred briquette;

Weight of pan+lid=815.5g
Weight of uncharred briquette(6pcs) =387.5g
Weight of water= 2.5 litres
Atmospheric Temperature= 32.0^0C
Relative Humidity= 56%
Ignition Time = 2:35pm
Final boiling Time=3:05pm

For charred briquette

Weight of pan+lid=815.5g
Weight of charred briquette(6pcs) =241.5g
Weight of water= 2.5 litres
Atmospheric Temperature= 30.6^0C
Relative Humidity= 57%

Ignition Time = 11:05am
Final boiling time =11:40am

For charcoal

Weight of pan+lid=815.5g
Weight of charcoal = 387.5g
Weight of water= 2.5 litres
Atmospheric Temperature= 31.7^{0}C
Relative Humidity= 57%
Ignition Time = 1:00pm
Final boiling time =1:22pm

Plate 3.25 Section of The Laboratory Emission Monitoring System

Plate 3.26: Samples of Ignited Uncharred Briquettes

Plate 3.27: Samples of Ignited Charred Briquettes

Plate 3.28: Ongoing Water Boiling Test

3.10.6 Gas Emission Analysis

The study analysed emission from the combustion of the briquettes and charcoal. It was done using the indoor air pollution meter. The main gas considered in the analysis was carbon monoxide (CO) since it is one of the most harmful gases to the health of humans. This analysis was done basically to compare the quantity of carbon monoxide and particulate matter emitted by the briquettes and charcoal. When combustion of the briquettes started, the indoor air pollution metre was hanged in the laboratory to monitor the emission during the test. After combustion, the meter was turned off and time was recorded as "test ends". A secure digital (SD) card was in the indoor air pollution metre which stored the data on the meter. Terreterm is a software program that was used to connect the metre directly to the computer. The data was then processed using Microsoft Excel Software. This software analyses the logged data, converts it into physical concentrations and provide output in graphical and tabular form.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 Physical Characteristics of Charred and Uncharred Briquettes

Tables 4.1 to 4.3 show the results of physical characteristics of charred and uncharred briquettes.

Table 4.1 Physical Characteristics of Uncharred Briquette

Binder Level (%)	**Colour**	**Mean Compressed Weight (g)**	**Average Height (mm)**	**Average Diameter (mm)**
5	Brown	103.07	49.34	51.64
10		104.43	51.11	51.68
15		107	52.06	51.51

The mean compressed weights of uncharred briquette ranged from 103.07 g to 107 g at 5 %, 10 % and 15 % binder levels. The average heights at 5 %, 10 % and 15 % binder levels ranged from 49.34 mm to 52.06 mm and the average diameters at 5 %, 10 % and 15 % binder levels ranged from 51.51 mm to 51.68 mm. Based on the values obtained it can be deduced that the mean compresses weight and average height values increased with increase in binder level.

Table 4.2 Physical Characteristics of Charred Briquette (P<2 mm)

Binder Level (%)	**Colour**	**Mean Compressed Weight (g)**	**Average Height (mm)**	**Average Diameter (mm)**
5	Black	83.64	36.63	50.35
10		86.64	37.03	50.29
15		88.43	37.96	50.09

The mean compressed weights of the charred briquette (P<2 mm) ranged from 83.64 g to 88.43 g at 5 %, 10 % and 15 % binder levels. The average heights at 5 %, 10 % and 15 % binder levels ranged from 36.63 mm to 37.96 mm and the average diameters with 5 %, 10 % and 15 % binder levels ranged from 50.09 mm to 50.35 mm. Generally, the mean compressed weight and average height values increased with increase in binder level but the average diameter values decreased with increase in binder level.

Table 4.3 Physical Characteristics of Charred Briquette (P>2 mm)

Binder Level (%)	**Colour**	**Mean Compressed Weight (g)**	**Average Height (mm)**	**Average Diameter (mm)**
5	Black	81.25	47.50	50.89
10		82.13	46.50	50.49
15		85.63	46.75	51.22

The mean compressed weights of the charred briquette (P>2 mm) ranged from 81.25 g to 85.63 g at 5 %, 10 % and 15 % binder levels. The average heights with 5 %, 10 % and 15 % binder levels ranged from 46.50 mm to 47.50 mm and the average diameters with 5 %, 10 % and 15 % binder levels ranged from 50.49 mm to 51.22 mm. The mean compressed weight values increased with increase in binder level.

4.2 Effects of Binder Level on Density of Briquettes

Table 4.4 Results of Densities of Uncharred Briquette

Binder Level (%)	Mean Compressed Density (kgm^{-3})	Mean Relaxed Density(kgm^{-3})	Compaction Ratio
5	999.06	656.05	1.52
10	968.14	629.55	1.54
15	987.42	681.07	1.44

The mean compressed density of uncharred briquette ranged from 968.14 kgm^{-3} to 999.06 kgm^{-3} with 5 %, 10 % and 15 % binder levels. Also the mean relaxed density of the uncharred briquette ranged from 629.55 kgm^{-3} to 681.07 kgm^{-3} which gave a compaction ratio ranging from 1.44 to 1.54.

Table 4.5 Results of Densities of Charred Briquette (P<2mm)

Binder Level (%)	Mean Compressed Density (kgm^{-3})	Mean Relaxed Density(kgm^{-3})	Compaction Ratio
5	1149.40	657.88	1.75
10	1153.07	696.84	1.65
15	1210.83	764.74	1.58

The mean compressed density of the charred briquette (P<2 mm) ranged from 1149.40 kgm^{-3} to 1210.83 kgm^{-3} with 5 %, 10 % and 15 % binder levels. The mean relaxed density of the charred briquette with (P<2 mm) ranged from 657.88 kgm^{-3} to 764.74 kgm^{-3} which gave a compaction ratio ranging from 1.58 to 1.75. The mean compressed and relaxed densities increased with increase in binder level.

Table 4.6 Comparative Results of Densities of Charred Briquette (P>2 mm)

Binder Level (%)	Mean Compressed Density (kgm^{-3})	Mean Relaxed Density(kgm^{-3})	Compaction Ratio
5	842.40	557.56	1.51
10	884.90	583.05	1.52
15	901.20	620.64	1.45

The mean compressed density of charred briquette (P>2 mm) ranged from 842.40 kgm^{-3} to 901.20 kgm^{-3} which gave a compaction ratio ranging from 1.58 to 1.75. The mean compressed and relaxed densities increased with increase in binder level.

Density is a very important parameter in that, the higher the density, the higher the volume ratio. Hence high density products are desirable in terms of transportation, storage and handling and also cost effective (Davies and Davies, 2013). It was observed from Tables 4.4 to 4.6 that the charred briquette (P< 2 mm) recorded the highest compaction ratio of 1.75 (5 % binder level). The least was recorded at 15 % binder level in all samples. The compaction ratio values as recorded by Sotannde et al., (2014) for briquettes produced from charcoal and Arabic gum were 1.11 and 1.32. These values are lower than the values obtained for the briquettes in this study. Higher compaction ratio indicates more void in the compressed materials and it is an indication of good and quality briquettes (Davies and Mohammed, 2013).

4.3 Equilibrium Moisture Content

Moisture Content

Table 4.7: Moisture Content (wet basis) of uncharred briquette at varying binder levels

Moisture Content (w.b) (%)			
	Binder Levels		
TIME(Minutes)	**5 %**	**10 %**	**15 %**
	Initial Weight (g)= 103.15	**Initial Weight (g)= 104.73**	**Initial Weight (g)= 107.19**
0	103.15	104.73	107.19
60	93.33	94.83	101.00
	Moisture Content at 60mins= 9.52 %	**Moisture Content at 60mins**=9.45 %	**Moisture Content at 60mins**=5.77 %
1440	72.46	74.37	75.28
	Moisture Content at 1440mins= 22.36 %	**Moisture Content at 1440mins=** 21.58 %	**Moisture Content at 1440mins=** 25.47 %
2880	65.03	68.80	71.31
	Moisture Content at 2880mins= 10.25 %	**Moisture Content at 2880mins=** 7.49 %	**Moisture Content at 2880mins=** 5.27 %
4320	50.98	52.04	53.04
	Moisture Content at 4320mins= 21.61 %	**Moisture Content at 4320mins=** 24.36 %	**Moisture Content at 4320mins=** 25.62 %
5760	48.17	49.08	49.98
	Moisture Content at 5760mins= 5.51 %	**Moisture Content at 5760mins=** 5.69 %	**Moisture Content at 5760mins=** 5.77 %
	Average Moisture Content= 13.85 %	**Average Moisture Content= 13.71 %**	**Average Moisture Content= 13.58 %**

Table 4.8: Moisture Content (wet basis) of charred briquette (P<2mm) at varying binder levels

Moisture Content (%)			
	Binder Levels		
TIME(Minutes)	**5 %**	**10 %**	**15 %**
	Initial Weight (g) = 83.75	**Initial Weight (g)= 85.67**	**Initial Weight (g)= 88.41**
0	83.75	85.67	88.41
60	78.50	80.00	83.67
	Moisture Content at 60mins= 6.27 %	**Moisture Content at 60 mins=** 6.62 %	**Moisture Content at 60 mins=** 5.36 %
1440	62.16	66.97	67.12
	Moisture Content at 1440 mins= 20.82 %	**Moisture Content at 1440 mins=** 16.29 %	**Moisture Content at 1440 mins=** 19.78 %
2880	43.13	46.38	47.29
	Moisture Content at 2880 mins= 30.61 %	**Moisture Content at 2880 mins=** 30.75 %	**Moisture Content at 2880 mins=** 29.54 %
4320	39.37	40.94	41.81
	Moisture Content at 4320mins= 8.72 %	**Moisture Content at 4320mins=** 11.73 %	**Moisture Content at 4320mins=** 11.59 %
5760	38.50	38.36	39.04
	Moisture Content at 5760mins= 2.21 %	**Moisture Content at 5760mins=** 6.30 %	**Moisture Content at 5760mins=** 6.63 %
	Average Moisture Content=13.73 %	**Average Moisture Content=14.34 %**	**Average Moisture Content=14.58 %**

Table 4.9: Moisture Content (wet basis) of charred briquette (P>2mm) at varying binder levels

Moisture Content (%)			
	Binder Levels		
TIME (Minutes)	**5%**	**10 %**	**15%**
	Initial Weight (g)=81.25	**Initial Weight (g)=82.13**	**Initial Weight (g)=85.63**
0	81.25	82.13	85.63
60	75.13	77.25	81.88
	Moisture Content at 60mins= 7.53%	**Moisture Content at 60mins=** 5.94%	**Moisture Content at 60mins=** 4.38%
1440	56.50	56.25	59.63
	Moisture Content at 1440mins= 24.80%	**Moisture Content at 1440mins=** 27.18%	**Moisture Content at 1440mins=** 27.17%

2880	47.53	49.37	51.95
	Moisture Content at 2880mins= 15.88%	**Moisture Content at 2880mins=** 12.23%	**Moisture Content at 2880mins=** 12.88%
4320	40.01	42.34	43.85
	Moisture Content at 4320mins= 15.82%	**Moisture Content at 4320mins=** 14.24%	**Moisture Content at 4320mins=** 15.59%
5760	39.37	40.07	40.21
	Moisture Content at 5760mins= 1.60%	**Moisture Content at 5760mins=** 5.36%	**Moisture Content at 5760mins=** 8.30%
	Average Moisture Content=13.13%	**Average Moisture Content=12.98%**	**Average Moisture Content=13.67%**

As shown in Table 4.7, the equilibrium moisture content of the uncharred briquettes ranged from 13.58 % to 13. 85 % (w.b) for 5 % to 15 % binder levels. For the charred briquettes (P<2 mm), the values ranged from 13.73 % to 14.58 % (w.b). Also for the charred briquette (P>2 mm), the values ranged from 12.98 % to 13.67 % (w.b). Observations made by Jack Huang, (2014) indicated that when the moisture content is lower than 10 % or higher than 18 %, the briquettes are not consistent and they tend to fall into pieces.

Raju et al. (2014) recorded moisture content that ranged from 15.32 % to 16.82 % w.b for paper rice husk and coconut coir briquettes and these values tend to be higher than the values obtained in this research. High percentage of moisture in biomass materials prevents their applications for thermo-chemical conversion processes including combustion (Raju et al., 2014). Moisture content in excess of 20 % would result in considerable loss of energy required for water evaporation during combustion at the expense of the calorific value and such a fuel may not be stable in storage (Aina et al., 2009). Hence the lower the moisture content of briquettes, the higher the calorific value.

4.4 Shatter Resistance of Briquettes

The measurement of the shatter resistance of briquettes is essential in terms of its handling, transportation, storage and weather conditions.

4.4.1 Effects of Binder Level on Weight Loss and Shatter Resistance

Table 4.10 Weight Loss and Shatter Resistances of the uncharred briquette

Binder Level (%)	Initial Weight(g)	Final Weight(g)	Percentage Weight Loss	Shatter Resistance (%)

5	47.485	42.225	11.08	88.92
10	47.460	46.650	1.71	98.29
15	47.205	40.985	13.18	86.82

Table 4.11 Weight Loss and Shatter Resistances of charred briquette (P<2 mm)

Binder Level (%)	Initial Weight(g)	Final Weight(g)	Percentage Weight Loss	Shatter Resistance (%)
5	38.475	24.82	35.49	64.51
10	38.040	31.12	18.19	81.81
15	39.320	28.59	27.28	77.72

Table 4.12 Weight Loss and Shatter Resistances of charred briquette (P>2 mm)

Binder Level (%)	Initial Weight(g)	Final Weight(g)	Percentage Weight Loss	Shatter Resistance (%)
5	40.96	27.90	31.88	68.12
10	41.24	39.38	4.51	95.49
15	41.09	40.18	2.21	97.79

The weight loss of the charred briquette (P>2 mm and P<2 mm) and the uncharred briquette due to variations in binder level was highly significant. In Table 4.10, the uncharred briquette at 15 % binder level recorded the highest weight loss of 13.18. Higher shatter resistance indicates that briquettes had high shock and impact resistance.

In Table 4.11, the charred briquette (P<2 mm), had a shatter resistance which ranged from 64.51 % to 81.81 % and the 5 % binder level recorded the highest weight loss which in turn produced the least shatter resistance.

In Table 4.12, the shatter resistance of the charred briquette (P>2 mm) ranged from 68.12 % to 97.79 %. The 5 % binder level recorded the highest weight loss which also accounted for the least shatter resistance of 68.12 %.

In the charred briquette (P<2 mm and P>2 mm), the least shatter resistance was recorded at 5 % binder level. Unlike the uncharred briquette, the least shatter resistance was recorded at 15 % binder level.

As observed by Husain et al. (2002), the durability of briquettes is a major function of the moisture content and density. Also, the higher the moisture content, the lesser the durability of briquettes but density tends to enhance it.

4.5 Briquette Stability (Length Expansion)

Stability serves as an index of the extent of resistance of briquettes to changes in their initial physical dimensions and shape (Mitchual, 2014). Briquettes compressed in an enclosed cylinder have the tendency to expand as the pressure is released. Normally the expansion takes place in the direction in which the load is applied. The briquette stability was measured in terms of its dimensional changes when exposed to the atmosphere.

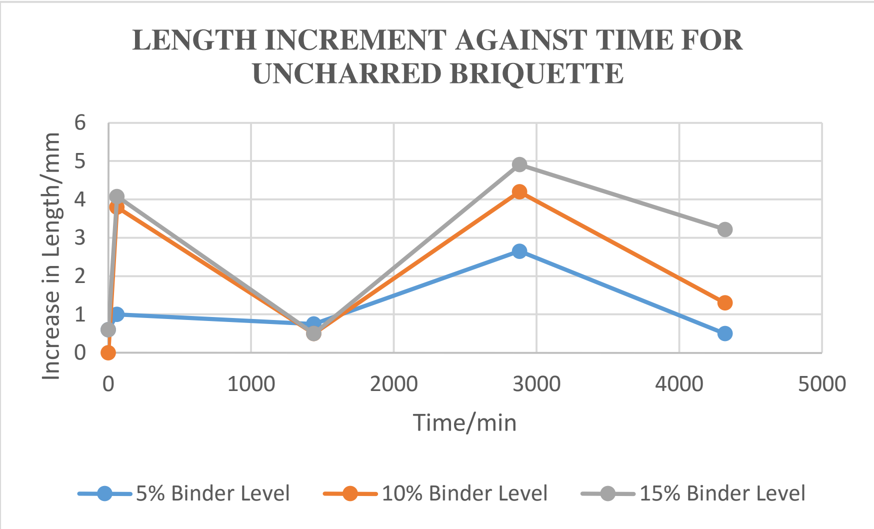

Figure 4.1: Height stability of uncharred briquette

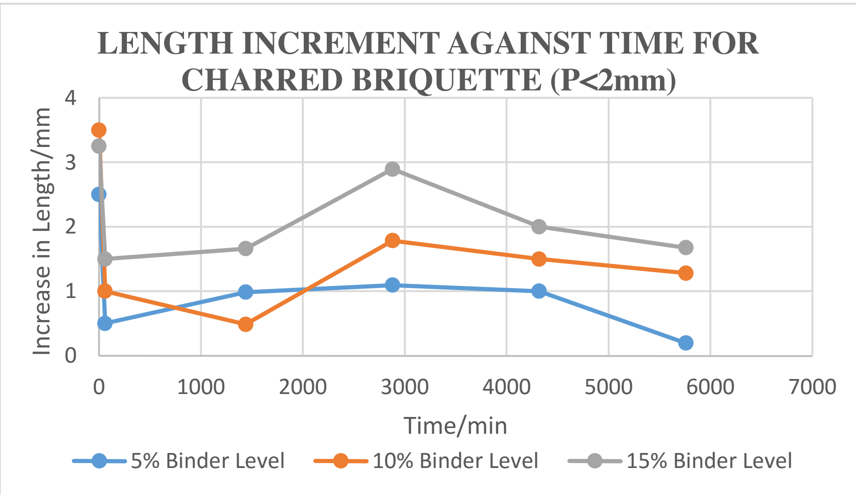

Figure 4.2: Height stability of Charred Briquette (P <2 mm)

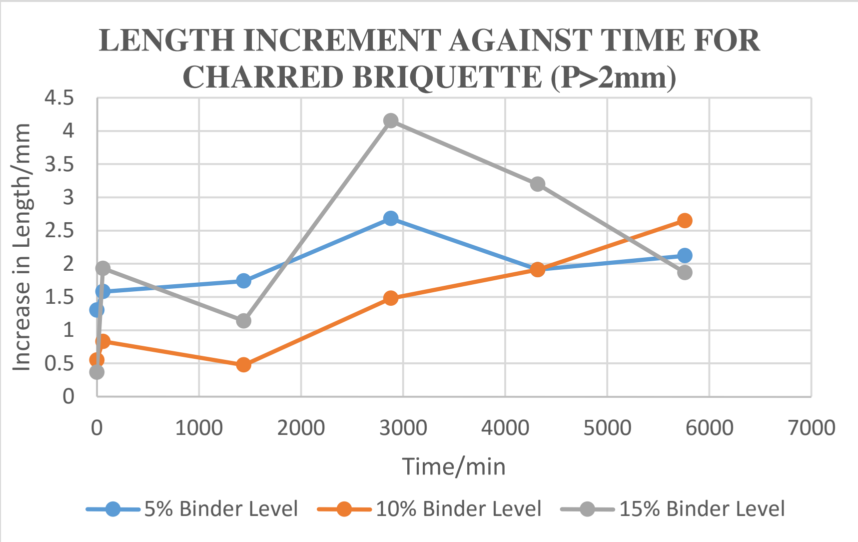

Figure 4.3: Height stability of Charred Briquette (P >2 mm)

The results from the stability test is evident of the trend observed in compressed and relaxed densities of the briquettes. The observed linear expansions were generally minimal. From figure 4.1, the uncharred briquette at various binder levels were all unstable with regards to height differences. The uncharred briquette at 5 % binder level recorded a least final difference in height (0.53mm) with the uncharred briquette at 15 % binder level recording the highest final difference in height of 3.22 mm.

The charred briquette with (P<2 mm) was also very unstable with respect to the changes in height. The 15 % binder level recorded the least final difference in height of 1.93 mm and it was also the most unstable of all the binder levels. The highest final difference in height recorded was 2.65 mm at 10 % binder level and it was more stable of all the binder levels.

Five percent binder level of the charred briquette (P>2 mm) was the most stable of all the binder levels but it recorded the least final difference in height (0.195 mm).

Also, 15 % binder level of the charred briquette (P>2 mm) recorded the highest final height difference of 1.675 mm.

From observations, the final difference in height of the uncharred briquette increases as the binder level increases but that cannot be said of the charred briquette (P<2 mm) which has the 10 % of the binder level being the highest and the charred briquette (P>2 mm) having the 15 % of the binder level being the highest. This confirms that stability of the briquette is a function of the binder levels (Suparin et al., 2008).

It was observed by Bruhn et al. (1959) that the type of material briquetted is an essential factor that have appreciable effects on product expansion. It is desirable that briquettes maintain their initial state, hence the less the change, the more stable the product (Al-Widyan et al., 2002).

4.6 Water Resistance

Figure 4.4 shows a graph of water resistance of briquettes at 5 %, 10 % and 15 % binder levels.

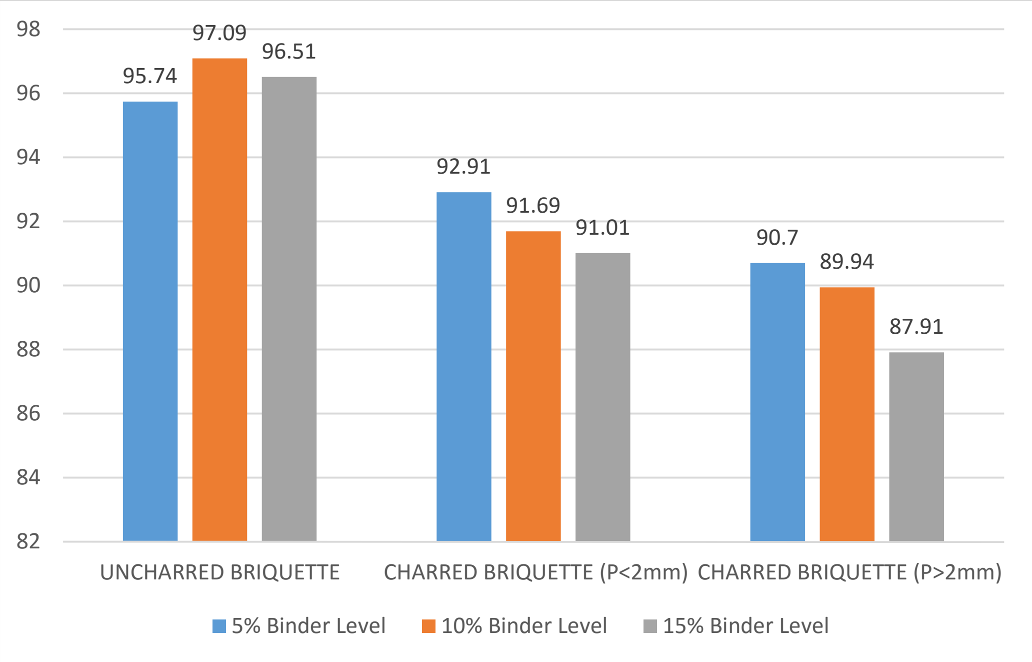

Figure 4.4: Water Resistance of Briquettes at different binder levels

The highest water resistance capacity was recorded at 10 % binder level with a value of 97.09 % and at 5 % binder level the least water resistance was recorded with a value of 95.74%.
The charred briquette (P<2 mm) recorded the highest water resistance of 92.91% at 5% binder level and recorded the least water resistance of 91.01 % at 15 % binder level.
Also, the charred briquette (P>2 mm) recorded the least water resistance of 87.91 % at 15 % binder level and the highest water resistance of 90.70 % at 5 % binder level.
It was observed that at 5% binder level for charred briquette both (P<2 mm and P>2 mm) produced the highest water resistance capacity which is an indication that the less the binder level, the higher the water resistance capacity.
Birwatkar et al. (2014) observed water resistance values of briquettes produced from mango leaves, Subabul leaves and saw dust ranging from 91.93 % to 94.16 % and the values obtained from this study are much higher with the highest value being 97.09 %.
The results obtained from the water resistance property of the briquettes produced from water hyacinth ranged from 52 % to 97.1 % as obtained by Davies et al. (2013).

The values obtained in this study is an indication that short-term exposure to rain or high humidity conditions during transportation and storage could not adversely affect the quality of the briquette.

4.7 Combustion Properties of Uncharred and Charred Briquettes

4.7.1 Effects of Binder levels on Combustion Properties of Briquettes

Ash Content

Figure 4.5 shows a graph of ash content of briquettes at 5 %, 10 % and 15 % binder levels.

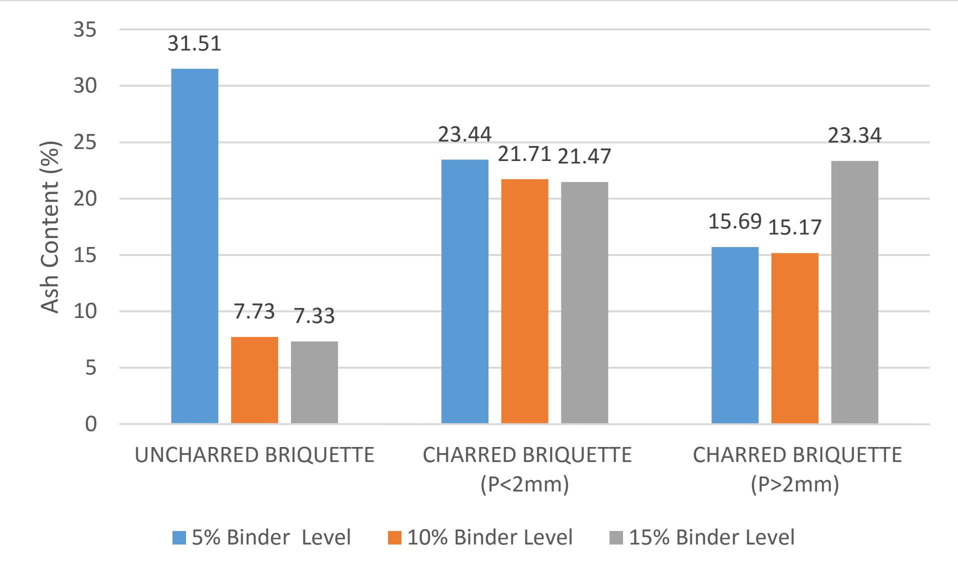

Figure 4.5: Ash Content of Briquettes at 5 %, 10 % and 15 % binder levels

The binder levels had an effect on the ash content of the briquettes. Fifteen percent binder level of the uncharred briquette recorded the least ash content of 7.33 % whiles the 5 % binder level of the uncharred briquette recorded the highest ash content of 31.51 %.

Low ash content offers high heating values for briquettes (Obi et al., 2013). 15 % of the binder level of charred briquette (P<2 mm) recorded the least ash content of 21.57 % and the highest was recorded at 5 % binder level (23.44 %).

Also the least ash content was recorded at 10 % binder level of charred briquette (P>2 mm) and the highest ash content was recorded at 15 % binder level.

Nicholas Akhaze Musa (2012) recorded ash content values of briquettes produced from rice husk, groundnut shell and saw dust ranging from 2.1 % to 18.21 %.

High ash content is said to reduce ignitibility of briquettes (Bhattacharya et al., 1990).

Volatile Matter

Figure 4.6 shows a graph of volatile matter of briquettes at 5 %, 10 % and 15 % binder levels.

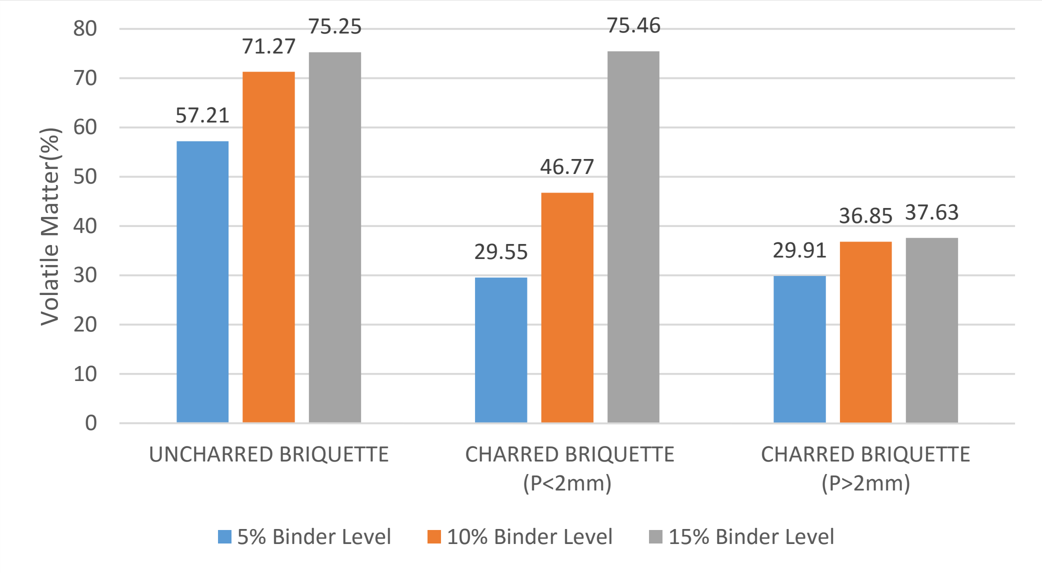

Figure 4.6: Volatile Matter of Briquettes at 5%, 10% and 15% binder levels

The highest volatile matter recorded was 75.25 %, at 15 % binder level and the least recorded was 57.21 % at 5 % binder level for uncharred briquettes. Also for charred briquettes (P<2 mm), the highest volatile matter was recorded at 15% binder level (75.46 %) and the least was recorded at 5 % binder level (29.55 %). The charred briquette(P>2 mm) recorded the least volatile matter of 29.91 % at 5 % binder level (29.91 %) and the highest volatile matter recorded was 37.63 % at 15 % binder level.

Observations made indicated that the higher the binder level, the higher the volatile matter for all the briquettes. The lower the volatile matter, the more the briquette is suitable for combustion. Birwatkar et al. (2014) recorded volatile matter values of briquettes produced from mango leaves, Subabul leaves and saw dust and the values obtained ranged from 68.7 % to 70.77 %.

Fixed Carbon

Figure 4.7 shows a graph of fixed carbon values of briquettes at 5 %, 10 % and 15 % binder levels.

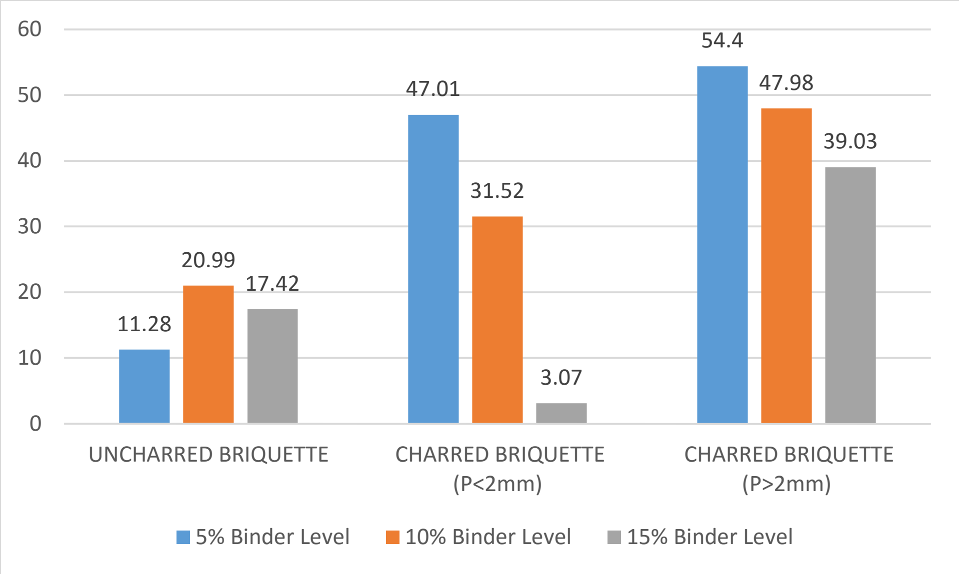

Figure 4.7: Fixed Carbon of Briquettes at different binder levels

The fixed carbon of a fuel is the percentage of carbon available for combustion (Efomah and Gbabo, 2015). The fixed carbon was also affected by the binder levels. At 10 % binder level, the uncharred briquette recorded the highest fixed carbon value of 20.99 % with the least being 11.28 % at 5 % binder level. Also, at 15 % binder level, the charred briquette (P<2 mm) recorded the least fixed carbon of 3.07 % and the highest recorded was 47.01 % at 5 % binder level. Furthermore, at 5 % binder level of charred briquette (P>2 mm),54.40 % fixed carbon was the highest recorded with the least recorded being 39.03 % at 15 % binder level. Thus, the fixed carbon decreased as the binder level increased for the charred briquette and so the less the binder level, the better, in this case 5 % binder level is the best.

The low fixed carbon content tends to prolong cooking time by its low heat release (Raju et al., 2014). Also the higher the fixed carbon content the better the charcoal produced because the corresponding calorific energy is usually high (FAO, 1995).

Ikelle et al. (2014) recorded fixed carbon values of briquette produced from coal dust and rice husk ranging from 27 % to 61.76 %.

Raju et al. (2014) recorded fixed carbon content values of briquettes produced from paper, rice husk and coconut coir and had values that ranged from 17.9 % to 18.6 %. The high fixed carbon values of briquettes in this study shows that the time used in cooking will reduce by its high release of heat.

Calorific Value

Figure 4.8 shows a graph of volatile of briquettes at 5 %, 10 % and 15 % binder levels.

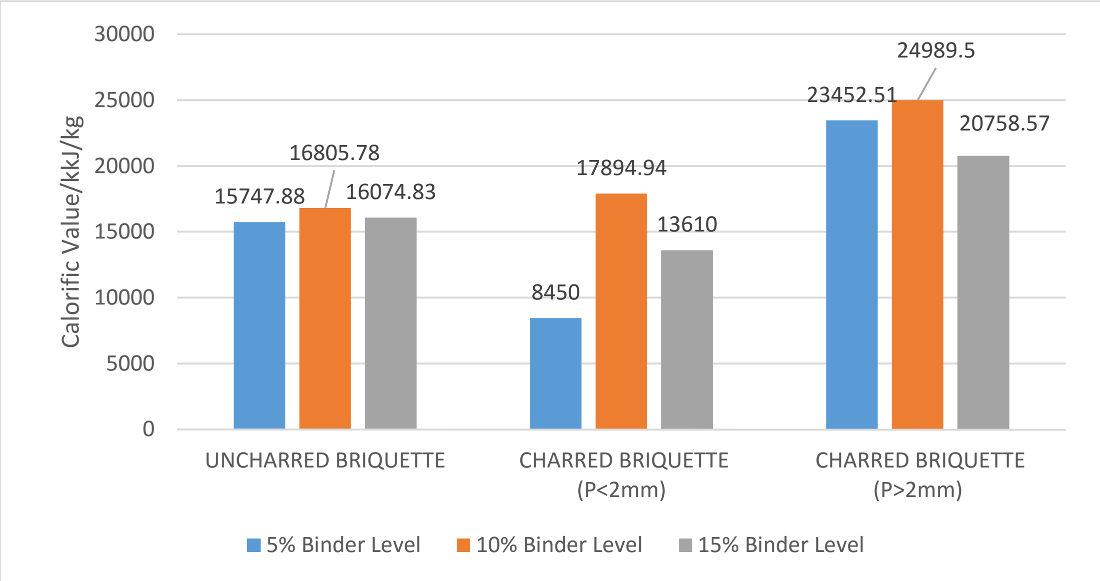

Figure 4.8: Calorific Values of Briquettes at different binder levels

The calorific value is the standard measure of the energy content of the fuel (Ikelle et al., 2014). Calorific values which also have a great significance on the level of binder recorded the highest value of 16805.78 kJ/kg at 10 % binder level for the uncharred briquette. The least was recorded at 5 % binder level at a calorific value of 15747.88 kJ/kg. The highest calorific value recorded was 17894.94 kJ/kg at 10% binder level and the least calorific value was 8450 kJ/kg at 5% binder level for the charred briquette (P<2 mm).

For charred briquettes (P>2 mm), the highest calorific value was recorded at 10 % binder level and the least calorific value, was recorded at 15 % binder level. Generally, the highest calorific value was recorded at 10 % binder level for all briquettes.

Ikelle et al. (2014) obtained calorific values of briquettes produced from coal and rice husk and these values ranged from 90.23 kJ/kg to 164.34 kJ/kg and these values are lower than the calorific values obtained in this study.

High calorific values in this study show that the energy content is high enough to produce heat required for household cooking and small scale industrial applications (Raju et al., 2014).

Heat Capacity

Figure 4.9 shows a graph of the heat capacity of briquettes at 5 %, 10 % and 15 % binder levels.

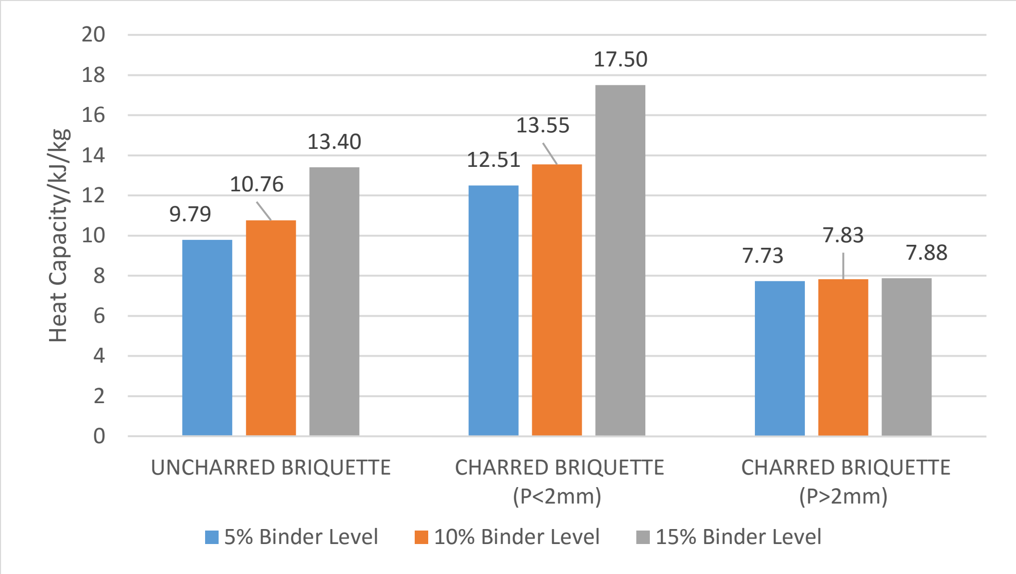

Figure 4.9: Heat Capacity of Briquettes at different binder levels

The heat capacity is also an important parameter which forms part of the energy content. The heat capacity at 15 % binder level recorded the highest value of 13.40 kJ/K and the least recorded was 9.79 kJ/K at 5 % binder level for the uncharred briquette.

The charred briquette (P<2mm) at 15% binder level recorded the highest heat capacity value of 17.50 kJ/K and the least recorded was 12.51 kJ/K at 5% binder level.

With the charred briquette (P>2 mm), the highest value recorded was 7.88 kJ/K at 15 % binder level and the least value recorded was 7.73 kJ/K at 5 % binder level.

The values obtained indicated that the heat capacity increased with increase in binder level.

4.7.2 Effects of Starch on the Calorific Value and the Heat Capacity

The binding material (starch) had a great influence on the calorific value of the raw biomass. The raw uncharred coconut husk recorded a calorific value of 16898 kJ/kg which made it higher than the calorific value of the uncharred briquette. The raw uncharred coconut husk recorded a heat capacity of 9.78 kJ/K. Also, the raw charred coconut husk recorded a calorific value of 21307kJ/kg which made it higher than the calorific value of the charred briquette (P<2 mm). The raw charred coconut husk (P<2 mm) recorded a heat capacity of 7.61 kJ/K.

The charred coconut husk (P>2 mm) recorded a calorific value of 17471 kJ/kg which was lower than the charred briquette (P>2 mm). The raw charred coconut husk(P>2 mm) recorded a heat capacity of 10.56 kJ/K.

Table 4.13: Results of calorific value and heat capacity analysis of raw uncharred coconut husk and raw charred coconut husk (P<2 mm, P>2 mm)

Samples	Calorific Value (kJ/kg)	Heat Capacity (kJ/K)
Raw Uncharred Coconut Husk	16,898	9.781
Raw Charred Coconut Husk, P<2 mm	21,307	7.61
Raw Charred Coconut Husk, P>2 mm	17,471	10.56

From Table 4.13, the calorific values of the raw coconut husk samples are higher than the briquette samples and this means that the starch present in the briquettes could be a factor for the reduction in the calorific values of briquettes.

4.7.3 Water Boiling Test Results

4.7.3.1 Comparison of the Briquettes with Charcoal

The water boiling tests were carried out to check the suitability of the briquettes in domestic use as fuel (Birwatkar, 2014). It was observed that briquettes burnt completely with uniform flame. The burning rate (how fast the fuel burns) and the calorific value (how much heat is released) are two combined factors that control the water boiling time (Onuegbu et al., 2011). The recorded duration for the water boiling tests were 30 mins for uncharred briquettes,35 mins for charred briquettes and 22 minutes for charcoal. It can further be deduced that amongst all, charcoal had the shortest water boiling time. Also the value of burning rate for uncharred briquette was 1.63 g/min, charred briquette, 1.66 g/min and charcoal recorded a burning rate value of 11.11g/min which was the highest among the briquettes.

Onuegbu et al. (2011) reported factors that could be responsible for burning rate of briquettes such as chemical composition, volatile matter content and geometry of the briquettes. With this study, volatile matter content and geometry influenced the burning rates of briquettes.

The specific fuel consumption of the three fuel sources were 19.6g/l (uncharred briquette), 23.2g/l (charred briquettes) and 97.8g/l (charcoal).

The lower the specific fuel consumption, the more economical the fuel source (Onuegbu et al. 2011).

Thermal Efficiency

Figure 4.10 shows the thermal efficiency values of briquettes and charcoal

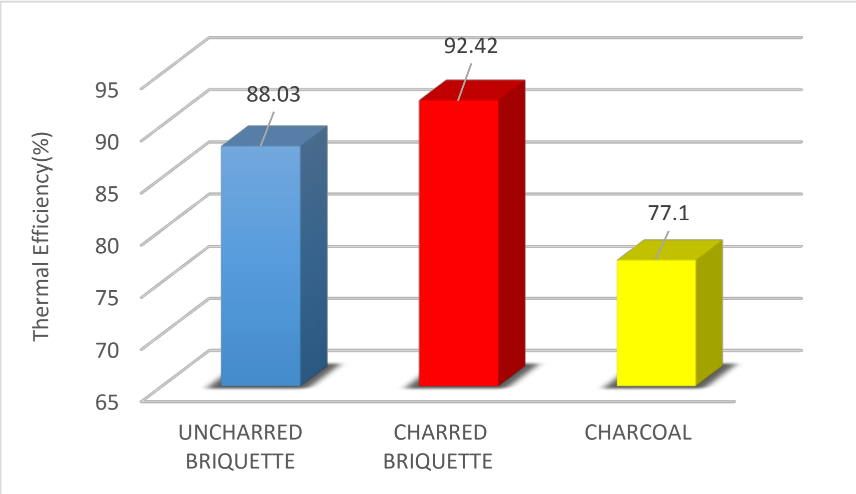

Figure 4.10: Thermal Efficiencies of Briquettes and Charcoal

The thermal efficiencies of the studied fuel sources were uncharred briquettes-88.03 %, charred briquettes-92.42 % and charcoal-77.10 %, making the charred briquette the highest followed by the uncharred briquette.

Murali et al. (2015) reported thermal fuel efficiency of briquettes produced from coconut pith (63.63 %), sawdust (61.62 %) and sugarcane (53.85 %). These values are lower than the obtained values in this study.

4.7.4 Emission Analysis of Charcoal, Charred and Uncharred Briquettes

The charcoal produced from sweet acacia recorded an average value of 1,765 $\mu g/m^3$ for particulate matter (PM) concentration and 561.1 ppm for carbon monoxide concentration. The charred briquette recorded an average value of 9,863 $\mu g/m^3$ of particulate matter concentration and 340.6 ppm for carbon monoxide concentration. The uncharred briquette recorded an average value of 14,328 $\mu g/m^3$ for particulate matter concentration and 519.7 ppm for carbon monoxide concentration.

The uncharred briquette recorded the highest average particulate matter of 14,328 $\mu g/m^3$ followed by the charred briquette (9,863 $\mu g/m^3$) with the least being charcoal (1,765 $\mu g/m^3$).

The values obtained show that charcoal (sweet acacia variety) recorded the highest carbon monoxide value with the least being the charred briquette. This means charcoal (sweet acacia) emits more carbon monoxide than the briquettes.

The high particulate matter of the briquettes could be attributed to the type of raw material and its physical and chemical compositions. Also, as seen from the results it can be concluded that carbonisation reduce particulate matter concentration and this accounted for low particulate matter emissions in charcoal.

High particulate matter concentrations are very harmful to human health affecting both the lungs and heart and as such the particulate matter of the briquettes should be controlled.

Figures 4.11 to 4.13 show the results of particulate matter and carbon monoxide of briquettes and charcoal.

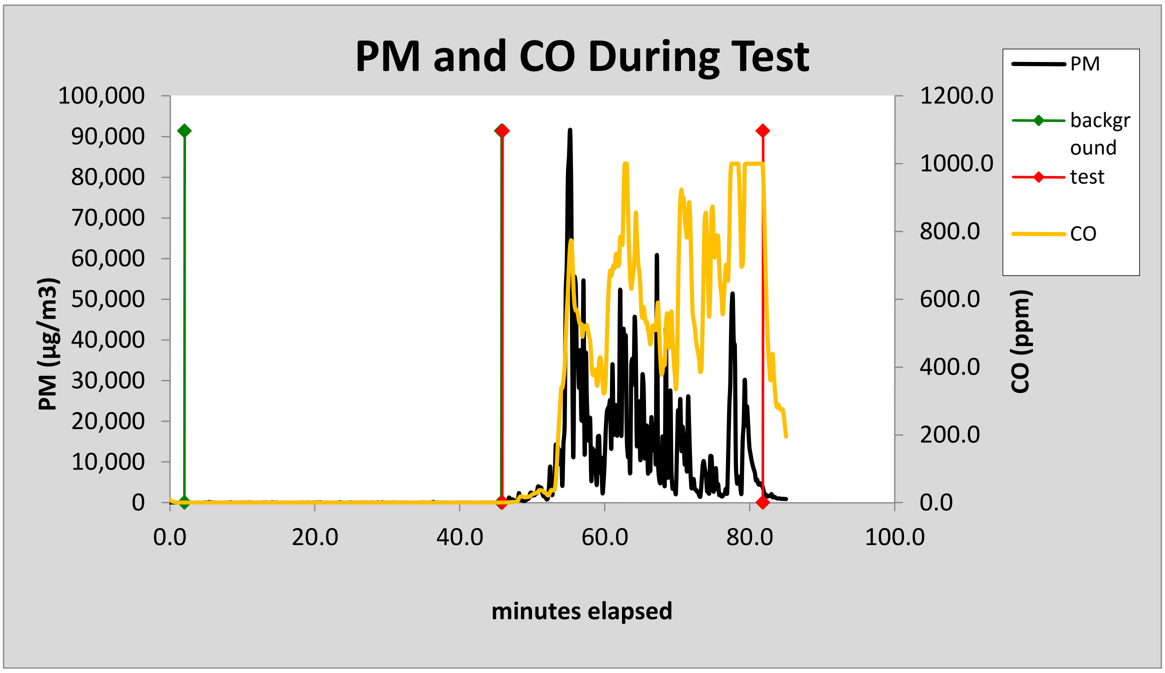

Figure 4.11: Graphical Representation of the Particulate Matter (PM) and Carbon Monoxide (CO) of Uncharred Briquette during Indoor Air Pollution Test.

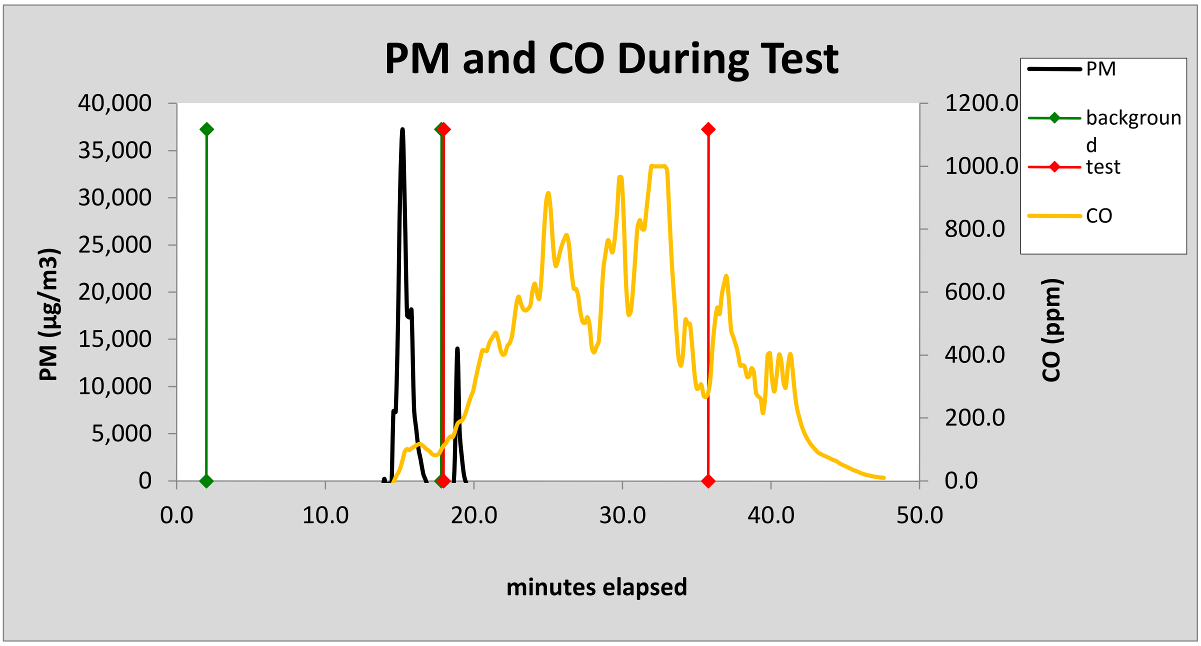

Figure 4.12: Graphical Representation of Particulate Matter (PM) and Carbon Monoxide (CO) of charred briquette during Indoor Air Pollution Test

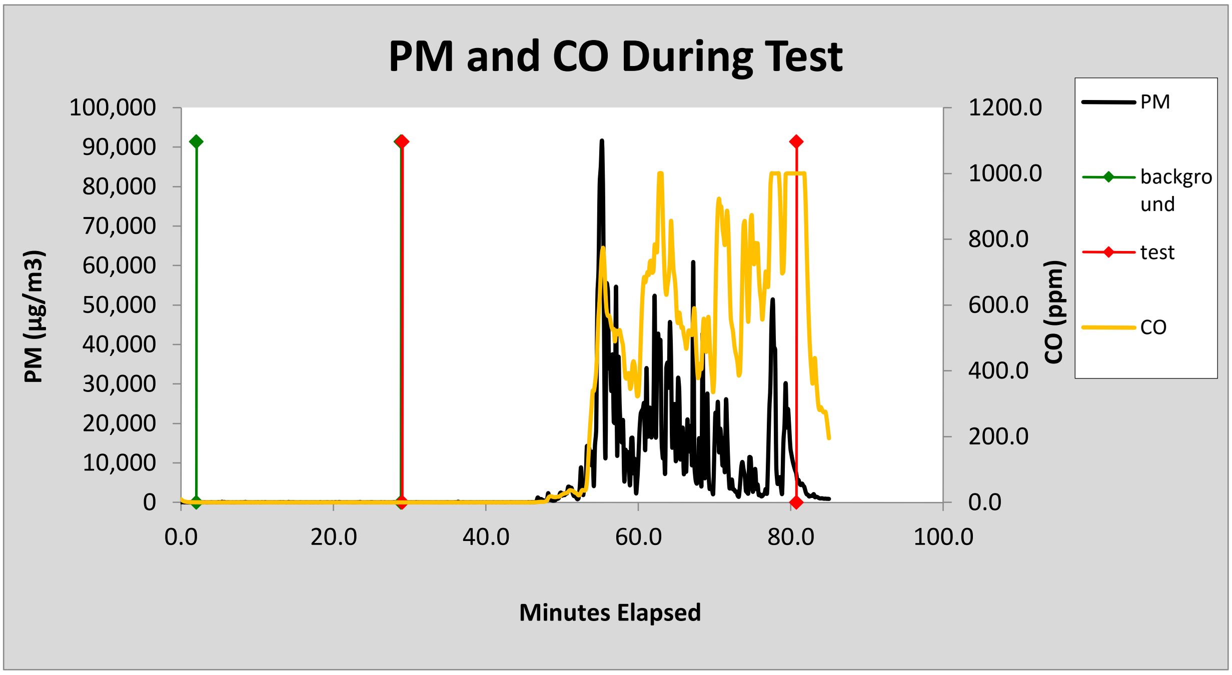

Figure 4.13: Graphical Representation of Particulate Matter (PM) and Carbon Monoxide (CO) of charcoal during Indoor Air Pollution Test

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Briquettes have gained worldwide recognition as an alternative source of energy compared to charcoal due to the fact that it is environmentally friendly, reduces deforestation and its associated negative impacts.

The conclusions drawn from this study are as follow;

1. The highest calorific value recorded for charred briquettes with particle size greater than 2mm, particle size less than 2mm and uncharred briquette were 24989.50 kJ/kg, 17894.94 kJ/kg and 16805.78 kJ/kg all at 10% binder level respectively.
2. Charred briquette had the highest thermal efficiency (92 %), followed by uncharred briquette (88 %) with charcoal having the lowest thermal efficiency (77 %). Increase in thermal efficiency will generally reduce fuel requirement during cooking.
3. The charred briquette recorded the lowest carbon monoxide concentration (340 ppm), followed by the uncharred briquette with a carbon monoxide concentration of 519 ppm with charcoal recording the highest carbon monoxide emission (561ppm). This indicates that charcoal poses more health problems. Also, the uncharred briquette recorded the highest particulate matter– 14,328 $\mu g/m^3$, followed by the charred briquette- 9,863 $\mu g/m^3$ with the least being charcoal- 1,765 $\mu g/m^3$.

5.2 Recommendations

The following recommendations are being made for the furtherance of this study:

1. Research and development on dried coconut husk briquettes should include cost-effective emission reduction strategies such as more efficient and improved cook stoves.
2. Due to the high potentials of raw biomass, there is a need for a further research on other biomass for the production of quality briquettes to help contribute to quality health and environmental management.
3. To help reduce particulate matter concentrations, the briquettes should be well carbonised before usage and for industrial applications, a centrifugal collector or a fabric filter should be used.

4. In order to ensure a uniform and complete combustion and also reduce harmful gases and smoke, a hole should be created in the briquette.

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APPENDIX

Briquette Stability

Table 4.14 Results of length increment against time for uncharred briquette

	Increase in Length(mm)		
TIME(Minutes)	**5%**	**10%**	**15%**
0	0.6	0	0.6
60	1.0	3.8	4.08
1440	0.75	0.5	0.5
2880	2.65	4.2	4.91
4320	0.5	1.3	3.22
5760	0.53	0.74	3.22

Table 4.15 Results of length increment against time for charred briquette(P<2mm)

	Increase in Length(mm)		
TIME(Minutes)	**5%**	**10%**	**15%**
0	2.5	3.5	3.25
60	0.5	1	1.5
1440	0.985	0.485	1.66
2880	1.093	1.785	2.895
4320	1	1.5	2
5760	0.195	1.28	1.675

Table 4.16 Results of length increment against time for charred briquette(P>2mm)

	Increase in Length(mm)		
TIME(Minutes)	**5%**	**10%**	**15%**
0	1.3	0.551	0.365
60	1.58	0.8313	1.93
1440	1.74	0.476	1.14

2880	2.68	1.48	4.15
4320	1.91	1.91	3.195
5760	2.12	2.65	1.868

Decrease In Weight Against Time

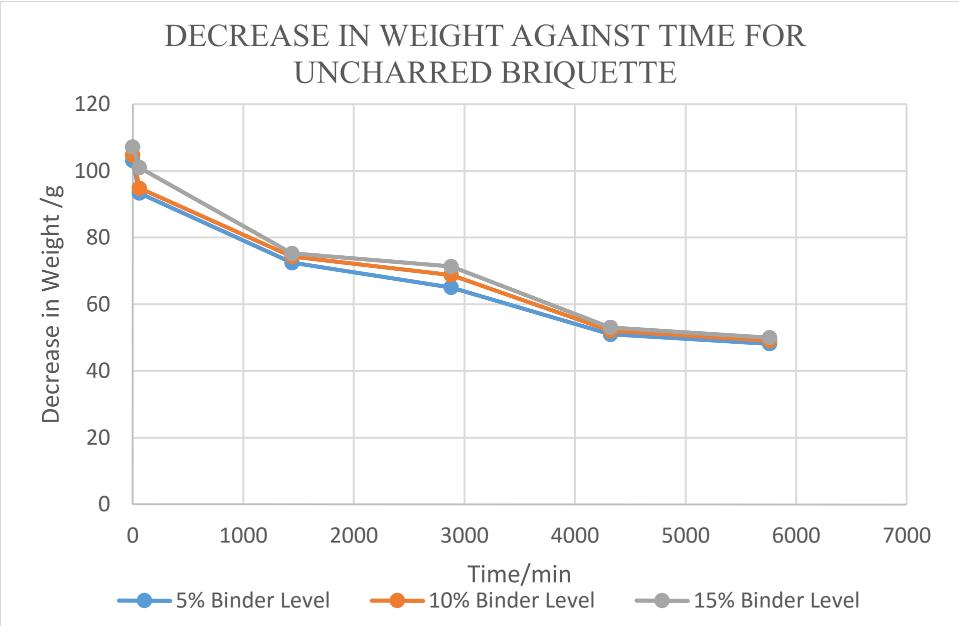

Figure 4.14: Decrease in Weight of Uncharred Briquette

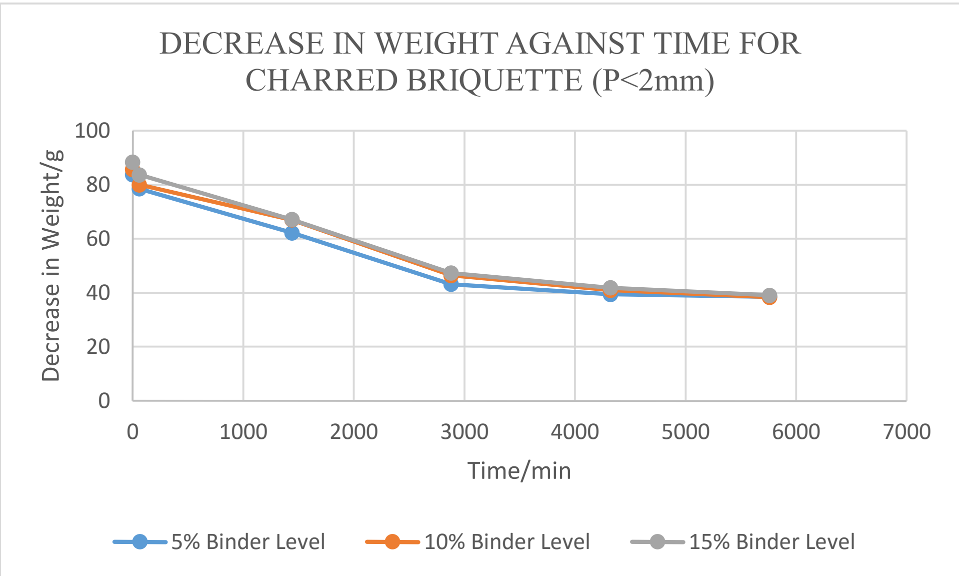

Figure 4.15: Decrease in Weight of Charred Briquette(P<2mm)

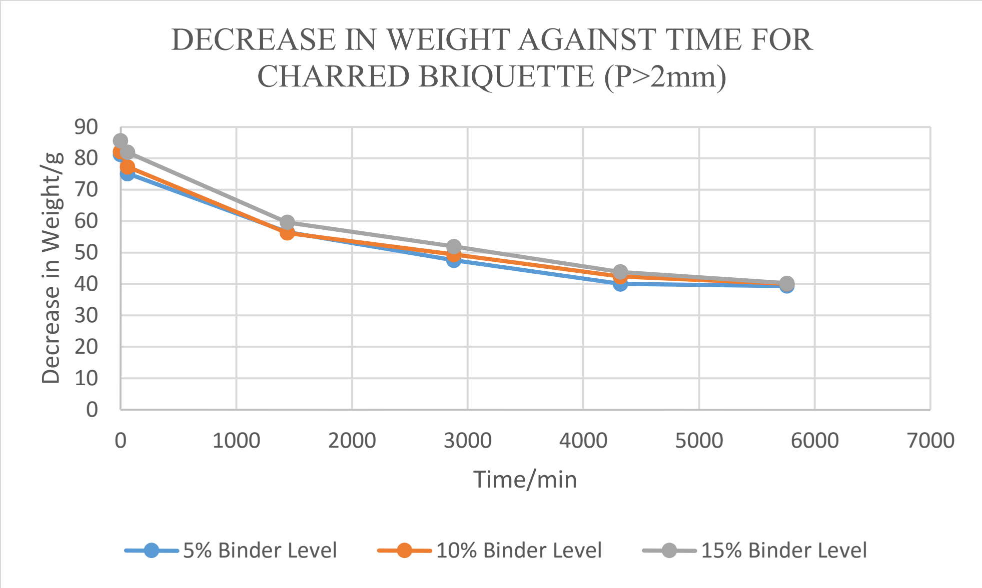

Figure 4.16: Decrease in Weight of Charred Briquette(P>2mm)

Shatter Resistance

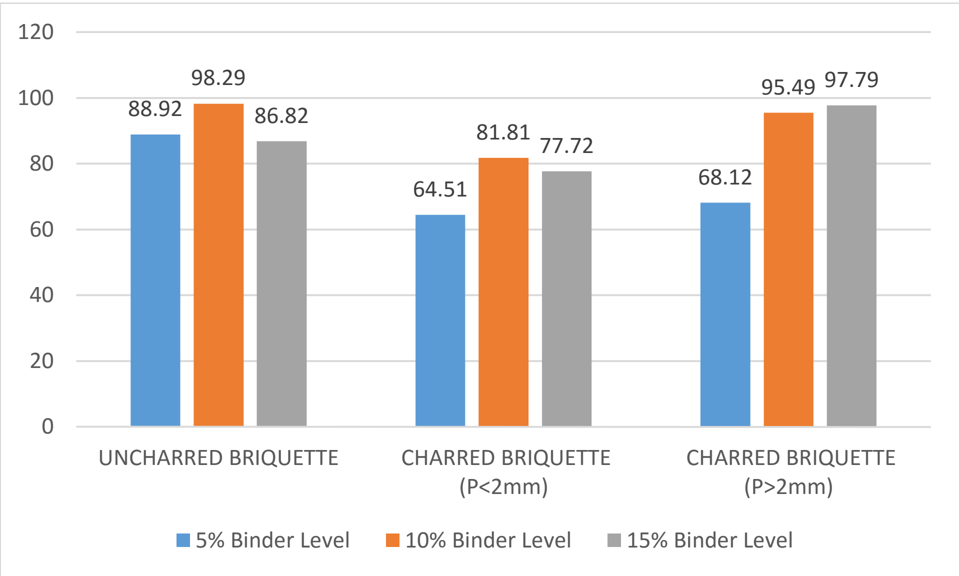

Figure 4.17: Shatter Resistance of Briquettes at Varying Binder Levels

Water Resistance

Table 4.17 Water Resistance Test Results of uncharred briquette at varying binder levels

Binder Level	Initial Weight(g)	Final Weight(g)	Water gained by briquettes (%)	Water Resistance Capacity (%)
5	47.00	49.00	4.26	95.74
10	46.66	48.02	2.92	97.08
15	47.55	49.21	3.49	96.51

Table 4.18 Water Resistance Test Results of charred briquette(P<2mm) at varying binder levels

Binder Level	Initial Weight(g)	Final Weight(g)	Water gained by briquettes (%)	Water Resistance Capacity (%)
5	38.06	40.76	7.09	92.91
10	37.90	41.05	8.31	91.69
15	39.04	42.55	8.99	91.01

Table 4.19 Water Resistance Test Results of charred briquette(P>2mm) at varying binder levels

Binder Level	Initial Weight(g)	Final Weight(g)	Water gained by briquettes (%)	Water Resistance Capacity (%)
5	39.37	43.03	9.30	90.70
10	40.07	44.10	10.06	89.94
15	40.21	45.07	12.09	87.91

Combustion Properties

Table 4.20: Combustion Properties of Uncharred briquettes at Varying Binder Levels

Binder Levels (%)	Ash Content (%)	Volatile Matter (%)	Fixed Carbon (%)	Calorific Value(kJ/kg)	Heat Capacity(kJ/K)
5	31.51	57.21	11.28	15747.88	9.79
10	7.73	71.27	20.99	16805.78	10.76

15	7.33	75.25	17.42	16074.83	13.40

Table 4.21: Combustion Properties of charred briquettes(P<2mm) at Varying Binder Levels

Binder Levels (%)	Ash Content (%)	Volatile Matter (%)	Fixed Carbon (%)	Calorific Value(kJ/kg)	Heat Capacity(kJ/K)
5	23.44	29.55	47.01	8450	12.51
10	21.71	46.77	31.52	17894.94	13.55
15	21.47	75.46	3.07	13610.00	17.50

Table 4.22: Combustion Properties of charred briquettes(P>2mm) at Varying Binder Levels

Binder Levels (%)	Ash Content (%)	Volatile Matter (%)	Fixed Carbon (%)	Calorific Value(kJ/kg)	Heat Capacity(kJ/K)
5	15.69	29.91	54.40	23452.51	7.73
10	15.17	36.85	47.98	24989.50	7.83
15	23.34	37.63	39.03	20758.57	7.88

Water Boiling Test

Table 4.23: Water Boiling Test Results of uncharred briquette

Initial Mass of Water(kg)	2.5
Final Mass of Water(kg)	2.26
Water Evaporated(kg)	0.24
Initial Water Temperature(^{0}C)	32.2
Final Water Temperature(^{0}C)	99
Mass of fuel consumed(kg)	0.049
Specific heat of water(kJ/kgK)	4.187
Specific fuel consumption(kg/l)	0.0196
Thermal Efficiency (%)	88.03
Burning Rate(kg/min)	0.00163
Heat Released(kJ/min)	26.47

Table 4.24: Water Boiling Test Results of charred briquette

Initial Mass of Water(kg)	2.5
Final Mass of Water(kg)	2.3865
Water Evaporated(kg)	0.1135
Initial Water Temperature(^{0}C)	30.8
Final Water Temperature(^{0}C)	99
Mass of fuel consumed(kg)	0.058
Specific heat of water(kJ/kgK)	4.187
Specific fuel consumption(kg/l)	0.0232
Thermal Efficiency (%)	92.416
Burning Rate(kg/min)	0.00166
Heat Released	22.068

Table 4.25: Water Boiling Test Results for charcoal

Initial Mass of Water(kg)	2.5
Final Mass of Water(kg)	2.379
Water Evaporated(kg)	0.121
Initial Water Temperature(^{0}C)	30.6
Final Water Temperature(^{0}C)	99.9
Mass of fuel consumed(kg)	0.2445
Specific heat of water(kJ/kgK)	4.187
Specific fuel consumption(kg/l)	0.0978
Thermal Efficiency (%)	77.1
Calorific Value (kJ/kg)	19200
Burning Rate(kg/min)	0.01111
Heat Released(kJ/min)	213.312

Gas Emission Analysis

Table 4.26: Results of Indoor Air Pollution Test of briquettes and charcoal

Samples	Start Time of Test Period	End Time of Test Period	Average Particulate Matter (μg/m^3)	Average Carbon Monoxide Concentration (ppm)	Average Temperature ($^{\circ}$C)	Average Humidity (%)
Charcoal	1:05 pm	1:23pm	1765	561.1	33.5	67
Uncharred Briquette	2:30 pm	3:06 pm	14,328	519.7	34.8	64
Charred Briquette	11:05 am	11:57 am	9863	340.6	32.6	65