# EXPLORING THE EFFECTIVENESS OF SEPARATION OF PITH/FIBRE FRACTIONS IN SUGARCANE BAGASSE BRIQUETTING

**Nkosinathi Emmanuel Madlala**

Discipline of Chemical Engineering,

School of Engineering,

University of KwaZulu-Natal

Durban

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**Nkosinathi Emmanuel Madlala**

Dissertation submitted in fulfilment of the Requirements for the Degree of Master of Science in Engineering (MSc Eng.) in Chemical Engineering

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School of Engineering,

University of KwaZulu-Natal

Durban

**Supervisor:** Dr Andrew C. Eloka-Eboka

**Co-supervisor**: Dr David Lokhat

**November, 2019**

# CERTIFICATION

As the candidate’s supervisors, we have approved this thesis for submission.

Signed……………………………….. Date: …22/11/2019…………..

**Dr Andrew C. Eloka-Eboka**

Signed……………………………….. Date…………………………..

**Dr David Lokhat**

# DECLARATION 1: PLAGIARISM

I, **Nkosinathi Emmanuel Madlala**, declare that:

1. The research reported in this thesis, except where otherwise indicated, is my original research work.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other person' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
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Nkosinathi Emmanuel Madlala

# DECLARATION 2: PUBLICATIONS

(1) **Madlala, N.E**., Eloka-Eboka, A.C. and Lokhat, D. (2019). Chemo-physical and thermal properties of sugarcane bagasse fractions (fibre and pith). Proceedings of the 18th International Conference on Sustainable Energy Technologies – SET 2019 20st - 22rd of August 2019, Kuala Lumpur, Malaysia. Full paper ***presented***

(2) **Madlala, N.E**., Eloka-Eboka, A.C. and Lokhat, D. (2019). Thermo-gravimetric analysis of bagasse fractions (Fibre and pith) for solid fuel beneficiation in boilers, stoves, and open fires. Proceedings of the International Conference on Sustainable Materials and Energy Technologies (ICSMET), Coventry University, UK.

In the two publications above, the candidate is the main author while the two other authors are supervisors of the project.

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# NOMENCLATURE

| | |
|---|---|
| TGA | Thermogravimetric analysis |
| PVA | Polyvinyl Alcohol |
| mm | millimetre |
| m | meter |
| MJ | Mega joule |
| GJ | Giga joule |
| kg | kilogram |
| h | hour |
| MW | Mega watt |
| mg | milligram |
| kWh | kilowatt hour |
| HV | heat value |
| ha | hectare |
| rpm | revolutions per minute |
| BISA | Brazil Institute of Sugar and Alcohol |
| GHG | green-house gas |
| CEST | Condensed Extraction Steam Turbine |
| HRSG | Heat Recovery Steam Generator |
| LHV | low heating value |
| HHV | high heating value |
| OSHA | Occupation Safety and Health Agency |

# ABSTRACT

Good understanding of the thermo-chemical properties and physical properties of bagasse biomass and its fraction is vital to the design of thermo-chemical conversion systems for energy co-generation in sugarcane mills. The present study was conducted using bagasse biomass collected from Tongaat Hullet Sugar Maidstone Mill in Durban to explore the effectiveness of separating bagasse into pith and fiber fractions to be used as biomass feedstock through briquetting.

In this study, bagasse biomass was dried to moisture content less than (< 10 %) and then separated into its fractions of: fibre and pith and then milled using hammer milling machine. The particle size analysis by laser particle size (0.39 – 0.683 mm) distribution was recorded for bagasse, fibre and pith. There were preliminary and details biomass characterization and analysis of the raw bagasse, pith and fibre. They include: ultimate and proximate analysis, thermogravimetric analysis (TGA) and calorific values using bomb calorimeters. An average mass of 50 g of samples of bagasse, fibre, and pith with 8 % (w/v) was briquetted using starch and PVA as binders to produce various briquettes and hybrid briquettes at 50 % (w/w) charcoal. These were then subjected to an average compression pressure of 462 kPa by manual piston briquetting with a cylindrical die of 0.05 m diameter and 0.088 m long to produce briquettes which were considered for detailed pre and post analysis. The analysis includes moisture content, bulk density, compressive strength, proximate analysis, elemental analysis, calorific values, cooking test, gas emission, dropping test and thermogravimetric (TGA) properties. This study reports that huge amount of energy is required to dry bagasse, fiber, and pith to be suitable to be used as a feedstock for briquetting.

Compared to coal and charcoal, bagasse biomass and its fractions of fibre and pith have lower energy density, bulk density at a range of (80 – 240 kg.m$^{-3}$) and lower ash content (1.75 % – 18.12 %). Briquettes bulk density demonstrated that charcoal and PVA improves bulk density of bagasse, fibre and pith by 19.24 %, 21.68 % and 9.63 % respectively. Results from proximate analysis and TGA curves also indicate high ash content from pith than in bagasse and fiber, high decomposition rate for pith than bagasse and fibre. High cooking test values were obtained from bagasse and fiber briquettes but lowest from pith briquette. All briquettes from bagasse and its fractions indicate low gas emissions which is an interesting result. Heating value (HV) was high in fibre (17.73 MJ.kg$^{-1}$) and bagasse (16.14 MJ.kg$^{-1}$) but lowest from pith (15.74 MJ.kg$^{-1}$) pre and post briquetting analysis. Contents of elementals; carbon, nitrogen, and hydrogen are almost the same for bagasse and fiber with probability ($p > 0.05$), while pith fractions demonstrate high oxygen content and lower carbon, hydrogen and nitrogen as compared to bagasse and fibre.

Results of this study could serve to establish a database for biomass potential of sugarcane raw materials and its fractions as the source of energy for energy co-generation and for decision making in terms of energy conversion technologies. Also, other industries could benefit from the use of bagasse biomass beyond the sugarcane industry by using the piths or fibre and their chemical potentials for specific other applications. Chemical compositions of bagasse such as hemicellulose and lignin can be extracted for value added products. The implication of this study indicates that piths and fibres when separated from bagasse can be beneficiated differently in terms of energy content and needs; beyond briquetting of bagasse biomass and briquetting increases thermal efficiency of bagasse as a bioenergy source.

# CHAPTER ONE: INTRODUCTION

## 1.1 Introduction

For the past five hundred years, the sugarcane and its industry have been a source of sugar used for domestic needs, alcohol production, sweeteners and feedstock for bioethanol fuel production from the sugarcane juice in the recent (de Souza *et al.*, 2014). In 1925, Henry Ford adopted the production of ethanol from grain and used it to fire his automobile engine (Ballinger, 1978). The Brazilian Institute of Sugar and Alcohol (BISA) in the early 1920’s, implemented energy policy on large scale production for bioethanol production for the automotive industry. In 1930, sugarcane crop become industrialised for bioethanol production, after Brazil Institute of Sugar and Alcohol implemented the policy into the power automotive sector in which actually began earlier than 1920’s (de Souza *et al.*, 2014). Sugarcane bioethanol in 1970’s became competitive in the market due to global petroleum challenges, awareness on greenhouse gases emissions and other climatic related issues. It became cheap due to the drastic improvements in the fermentation technology for bioethanol production (Sahu and Chaudhari, 2015).

Sugarcane has a high biomass fraction per plant for bioethanol production. It was reported that accumulation of biomass above the ground is 550kg.ha$^{-1}$.day$^{-1}$ for rain-fed sugarcane plantation which makes it a potential crop for biomass fuel production (de Souza *et al.*, 2014). Biomass is the product of the crop after its efficient conversion of solar energy and carbon dioxide to biomass (Galloway, 1977). The major biomass used for fuel briquetting are sugarcane bagasse, coffee husk, rice husks, coir piths, jute sticks, groundnut shells, stalks of cotton and mustards (Sapariya *et al.*, 2013). Sugarcane produces two types of residues: trash (straw) and bagasse. Trash is normally left out in the field or burnt *in situ* to clear the field. On the average, one hectare of sugarcane plantation generates ten tonnes of sugar cane trash (Sapariya *et al.*, 2013). Bagasse generated by one tonne of sugarcane crushed on the average, is 300 kg. Sapariya *et al.* (2013) indicated that sugarcane trash has no value for use as cattle fodder but there is a potential for its use as fuel. Most researchers have seen the need to convert these biomass as solid densified fuels for different applications. Canilha *et al.* (2013) highlighted in their study the uses of straw (trash) residues. Sugarcane trash can be used for:

- as fuel for direct combustion.
- as raw material for production of char through pyrolysis, oil or gas.

- as raw material for convention by gasification and synthesis to methanol, as a ruminant feed.
- as substrates through anaerobic digestion for methane production.

Bagasse has been used as cattle fodder and energy/fuel in sugarcane mills. Biomass production is more driven by photosynthesis and source-sink relationship in the plant during growth and bioenergetic transformations. Since sucrose in sugarcane is produced by photosynthesis on the green leaves and then transported to the culm sink for storage, it is then possible to harvest this stored energy for use in the biomass after harvest (Ensinas *et al.*, 2006a). This concept was demonstrated by the increase in sucrose contents achieved through 20% photosynthesis rate increase from young and old leaves (de Souza *et al.*, 2014). After sugarcane crop reached its maturity and harvested, crushing of sugarcane from sugarcane mill for juicy extraction, the biomass called bagasse is obtained. On average, sugarcane crop cultivar consists of 24% sucrose and 14% of fibre (Pandey, 2007). Bagasse biomass when leaving the mill tandem, conventional bagasse have average of 50% moisture content, with 55-60% of fibre, the other fraction consists of pith tissue at 30 - 35% (Lois-Correa, 2012a). Because bagasse has relatively low density and volatile in nature at fresh production, chemical and biological changes with time makes its storage and handling very crucial.

In South Africa, it has been estimated that for every 100 tonnes of sugarcane harvested and milled, 11.8 tonnes of sugar are produced alongside 28 to 30 tonnes of bagasse biomass (Mashoko *et al.*, 2010). Bagasse can generate 30 kWh of electricity during co-generation process but this can be improved up to 120 kWh of electricity depending on boiler efficiency and storage technology which influences biofuel properties of bagasse by controlling fermentation and heat rising (Mashoko *et al.*, 2010;Hamzeh *et al.*, 2013). Sugar processing industry produce tonnes of bagasse during sugarcane crushing season, bulky bagasse produced is prone to decay or spontaneous combustion due to poor storage (Teixeira *et al.*, 2010). There are different storage technologies for bagasse namely: balling, briquetting and pelleting. Other methods have indicated non-improvement in bagasse biomass fuel content except briquetting. Briquetting technique is the densification of loose biomass by subjecting it under heavy mechanical pressure to form compacts of certain shapes and sizes preferable by end market users (Sapariya *et al.*, 2013). Densification of biomass into briquettes and pellet is the best method of achieving intrinsic density material and bringing uniformity for combustion equipment (Bazargan *et al.*, 2014). There are vast literatures on biomass densification for solid fuel application. These include: But not much is available for improving their fuel qualities by separation of different component fractions or by briquetting. There are two different types of briquettes namely: non-carbonized and carbonized fuel briquettes (Grover and Mishra, 1996).

Briquetting increases thermal efficiency of bagasse as the source of energy. Sapariya *et al.* (2013) indicated that briquetting can increase bulk density of loose biomass from 0.1 to 0.2 $g.cm^{-3}$ and 1.2 $g.cm^{-3}$. This physical improvement increases duration of burning in the boilers to produce high heat value. Bio-briquetting allows hybridizing of different biomasses from different agricultural crops to be mixed with coal ash with 10 or 25% of biomass. This type of briquetting increases aggregation of biomass with coal to form high pressure briquettes. Different mechanical densifications of biomass are categorized into five instruments viz: roll press, piston press, pelletization, screw press and low pressure or manual press densification. Screw densification is popularly used than piston presses. Two types of screw are conical and screw press. Conical press is a good densification technique because pre-heating is important in briquetting to reduce energy required to compress biomass which also reduces moisture content during compression for better heat transfer.

Different biomass in our environment are being used for briquette fuels, those materials includes: charcoal dust, wastes from bio-product industries such as: sawdust, invasive plants mostly water hyacinth, agro-processing residues, waste papers, cardboards and agricultural residues including grasses (Grover and Mishra, 1996). From these elucidated biomasses, extra constituents are required to improve adhesive forces from the loose biomass material to form briquettes (Sapariya *et al.*, 2013). For briquette technology of biomasses, preparation and addition of accelerants, binders, fillers and pre-heating before densification are necessary. Densification is not only affected by the physical, physical actions and chemical state of ingredients such as temperature and pressure for mechanical heavy machine to combine ingredients, moisture content of the ingredients, drying and particle size are also factors (Brienzo *et al.*, 2009b;Mashoko *et al.*, 2010;Teixeira *et al.*, 2010). Except bagasse being used in sugarcane industry but also in the pulp and paper industry is being used. Paper industry requires clean bagasse material which comprises only clean cellulose (high-quality fibre) not hemicellulose which constitutes pith and other fibrous materials which are of less importance (Atchison, 1971a).

The pith approximately makes 30% of the dry weight of the cane stalk. Since 1950, different methods has been developed to effectively extract unwanted fibrous materials from bagasse to improve paper quality (Atchison, 1971b;Brienzo *et al.*, 2009a). Mechanical and chemical methods have been employed since then in different industries but depending on the main production of the industry. They are different mechanical depithers for separating pith from bagasse: S.M Caribe depither, Kimberly KC-4 depither, and Horkel depither. Lois-Correa (2012a) reviewed the cost and power consumption of depithing and non-depithing systems on the moist bagasse with 50 percent of moisture by evaluating its technical factors which are vibration and temperature value. The use and installation of the depithing machines in the industries dated back between 1912 and 1914 (Lois-Correa, 2012a).

Most depithing machines uses high shear compounding for pith separation. This is because of the impact of heavy swinging hammers, which impairs cellulose thereby compromising the quality of fibrous matter required by the paper industry (Hamzeh *et al.*, 2013). Depithing no doubt is the most effective method of separating fibrous materials from bagasse and does not compromise the air quality and overall environment thereafter because no chemical extraction is involved. Unlike chemical extraction methods which are chemically intensified by using strong acid in large volumes. Disposal, storage and handling become a challenge. But chemical extraction method maintains the quality of fibrous matter (Atchison, 1971b;Brienzo *et al.*, 2009a). But it has been identified that bagasse has good biomass fuel properties because it constitutes high volatile matter than when it is hybridized with coal ash which exhibits less volatile characteristics (Raju *et al.*, 2014). But this research has the motivation to establish that hybridizing bagasse with other fuel materials such as coal, charcoal or fly ash can improve physical and biofuel properties for industrial purposes.

The effective separation of pith fraction from fibre can minimise bagasse dusts, rapid heat increase through oxygenated combustion and possible fermented gases which results in spontaneous burning of piles of bagasse in the storage area. Some of the results obtained in this study can be used to make meaningful deductions and inferences on this potential application and technology and make necessary recommendations.

## 1.2 Background of Study

Sugarcane biomass is abundant in South Africa in KwaZulu-Natal province. In South Africa, it is estimated that 20 to 22 million tons of sugarcane is produced from 430 000 hectors of land, which produces biomass that has the equivalent energy value of about 1.75 million tons of coal which produces 1600 MW of electricity on the average. The normal utilisation of sugarcane as an energy crop, studies indicate that only 30 percent of sugarcane crop is used to generate and produce electricity and ethanol. The potential of sugarcane crop as an energy source is approximately equivalent to 1.2 barrels of crude oil. Biomass is projected as being a potential energy source for the next centuries since it has the potential to replace conventional energy sources because sugarcane biomass such as bagasse has lower net carbon dioxide under proper utilisation technology for energy cogeneration.

Since sugarcane biomass stands out as a promising energy research project for funding, stated under Kyoto Protocol, it is proposed for clean development mechanism in order to mitigate greenhouse gases (GHG) during energy generation. About 2.5 million tons of sugarcane per annum is crushed in 15 mills around KwaZulu-Natal province which require internal power estimated to 35-40 kWh per ton, with only two mills located in Mpumalanga. The harvested sugarcane is transported to the sugar mills at a rate of 90 tons per hour to 550 tons per hour of crushing capacitor. Tongaat Hulett Ltd. confirmed in their production that; for every 100 tonnes they harvested and crushed, 28 to 30 tonnes of bagasse is produced. Bagasse is used for energy cogeneration to produce electricity and steam to be used during milling process. Generally, sugarcane bagasse emanates out from the mill with approximate 50 percent of moisture, which affect its energy conversion efficiency. High moisture content of biomass such as bagasse lowers energy content and heat transfer, therefore superior qualities of bagasse biomass is required to produce a unit of energy.

Bagasse is not only used for energy cogeneration, but also used for other purposes in sectors such as agriculture, pulp and paper industry. Tongaat Hulett Ltd separates bagasse separated into its fractions of pith and fibre using mechanical depithers to produce agricultural animal feeds and in paper making industry for pulps. High moisture content and presence of pith in bagasse biomass present a challenge to be used as a bioenergy feedstock and for the pulp and paper industry. Briquetting technology seems as the potential solution to preserve energy quality of bagasse during storage for off-crop season and improve energy density of this important raw material - bagasse.

During sugarcane crushing seasons at the sugar mill, piles of bagasse accumulate in the stock yards. The raw material residues have the potential to cause pollution in the environment, also can induce some infectious diseases to local people due its persistent odour and from dust particles such as bagassosis. In addition, there is likelihood of fire outbreak stemming from spontaneous fire as a result of oxygen penetration of the piles and unintended reaction with fuel substances in contact with bagasse. When this happens, tons and tons of bagasse raw materials are lost. But they are various options of bagasse storage suggested in the literature. These include: wet bulk storage, bulk storage without added water, baled storage, pelleting, torrefaction which changes biomass properties and provides superior fuel quality for gasification and combustion usage with briquetting and bio-oil production. The extent of the storage of bagasse is very important for the conservation of its fuel value which can be used during off crop seasons in sugar mills, rather than using non-renewable coal or any other auxiliary fuels.

However, due to improper utilisation of energy conversion technology in boilers and poor bagasse storage, increases cost in sugar mills than making profit by using the supposedly referred ‘wastes’ (raw materials) to produce off grid-generated electricity from bagasse which can also be supplied to the grid systems through national power supply. But energy conversion of bagasse using boilers still has efficiency problems. It has been estimated that; the electricity efficiently generated by boilers is between 10 to 20 percent as compared to gasification process which has the net electricity efficiency range of between 67 to 80 percent. Also, the combustion of bagasse has long start-up duration of 8 hours in boilers before it burns more efficient. This study aims at improving bagasse biomass in order to thrive better in all thermochemical energy conversions. Briquetting has indicated the potential to improve storage and conservation duration of bagasse and its fuel properties, also can reduce moisture content up to 14 to 16 percent after briquetting since moisture and calorific value determines energy output content of bagasse. This study is geared at improving briquetting technology by evaluating the potentials of briquetting separated bagasse to unseparated bagasse, piths and fibres and evaluate their fuel properties. This can help paper and pulp industries to utilise the separated fibres and piths to other industries without interference with energy production and food supply chain.

## 1.3 Motivation of the Study

- Availability of bagasse in large quantities produced during sugarcane crushing by sugarcane mills in South Africa.
- Briquetting technology does not interfere with the food supply chain.
- The world is seeking various solutions to energy crisis and demands by venturing into renewable bioenergy sources.
- Feasibility problems on the lager industrial scale for briquetting storage technology.

## 1.4 Research Problem

The presence of pith in bagasse and its storage has posed several technological problems for many years. Pith has the lager surface area and can absorb 20 times of water of its weight (Lois-Correa, 2012a). The unseparated or integral bagasse is prone to decay and losses its fuel value through fermentation and the increase of heat on the piles of bagasse which then results in tons and tons losses of bagasse for energy co-generation during off-crop season for sugarcane mill is of utmost concern This makes it very difficult to obtain the full benefit and profit on investment in the equipment for energy co-generation.

## 1.5 Research Aim

The aim of the project is to explore the effectiveness of separating pith and fibre of the sugarcane bagasse and its effects on the physical, chemical and biofuel properties of the briquettes made thereof from bagasse and hybrid (with charcoal) briquettes.

## 1.6 Objectives

1. Preliminary characterizations of raw sugarcane bagasse (piths and fibre fractions) to ascertain relevant properties. This will include bomb calorimetry, proximate and ultimate analysis, elemental analysis, particle size determination using different methods.

2. Separation of pith/fibre fraction using chemical separation, mechanical separation and wet techniques.

3. Briquetting separated piths, fibres and unseparated bagasse under mechanical pressures and compressive strengths and bulk densities
4. Performance and emission testing of briquettes
5. Sugarcane bagasse must undergo the briquetting procedure, that bagasse will be classified as unseparated biomass. Another set will undergo the same briquetting procedure with a biomass of pith separated from fibre.
6. To explore the effectiveness of separating pith and fibre, the briquettes are to be evaluated for: moisture, ash, fixed carbon, volatile matter, calorific values, sulphur content, combustion/heating values, compressive strength and bulk density.

## 1.7 Research Questions

- What is the best method suitable for industrial operation for separating pith/fibre fractions?
- Does the absence of pith fraction in bagasse biomass compromise the physical, chemical and biofuel properties of the briquette manufactured from bagasse?
- Which binder between polyvinyl alcohol (PVA) and starch will yield briquettes with optimum improved physical strength, chemical and biofuel properties for briquette?

## 1.8 Significance of the Study

- The study will contribute in improving briquetting technology to minimise losses of bagasse and also significantly improve the benefit of investing on energy co-generation equipment, by evaluating the effects of pith, fibre, and charcoal hybrid briquette on physical and biofuel properties. To enable the use of bagasse for energy co-generation during and after the crushing season.
- To recommend the industrial economical viable effective methods of separating pith/fibre fractions. Also advance green economy, cost effective storage technology and promote environmentally friendly fuel.
- To show the importance and the value of the depithed bagasse for other industrial sectors other than pulp and paper industry; to minimise bulk waste handling problems of sugarcane bagasse in industries and to minimize environmental pollution, bagasse dust and bagassosis.

### 1.9 Scope of Research/Limitations

- To review different pith/fibre separation methods that are more adequate or satisfactory in the industrial setup.
- Use of separated, unseparated fibre fractions, charcoal, binder at different ratios in briquetting technology.
- All recommendations are geared towards scale up, commercialisation and industrial expansion.

### 1.20 Thesis Overview

Chapter One of this thesis is the road map of the study. Chapter Two present the literature survey of the study; related works were assembled and evaluates from the densification of biomasses, a method that is in place for pre-treatment of biomass, analysis employed to quantify biomass properties to be able to find out the effectiveness of separation of bagasse to pith and fibre fractions and briquetting technologies were explored. Also, research gaps were identified in terms of bio-energy production specifically from biomass for energy cogeneration and improvement thereof. Chapter Three quantifies the advances and information in literature on sugarcane processing practices specificity on the technology used for steam and electricity generation and instrumental configurations used in sugarcane milling factories. It was pointed out and highlighted that, the use of back pressure turbine is no longer suitable since steam demand is very high while the use of condensed extraction steam turbine (CEST) is modern and adopted in countries such as Brazil, India and Mauritius which produce surplus electricity for their countries using sugarcane biomass as feedstock. Chapter Four is the overall methodology of the study on how each objective was achieved and on evaluating physical, chemical, energy and emission properties of bagasse biomass and its fractions of fibre and pith. Chapter Five of this thesis discusses the relevance of the results for physical, chemical, energy and emission properties of the briquettes manufactured compared with findings in literature. Where the high point of the result demonstrated that the use of fibre fraction, PVA binder and charcoal can produce briquettes of good quality in terms of physical and energy properties but not good to be used in household by humans. Chapter Six concluded that sugarcane milling factory should begin to invest in briquetting facilities and efficient cogeneration facilities. Also, recommend is a detailed study on parameters of briquetting and on simulating the performance of briquettes manufactured in cogeneration facilities for sugarcane milling factory decisions.

# CHAPTER TWO: LITERATURE REVIEW

## 2.1 General: Sugarcane

Sugarcane (*Saccharum officinarum*) crop belongs to the Poaccac family and a monocotyledon. It is originated from Asia and Oceania (Santos *et al.*, 2015). Sugarcane is a type of grass plant with the outside fibres covering the soft central pith which is rich in sucrose juice (Hugo, 2010). Also regarded as the tropical crop, with 12 to 24 month cutting cycles, sporouting between latitudes 35° N and 30° S at the sea level of up to 1000 m and below this altitude (Santos *et al.*, 2015). It a rich solar energy reservoir from its biomass with a yield per annum of approximate 80 tons per hectare. During photosynthesis, $CO_2$ is captured by sugarcane crop which then returns back during combustion of sugarcane, thus neutralising the initial process. Since sugarcane crop is one of the crops that produces the highest biomass yield per annum, literature has it that up to 8 tons/hectare of sugar plus bagasse can be produced annually. Sugarcane is grouped as the fibrous plant with the interwoven biomass after extraction of sucrose called bagasse. It has recently been a priority for many industries to turn bagasse into reliability to improve profit margins and to produce bioenergy.

Sugarcane lifts economies of many countries like; Brazil, India and including South Africa since sugarcane has an energy rate generation of 0.5 to 2 $GJ.ha^{-1}$ of energy (Smithers, 2014), One-third of sugarcane energy is available in tops and leaves which are generally referred to as trash. In South Africa, 1 353 million tons of trash is also available for cogeneration of heat in boilers (Smithers, 2014). However, this figure is achieved because of increasing adoption of mechanical harvesting, but due to the slopyness of sugarcane fields which mostly in South Africa is less than 12 percent, it therefore makes mechanical harvesting difficult (Smithers, 2014). Canilha *et al.* (2013) indicated that Brazil harvests more than 602 million tons of sugarcane for sugar alcohol mills in relation to the world sugarcane production scale which is estimated to be approximate 1.6 billion tons (Canilha *et al.*, 2013). In South Africa, it is estimated that approximately 20 million tons of sugarcane is crushed per annum (Mashoko *et al.*, 2013).

Moreover, sugarcane is produced in 430 000 ha, then delivered to 15 sugarcane mills across the country (Smithers, 2014). After sugarcane harvesting, straw and sugarcane bagasse after crushing are the raw products of sugarcane. Canilha *et al.* (2013) presented the fact that sugarcane straw can be burnt after harvest and be applied for: (1) direct fuel combustion and (2) raw materials during gasification and synthesis to produce alcohol - methanol. Since sugarcane leaf residues have high calorific values and low micro pollutants under well improved energy cogeneration technology (Smithers, 2014), it therefore presents huge potential for various renewable energy applications. Sugarcane is made up of four fractions which are: fibre, non-soluble solids, soluble solids and pith. All these fractions and their magnitude mainly depends on agro industrial processing, mainly the type of cultivar, geographic location and climatic conditions. After sugarcane production and processed into sugar, these fractions are left behind as ‘wastes’ now raw materials in the form termed “bagasse”.

## 2.2 Bagasse as a Waste Material

Bagasse is a heterogeneous biomass which is a fallout of sugarcane during sugarcane crushing for juice extraction. Bagasse is a low bulk density biomass ranging from 150 to 200 $kg.m^{-3}$ (Anukam *et al.*, 2016). The entire world produces approximately 279 million metric tons of biomass which includes bagasse (Demirbas, 2010). In Uganda, Bagasse as the waste/raw material presented as having huge potential for biofuel (Lubwama and Yiga, 2017). Also bagasse could be used as absorbent for waste removal, heavy metal removal and for improving soil nutrient levels (Gupta and Ali, 2004). Activation of carbon can be archived on bagasse wastes to remove heavy metals in waste water (Mohan and Singh, 2002). Adsorption of heavy metals is estimated to be about 96 to 98 percent, and the adsorption is exothermic in nature with the use of bagasse.

Mohammad and Kamruzzaman (2011) in their study, presented that agricultural biomass has ash contents between 5-20 percent including bagasse biomass. Due to high ash content but not as compared to coal, high level of ash content results in sluggish behaviour in energy conversion. The ash residue can be collected from boilers and be used in the construction industry to replace concreate and so nothing is wastes or lost (Canilha *et al.*, 2013). Harnessing of bagasse biomass through biotechnology can reduce pressure on other food crops for energy generation also the ash residue as wastes after combustion. However, the use of biomass as energy source has produced no visible success from the previous years, because of adaptation difficulties (Felfli *et al.*, 2011) and due to cost intensive projects on bioenergy in developing countries. Smithers (2014) in his study indicated that lignocellulosic residues can mitigate environmental impact resulting from conventional energy sources than to be viewed as the wastes. Although, bagasse is a viable and readily available biomass, high recovery costs are associated with it. For storage, transportation and for briquetting for large scale energy production (Smithers, 2014). Most sugarcane mills in South Africa burns bagasse residue inefficiently due to high moisture content associated with it and high recovery costs for drying and improvement of bulk density (Inyang *et al.*, 2010).

When bagasse leaves the milling process, it consists of soluble and non-soluble matters such as rock particles, sands/soil and extraneous inorganic matters (Canilha *et al.*, 2013). Heterogeneity in sugarcane bagasse is mainly influenced by conditions during agricultural production and type of cane harvesting. However, bagasse constituency confers non-waste perception but as a raw material with potential for bioenergy reliability.

## 2.3 Constituent of Bagasse

Anukam *et al.* (2016) indicated that in order to understand the thermochemical conversion of bagasse biomass, analysis of macro and micro structures is vital also its physical and chemical properties. Bagasse contains about 43-52% of fibre cylindrical in shape, 45-50% moisture, 2-6% soluble solids and very wide range of particle sizes (Rasul *et al.*, 1999b;Valix *et al.*, 2017). On average bagasse has long fibre up to 6 cm and very thin in size. Bagasse biomass constitutes macrostructure which are fibrous lignocellulosic with: cellulose, hemicellulose and lignin which are more spherical in shape and highly irregular in structure consisting of phenolic hydrocarbons and aromatics (Mohammad and Kamruzzaman, 2011). The chemical composition of bagasse consist of carbon, hydrogen and oxygen (C, H, and O) which are presented as $CH_xO_y$ due to variation in bagasse sources (Rasul *et al.*, 1999a). The percentage of CHO in dry biomass ranges between 38% to 50%, 5% to 7% and 33% to 45% respectively. The percentage of chlorine (Cl) and sulphur (S) is very low for most bagasse depending on the sugarcane cultivar and agricultural management. The lignin which acts as the binding agent in both cellulose and hemicellulose melts at temperatures greater than 140 ℃. Bagasse also consists of microstructure which are organic and inorganic matters, soluble such as sucrose and waxes (Canilha *et al.*, 2013). But bagasse during combustion also contains metallic ions and other acidic substances in very small quantities due to cellulose and hemicellulose presence through decarboxylation process (Leal *et al.*, 2013). Hemicellulose is of best interest in many industries, because of its distinctive properties and composition (Canilha *et al.*, 2013). Bagasse biomass constituents are used for value added products. Separation and extraction of bagasse constituents is vital to diverse industries in the manufacturing of value added products. Different extraction methods are employed to extract its constituents for value added products such as dilute acid which is mainly used for hydrolysis of hemicellulose to be used for depolymerisation (Canilha *et al.*, 2013). Within cellulose, hemicellulose, and lignin, they are fibres and parenchymatous tissue (pith) (Lois-Correa, 2012b). Fibre is of great interest in pulp and paper industry while pith is of great interest in livestock feeding and other applications. Bagasse generate ash after combustion or thermo-conversion. The ash is rich in silicon which has been used as to supplement for concrete in construction (Oladele, 2014). Furthermore, chemical and physical behaviours of bagasse biomass is important to identify and to validly determine its potential for value added goods and products.

### 2.3.1 Chemo-physical constituents

In general, coal has better energy density as compared to agricultural biomass including bagasse (Mohammad and Kamruzzaman, 2011). Energy potential of biomass is determined by proximate and ultimate analyses (Anukam *et al.*, 2016). Proximate and ultimate analysis provide the fundamental physical and chemical properties of biomass. Carbon, hydrogen, nitrogen, oxygen and sulphur (CHNOS) are the major elements which characterise physical and chemical characteristics of bagasse biomass (Table 2.1). Whereas bulk density, moisture content, particle size and shape also determined by structure of biomass is made up of CHNOS elementals. Which are mainly distributed in bagasse macro-molecular substances which are: cellulose, hemicellulose and lignin (Figure 2.1). In addition, biomass such as bagasse consists of alkali metals (Na, P, K, Ca and Mg) and trace elements. However, bagasse biomass have very low trace element (Mn, Cr, and Cu) contents as compared to forest biomass (Ahiduzzaman, 2011). Therefore, bagasse and sugarcane trash is the reliable renewable source of energy available due to the mentioned chemical constituents and as a potential environmental friendly fuel. Bagasse and straw biomass is a reliable for second generation of ethanol and methane gas, because of chemical composition of lignocellulosic sucrose at high moisture content through anaerobic digestion (Canilha *et al.*, 2013). Also, bagasse biomass is regarded as an efficient fuel during combustion at moisture content less than 5%. During combustion, carbon and hydrogen are the important elements for heat generation, only at reduced oxygen environment to prevent more of $CO_2$ and $H_2O$ to be formed. Sugarcane bagasse also constitutes non-structural matter after burning namely ashes which consist of silicon (Si) at a magnitude of 1.0 to 2.8 percent and extractives of 4.6 to 9.1 percent (Canilha *et al.*, 2013). Bagasse has low ash content as compared to other agricultural residues such as rice straw, husks and wheat (Canilha *et al.*, 2013).

The chemical composition of bagasse biomass such as alcohol and carboxylic acids group which are cellulose, hemicellulose and lignin improves bagasse ignition and reactivity stability (Anukam *et al.*, 2016). When it is used as fuel during gasification or any other conversion process, these constituents play vital roles. However, the disadvantage of other biomasses such as grasses consist of inorganics such as KCl and $K_2SO_4$ due to their fast growth rate. Biomasses of this kind have low heat transfer coefficients due to their high deposition on the surface of heat transfer equipment and can be corrosive to the boilers due to high explosions of KCl. Jorapur and Rajvanshi (1997) stated that bagasse inorganics can be determined from ash analysis but bagasse generally have low content of sulphur and other inorganic or metals. The high content of oxygen than carbon in bagasse biomass deprives or lowers its high heating value. Bagasse heating value ranges between 17 to 20 MJ.kg$^{-1}$ which confers it as a low energy density material in comparison with coal. The heating value is usually measured using bomb calorimeter under sufficient/complete air. But the heating value can be measured using two well-known equations; Dulong Equation (1) which is used when the oxygen gas of the biomass is less than 10 percent with a known CHNOS content in percentage and Bole Equation (2) thus:

$$HV(MJ.kg^{-1}) = 33.823 \times C + 144.250 \left(\frac{H-O}{8}\right) + 9419 \times S \qquad \text{Equation (1)}$$

In Bole Equation, there are no specification or content of oxygen gas stipulated as long as elemental analysis is present for determination viz:

$$HV(MJ.kg^{-1}) = 35.160 \times C + 116.225 \times H - 11.090 \times N + 10.465 \times S \qquad \text{Equation (2)}$$

Also, agricultural wastes such as bagasse have low bulk density of between 80 to 150 kg.m$^{-3}$ and 15 to 200 kg.m$^{-3}$ which differs with cultivars and geographic locations. Low bulk density result in technical limitation to be used as energy feed stock, due to difficulties for; storage, loading, and transportation. Densification technology improves its bulk density (Tumuluru *et al.*, 2010).

**Table 2.1 Proximate and Ultimate analysis of sugarcane bagasse on dry basis**

| **Proximate Analysis** | | | | |
|---|---|---|---|---|
| ***Moisture*** | ***Volatile matter*** | ***Fixed carbon*** | ***Ash*** | ***References*** |
| 1.14 | 69.99 | 16.39 | 1.42 | (Anukam *et al.*, 2013) |
| 9.51 | 74.98 | 13.57 | 1.94 | (Islam *et al.*, 2003) |
| 13.5 | 84.5 | 11.6 | 2.7 | (Das *et al.*, 2004) |
| 40 | 71.24 | 13.14 | 7.69 | (Sapariya *et al.*, 2010) |
| 15 | 75.8 | 20.1 | 4.2 | (Sapariya *et al.*, 2010) |

| **Ultimate Analysis** | | | | | |
|---|---|---|---|---|---|
| ***C*** | ***H*** | ***O*** | ***N*** | ***S*** | ***References*** |
| 44.1 | 5.7 | 47.7 | 0.2 | 2.3 | Anukam et al. (2013) |
| 43.77 | 6.83 | 47.46 | Not reported | Not reported | (Islam *et al.*, 2003) |
| 56.32 | 7.82 | 27.54 | 0.89 | Not reported | (Das *et al.*, 2004) |
| 44.1 | 5.26 | 44.4 | 0.19 | Not reported | (Jorapur and Rajvanshi, 1997) |
| 44.1 | 5.26 | 44.4 | 0.19 | Not reported | (Anukam *et al.*, 2016) |

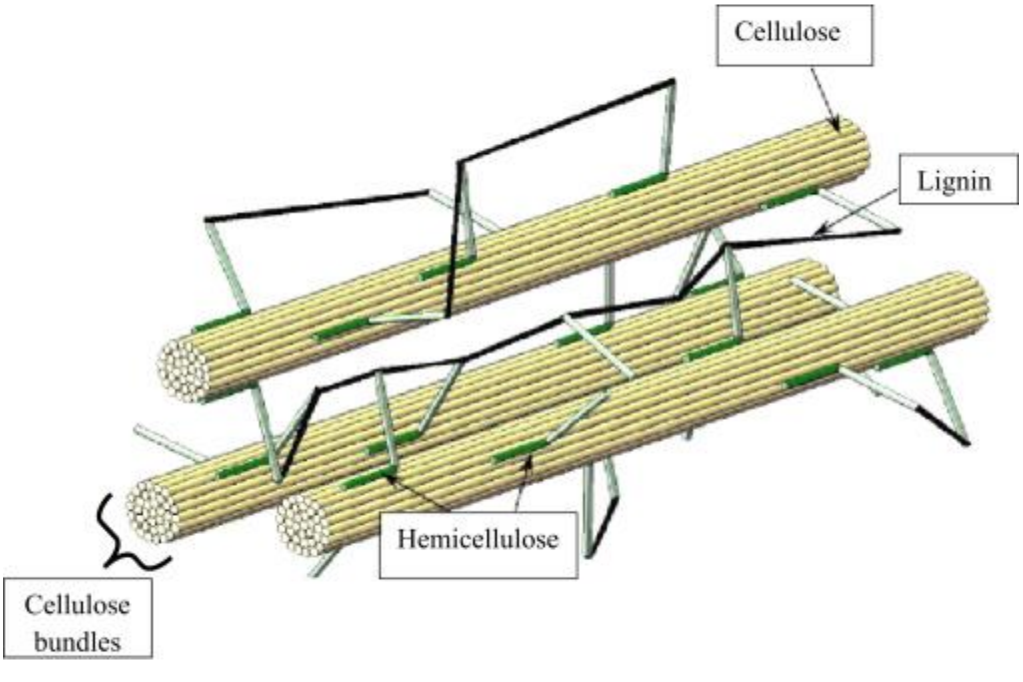

**Figure 2.1 structural constituent of Sugarcane bagasse** (Anukam *et al.*, 2016)

It became a challenge to compare chemo-physical constituent of bagasse which has diverse origins and analysed using different methods. Table 2.2 shows the implication of the variation of chemical constituents across different countries for the same sugarcane cultivar.

**Table 2.2 Chemical composition (% w/w dry) for Brazil and other countries of the world** (Martin et al. 2007; Canilha et al., 2011)

| **Constituency** | | **%** | |
|---|---|---|---|
| | **Brazil** | **Cuba** | **USA** |
| Cellulose | 38.8 | 43.1 | 39.6 |
| Hemicellulose | 25.8 | 31.1 | 29.7 |
| Lignin | 19.1 | 11.4 | 24.7 |
| Ash | 1 | 55 | 4.1 |
| Extractives | 6.8 | | 14.3 |

Physical properties of bagasse such as particle size using sieve and laser analyser, permeability, water holding capacity and bulk mechanical properties are covered by Rainey *et al.* (2013) as it shows that there are no traditional method of determining bagasse particle sizes. The removal of pith in bagasse no doubt improves permeability while it reduces water holding capacity and bulk mechanical properties. The summary of constituency of bagasse biomass for its use as source of energy and other commercial products is presented in Figure 2.2.

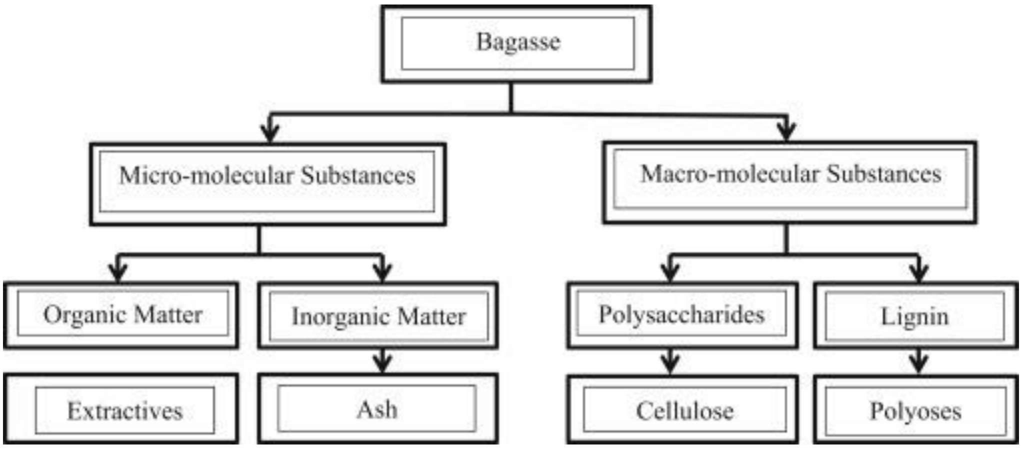

**Figure 2.2 Schematics of sugarcane bagasse constituency** (Anukam *et al.*, 2013)

## 2.4. Separation of Pith and Fibre in Bagasse

### 2.4.1 Chemical Separation

The three chemical composition in bagasse; cellulose, hemicellulose and lignin have strong close association in their hemicellulose-lignin-cellulose complex. To separate bagasse to different constituencies, requires selective pre-treatment technique (Canilha *et al.*, 2013). For extraction of fibres, rind can be separated from lignin by using alkali treatment using normal sodium hydroxides (NaOH) (Asagekar and Joshi, 2014). The concentration of NaOH determines the amount of lignin that can be removed, which give characteristics of fibre that can be yielded. Brienzo *et al.* (2009a) indicated that the effect of varying temperature, hydrogen peroxide concentration, reaction time, magnesium sulphate in the extraction of lignin and hermicellulose in bagasse by comparing yields (Table 2.3). Since piths are regarded as the extraneous substance with 40 percent fraction in bagasse (Clarence, 1955), Rainey *et al.* (2013) indicated that the removal of piths before storage of bagasse reduces dust number and moisture content by 50 and 30 percent respectively. The depithing procedure for vibrating sieves were that 1.0 kilogram of bagasse is depithed to fibre and pith as covered in the earlier work of Rainey *et al.* (2013).

**Table 2.3 Yield of hemicellulose and lignin in % after solubilized of bagasse in $H_2O_2$ treatment at a pH range of 11.6** (Brienzo et al., 2009b)

| Run | Temperature (°C) | Hydrogen peroxide (%,w/v) | Reaction time (h) | Magnesium sulphate (%, w/w) | Lignin content(%) | Hemicellulose yield (%) |
|---|---|---|---|---|---|---|
| 1 | 20 | 2 | 4 | 0 | 10 | 52 |
| 2 | 60 | 2 | 4 | 0 | 10.2 | 49.1 |
| 3 | 20 | 6 | 4 | 0 | 5.9 | 86 |
| 4 | 60 | 6 | 4 | 0 | 12.2 | 74.2 |
| 5 | 20 | 2 | 16 | 0 | 14.1 | 67 |
| 6 | 60 | 2 | 16 | 0 | 13.7 | 49.5 |
| 7 | 20 | 6 | 16 | 0 | 7.4 | 78 |
| 8 | 60 | 6 | 16 | 0 | 9.6 | 60.8 |
| 9 | 20 | 2 | 4 | 0.5 | 9.3 | 38.3 |
| 10 | 60 | 2 | 4 | 0.5 | 9.1 | 46 |
| 11 | 20 | 6 | 4 | 0.5 | 5 | 52.5 |
| 12 | 60 | 6 | 4 | 0.5 | 7.2 | 79.8 |
| 13 | 20 | 2 | 16 | 0.5 | 12.9 | 72.6 |
| 14 | 60 | 2 | 16 | 0.5 | 9.2 | 66.6 |
| 15 | 20 | 6 | 16 | 0.5 | 4.6 | 60.9 |
| 16 | 60 | 6 | 16 | 0.5 | 6.1 | 64.9 |
| 17 | 40 | 4 | 10 | 0.25 | 11 | 90.5 |
| 18 | 40 | 4 | 10 | 0.25 | 10.4 | 93.5 |
| 19 | 40 | 4 | 10 | 0.25 | 9 | 94.5 |

### 2.4.2 Mechanical Separation

Lois-Correa (2012b) investigated the efficiency of producing a quality fibre from two type of depithers machine namely; Horkel and S.M Caribe in Cuba. The efficiency of the machines was evaluated by looking at two parameters; mechanical and technological parameters as illustrated in (Tables 2.4 and Figure 2.3). Mechanical evaluation; vibration velocity and temperature in the rotor as it swings and rotor bearings. Technological evaluation was evaluated based on the fibre quality produced from depithed bagasse (Table 2.4).

**Table 2.4 Fibre quality comparison between the two types of depithers** (Lois-Correa, 2012b)

| **Parameters** | **Depither Horkel** | **Depither S.M Caribe** |
|---|---|---|
| Fibre in moist depithed bagasse % | 68.4 | 80.4 |
| Fibre in wet depithed bagasse % | 76 | 86 |
| Brightness degree % | 45.0-46.0 | 53.0-54.0 |

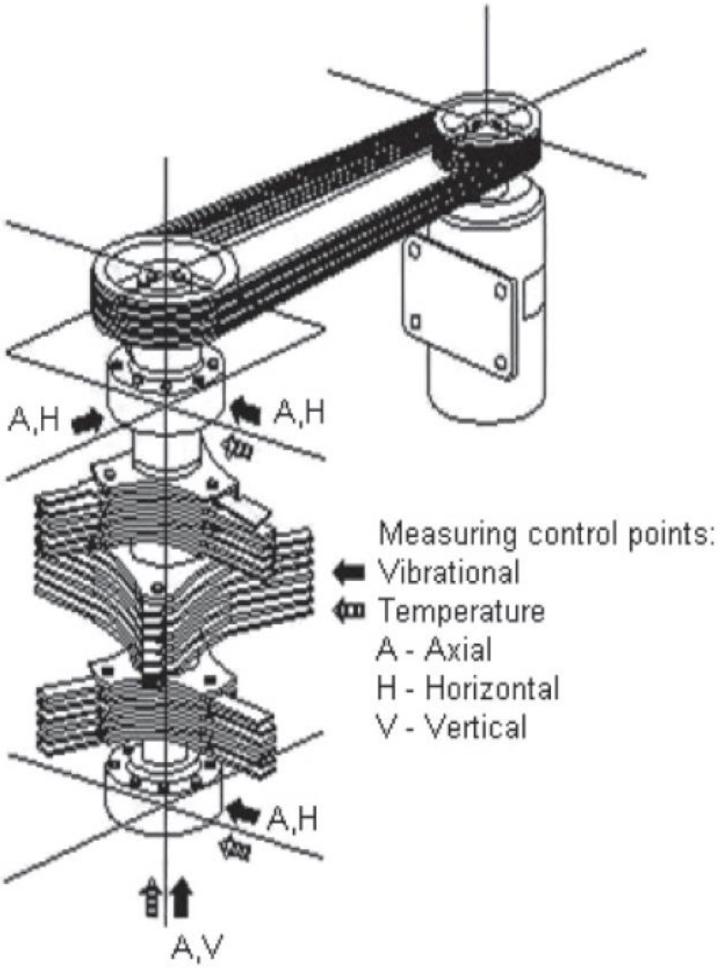

**Figure 2.3 Vibration and temperature control point in the vertical rotor** (Lois-Correa, 2012b)

Also Hansen (1955) conducted a study on the laboratory small swinging hammer depither, which yielded 35 percent of fibre (dry basis). The yield was observed after the discovery of moist bagasse being in a good state for biomass separation as reported by Lois-Correa (2012b), and further more being separated by water, were pith floats and fibre sinks on the bottom of the water. Both authors concluded that during screening and floatation, water circulation should be increased to better separate the pith from fibre after hammer beating. The similar technological technique is used to separate bagasse called wet abrasive technique reported by Lathrop *et al.* (1955) which lately was adopted by Lokhat and Bernhardt (2017) on the study of cleaning and drying of sugarcane bagasse. In both technologies the moisture of separated fractions and its quality also depends on: rotational speed of swinging hammer and drum, feed rate of the biomass and flow rate and temperature of the blowing air.

## 2.5 Bagasse as a Biomass for Energy Production

Biomass such as bagasse and its energy sources depends on its moisture, carbon, hydrogen, oxygen and ash contents (Mohammad and Kamruzzaman, 2011;Anukam *et al.*, 2016). There are however issues with the adoption and utilisation of bagasse as an energy feedstock due to its; low bulk density, low energy density, high moisture content and high metallic ion content (Tumuluru *et al.*, 2010). Also, there are issues of its heterogeneous size in weight, shape, particle orientation and storage related problems because of its high level of impurities. The afore-mentioned factors affect heat values of bagasse biomass but can be improved by the use of the entire sugarcane crop waste/raw material which are bagasse and straw/trash. Leal *et al.* (2013) studied the high heating value (HHV) of an entire sugarcane crop (bagasse and straw) per milligram (mg) and found out that the heating value is 7.4 GJ with 70 percent moisture content. However, the heat value of bagasse is reduced by the presence of high oxygen to carbon dioxides ratio. Anukam *et al.* (2016)'s comprehensive review indicated that bagasse have low metallic ion or inorganics which has been supported by Anukam *et al.* (2013) in another study.

Due to low inorganic or metal elements and emission of particulates which makes bagasse a good renewable and friendly energy biomass, its poor energy conversion technology and pre-processing brings drawbacks of bagasse in terms of the production of potential stored energy (Anukam *et al.*, 2013). For efficient energy conversion of bagasse, appropriate pre-processing technologies of sugarcane bagasse are to be implemented in order for it to be used as fuel thus overcoming all other negative factors which may affect its potential application and utilisation as an energy feedstock (Asagekar and Joshi, 2014). During the stockpiling of bagasse, its moisture holding capacitor can be reduced to approximately 43 percent by the removal of piths (Rainey *et al.*, 2013). However, Yadav *et al.* (2003) argue that piths contribute 93 percent of the total energy generated by bagasse and further indicated that fibres and epidermis contribute only 7 percent of the total energy. Therefore Rainey *et al.* (2013) further posited in their study that, removing pith from bagasse does not improve combustion properties. Nassar *et al.* (1996)

therefore conducted a study which proved that moisture has a significant role in high heat value, calorific value of 50 percent moisture of wet bagasse was found to be 2220 kcal.kg$^{-1}$ while for dry bagasse with 7.3 percent was found to be 4041 kcal.kg$^{-1}$. However, its energy content can also be improved by harvesting leaves and tops to add up in the energy generation for boilers (Smithers, 2014). The composition has different chemical and physical constituencies. Bagasse has low level of nitrogen and sulphur which makes it a potential biofuel (Nassar *et al.*, 1996). Also has a low net carbon dioxide per unit of energy produced as compared to coal (Beeharry, 2001). Bagasse as the energy source through briquetting in Uganda has the potential to reduce energy costs, promote cleaner energy for domestic cooking (Lubwama and Yiga, 2017). Sugarcane bagasse, is widely used in sugarcane mills as the source of heat and electricity generation (Canilha *et al.*, 2013).

But due to the high moisture content, low density, and low heating value, also the high cost accruals during transportation, handling and storage. To overcome all drawbacks, densification to briquettes which is discussed in section 2.6.4 is the solution for enhancement in order to be used as solid fuel (Felfli *et al.*, 2011). Nassar *et al.* (1996), studied the pyrolysis and combustion behaviour of bagasse which will be discussed in section 2.6.2. The results indicated that during combustion, the exothermic heat flow was reached at a lower temperature ranges between 280 and 520 degrees Celsius; while during pyrolysis, exothermic heat flow occurred between 300 and 600 degrees Celsius. This result indicates that, bagasse can supply heat and steam to sugarcane mill through combustion.

## 2.6 Different Technologies for Beneficiation of Bagasse

There are two technological categories at which sugarcane biomass can be useful. These technologies are: Thermo-chemical and bio-chemical processes (Mohammad and Kamruzzaman, 2011). Thermo-chemical pathways have four processes: combustion, pyrolysis, liquefaction, densification to obtain uniform properties (Anukam *et al.*, 2016) and gasification are the main thermo-chemical conversion technology for biomass (Wang *et al.*, 2008). Bio-chemical processes involve: anaerobic digestion and alcoholic fermentation. Sugarcane residues, bagasse and trash have been popular for biotechnological and non-biotechnological applications for the last three decades (Das *et al.*, 2004). There are major technological and economic challenges in the utilization of sugarcane biomass for value added commercial production such as: xylitol, organic acids, single cell protein, bioethanol and so on. The first being its physical properties and the second is the cost involvement in cleaning, drying and densification.

Bagasse can also be used as raw material for the cultivation of microorganisms for production of value added products. The microorganisms which mostly are used by food, medical and soil fertility industries. Srinivasan and Han (1969) presented the fact that bagasse has been used in the pulp and paper industry and in agriculture mulching for water conservation. This also produces methane gas during decomposition to release nutrients into the soil. In addition, during methane gas production through anaerobic digestion using bagasse as feed stock, a golden liquid, a by-product of methane gas is left in the digesters (Demirbas, 2010). The by-product is called slurry and it is rich in ammonia for nitrogen inputs and for agricultural nutrient recovery.

### 2.6.1 Gasification

Gasification is one of the most flexible technology for biomass conversion to clean energy (Jayah, 2002;Gustafsson, 2011). It is a thermochemical process which yields producer gas (Mohammad and Kamruzzaman, 2011). Mohammad and Kamruzzaman (2011) stated that gasification occurs at a temperature range between 500 to 800 ℃ while Anukam *et al.* (2016) contrary indicated that gasification of char of the biomass occurs at temperatures above 800 ℃ as illustrated in Figure 2.4. However, Figure 2.4 presented all the phases the biomass undergoes which varies from different temperature ranges up until the final stage of gasification of biomass char to yield a gas. Wang *et al.* (2008) indicated from their study that moderate moisture content in biomass is important for gasification. About 5 to 30 percent moisture content is good for gasification of biomass for economical operation of the gasifier. The moisture improves vapour for heat and mass flow in the reactor from different sections. The heat and mass flow occur in four stages which are: drying, pyrolysis and oxidation and reduction. The energy required in these processes can be exothermic or endothermic. The use of gasification system has endless benefit in; efficiency, environmental protection, feedstock flexibility, product flexibility, and carbon capture storage and utilisation. With the major product remaining the priority for the whole process.

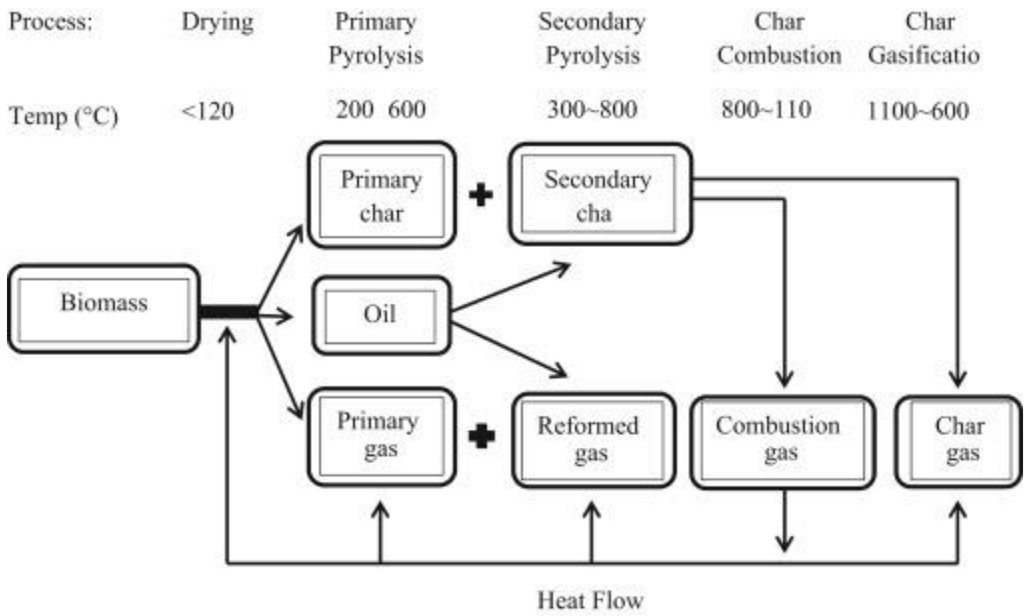

**Figure 2.4 Flow of temperature and mass from the gasification system** (Gustafsson, 2011)

For sugarcane gasification, the major products are: CO, $H_2$, $CH_4$, $CO_2$, $C_2H_4$, and $C_2H_6$ as illustrated in Figure 2.5. Ash is the final product at a lower rate temperature, more yields of char which has the effect on the producer gas is produced. Moreover, De Filippis *et al.* (2004) dwelt on an innovative technology of gasification of bagasse biomass using two stage reactor which does not produce tar and liquid hydrocarbons as end products. To eliminate the formation of tar during gasification, is to improve the efficiency and yields of gas formation.

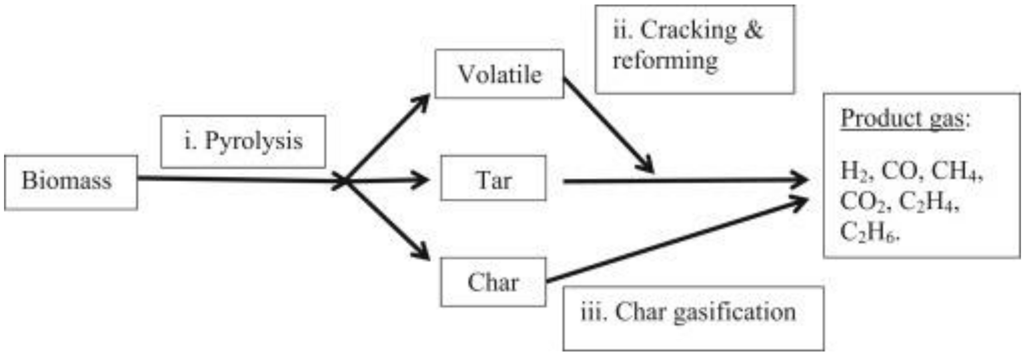

**Figure 2.5 Gasification process of sugarcane biomass** (Anukam *et al.*, 2016)

### 2.6.2 Pyrolysis

For biomass to be a worthy fuel for pyrolysis and gasification, it should possess high volatile, hydrogen content and have less fixed carbon content for less heat requirement for reaction (Mohammad and Kamruzzaman, 2011). During gasification, the second stage in the reactor is where the pyrolysis takes place at the temperature ranges of 200 to 600 °C. In the absence of air, this process is able to break the biomass to its char, tar, bio-oil and volatiles (Anukam *et al.*, 2016). The metallic ions in ash can be extracted using water washing method, for the gas and char to be used in boilers without corrosion problems. At the temperature range of 250 °C, the tar is formed in the bottom of the reactor. Further increase in the internal temperature above 600 °C, the tar trickles into hydrocarbons gas where methane gas is formed (Islam *et al.*, 2003). The quality of gas and char produced depends on many factors and since 80 to 95 percent of the feedstock biomass is converted to liquid phase, this becomes possible. The quality factors are: gas resident time, particle size of the material, temperatures of the system, and heating rate which also determines the rate of reaction. In the experimental process, the thermo-gravimetric analysis (TGA) gives important information about overall pyrolysis of the biomass for characterisation.

### 2.6.3 Liquefaction

Liquefaction requires high moisture biomass at a temperature up to 350 °C at pressure of 200 atm with processing time in minutes (Canilha *et al.*, 2013). Moderate temperature and high pressure characterised the process for the production of crudes like oil; in biomass, bio-oil is the main product. The biomass is broken down into fragments and degraded to smaller compounds by deoxygenation, dehydration, dehydrogenation and decarboxylation, also thermal depolymerisation (Demirbaş, 2000). The product output for liquefaction is liquid oil, bio fuels, bio chemical, hydrogen and alcohols.  Products can be also converted to hydrocarbon fuels and other commodity chemicals. High ash content and rigid cell wall structure affect liquefaction yields in biomasses such as bagasse due to high fibre content. However, for bio-chemical conversion, fermentation and anaerobic digestion can be utilized to produce biogas (Mohammad and Kamruzzaman, 2011).

### 2.6.4 Densification

#### 2.6.4.1 Extrusion

Since briquetting is the process of subjecting biomass residue under mechanical stress through compression, it is necessary to adopt the technology as an effective conservation strategy (Sapariya *et al.*, 2010). In 1880, the United States was the first country to patent biomass densification issued by William Smith. They are two widely used technologies for biomass densification which is pelleting and briquetting. Briquetting is more flexible in terms of biomass type and physical properties of biomass; such as particle size and high moisture content biomass. While pelleting is not suitable for any biomass which also requires binder to form pellets. Briquetting technology has diverse types including screw press as illustrated in Figure 2.6 which requires and consumes high energy due to compressing and pushing of biomass at a compaction ratio of 2.5:1, which increases its specific energy requirements (Sapariya *et al.*, 2010). Pellet mill has a lower specific energy requirement compared to screw press. Pretreatment is used to improve energy savings during the process (Tumuluru *et al.*, 2010). Pelletization and briquetting are called binder less, because of high pressure compaction. Screw press and piston press are the widely used method for pelletization and briquetting with a standard size of briquette of 60 mm in diameter due to high pressure which further results in temperature rise within biomass particles (Sapariya *et al.*, 2010).

Densification of loose biomass is usually done using mechanical, hydraulic method as detailed in section 2.6.4.2, and roller presses (Tumuluru *et al.*, 2010). The final product, briquette is regarded as clean and green fuel and can be used in furnaces, open fires, and boilers. The briquette machine handles high moisture and lager particle size biomass. It can densify the biomass without any binder. Tumuluru *et al.* (2010) indicated that briquetting the biomass improves its calorific value; its use in furnace designs for other fuels, reduce particulate emissions from biomass, and promotes uniform shape and size (homogeneous) and makes it easy for design of boilers. But, the main disadvantage of briquetting is the production of ash as by-product during combustion process in boilers due to alkali content in biomasses. However, in sugarcane bagasse, alkali content is below the thresholds as compared to other biomasses such as rice husk because of short grassy nature (Garivait *et al.*, 2006).

To reduce energy requirement during densification and improve binding strength of the briquette, the biomass can be pre-heated at the temperature of 100 to 130 degrees Celsius and moisture adjusted between 10 to 12 percent. This further improves bulk density of biomass ten folds.

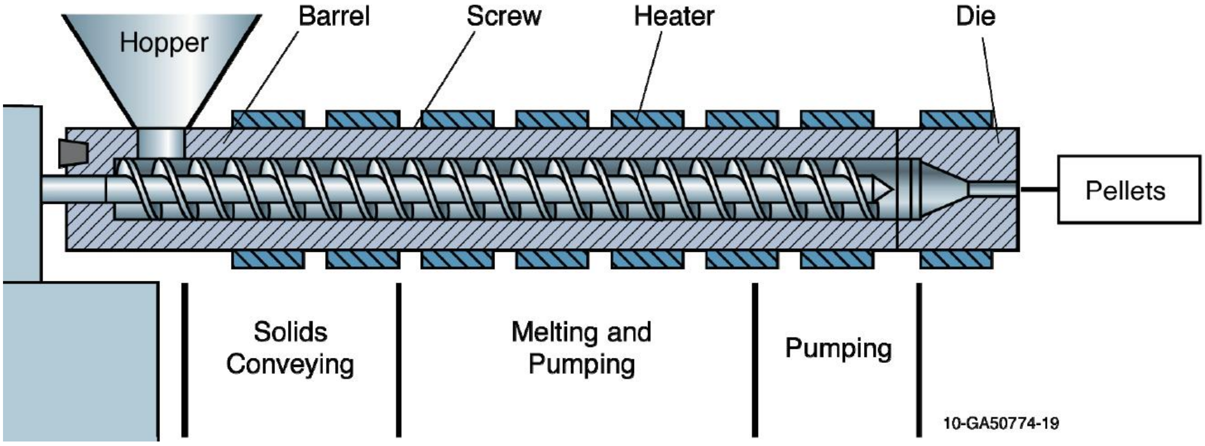

**Figure 2.6 Extruder briquetting machine** (Tumuluru *et al.*, 2010)

Comparing screw press and piston press, wear of part and high maintenance cost is observed in screw press due to shear of biomass and extruded through a heated tapered die. But briquette logs produced are highly efficient in combustion (Figure 2.7). Due to increase in the surface area with the center cylinder in the briquette, ignition is improved and enhanced.

**Figure 2.7 Briquette produced using an extrusion machine pre**ss (Tumuluru *et al.*, 2010)

Because biomass is renewable and a sustainable energy feedstock, most countries are harnessing these potentials with all intents and purposes. In Europe and America, there have been in strategies embarked upon in energy production from biomass to the market (Tumuluru *et al.*, 2010). To combat global warming due to exponential increase in the energy demand as a result of economic development, the need to inject biomass resources into the energy stream becomes very necessary if not crucial. This furthers the idea and strategy that, Africa also requires to venture and key into the different technological evolution in terms of harnessing biomasses as energy resource. African countries are blessed with natural resources and produces diversities of biomasses which can be used as the pools to end poverty and energy insecurity within the eco-economic systems.

#### 2.6.4.2 Hydraulic Piston Pump

They are two types of piston press, Punch technology and Hydraulic press (Sapariya *et al.*, 2010). The Punch technology produces briquette of 60 mm in diameter with power requirement of 20 kW for 700 $kg.hr^{-1}$ compression capacity. Hydraulic piston briquette machine is the widely used for small scale biomass densification due to its compactness and low input levels (Anukam *et al.*, 2016). Sapariya *et al.* (2010), showed that, the mechanical piston press can have a compression capacity up to 1800 $kg.hr^{-1}$, with power requirement of 37 kW for briquetting. The energy to the piston is transferred by the electrical motor to the high pressure hydraulic system with a lower compression pressure ranging from 40 to 135 $kg.hr^{-1}$ for hydraulic piston press (Tumuluru *et al.*, 2010). Its operation is based on the fluid-pressure transmission based on Pascal's law. Due to lower compression capacity, the hydraulic piston press produces a briquette with bulk density less than 1000 $kg.m^{-3}$. However, the hydraulic piston press (Figure 2.8) allows biomass with moisture content greater than 15 percent, unlike mechanical piston press which requires biomass at a moisture content less than 10 percent (Anukam *et al.*, 2016).

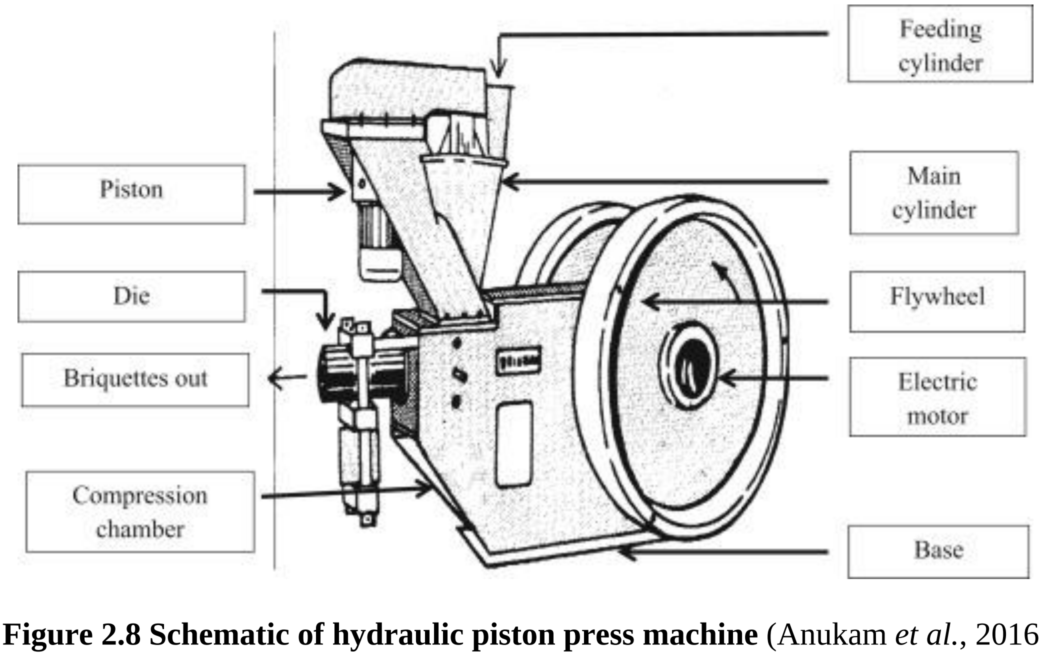

**Figure 2.8 Schematic of hydraulic piston press machine** (Anukam *et al.*, 2016)

The briquettes (Figure 2.9) are realised from the die with a relatively warm temperature and very fragile, before can be cut into desirable size, cooling is vital to improve it strength (Sapariya *et al.*, 2010). The main advantage of this machines is its daily service, which is limited, with the die, piston and cylinder which are wearing parts and requires servicing for the best performance of the machine. The estimated service life of this parts ranges between 500 to 1000 hr.

**Figure 2.9 Briquette made from hydraulic press machine** (Anukam *et al.*, 2016)

#### 2.6.4.3 Mechanical Piston Press

Mechanical piston press is the commercial scale briquetting machine with a briquetting capacity of 200 to 2500 kg.hr$^{-1}$ (Figure 2.10). It requires power of about 40 kW in the average (Sapariya *et al.*, 2010). The compression ranges from 110 to 140 MPa, under high fraction which in combination rises the temperature of the biomass and the lignin melts which originally acts as the binder. There is continuous eccentric rotation connected to a plunger to compress biomass material, but the compression capacity can be only manipulated through modification of conic die size (Anukam *et al.*, 2016). The diameter of die ranges from 40 to 125 mm and determine briquettes quality parameters. The compression occurs twice; from vertical direction (pre-compression) and again in the horizontal direction (Anukam *et al.*, 2016). In the mechanical piston press machines, the energy is transmitted through electrical motor instead of hydraulic motor which gives it a good performance and greater life span on operation than hydraulic piston pump (Rasul *et al.*, 1999a). Also mechanical piston press yields greater investment returns. The industrial setup of mechanical piston press machine is as illustrated in (Figure 2.11).

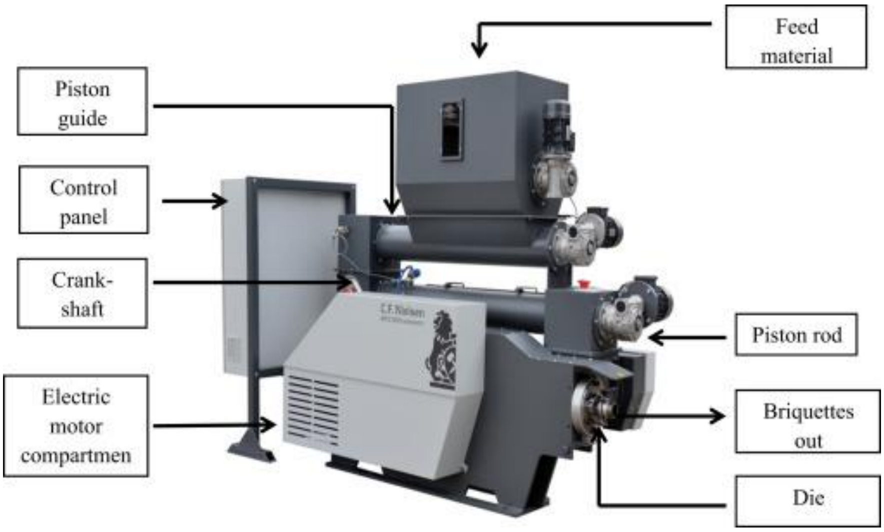

**Figure 2.10 Mechanical Piston press briquette machine** (Anukam *et al.*, 2016)

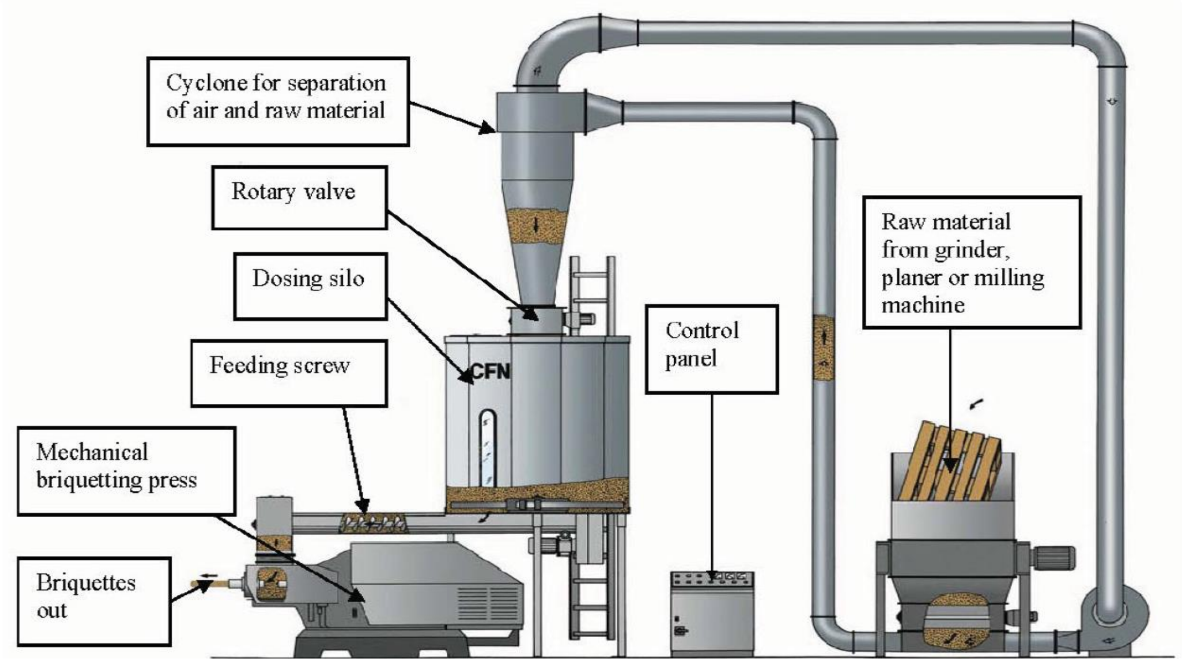

**Figure 2.11 Continuous mechanical piston press in the industrial configuration** (Tumuluru *et al.*, 2010)

### 2.6.4.4 Roller Press

Tumuluru *et al.* (2010) presented a roller press biomass densification machine which uses compression (pressure) and agglomeration principles (Figure 2.12). This was developed in the early 1870 by Johanson and Pietsch. Sapariya *et al.* (2010) indicated that the roller press was mainly used for carbonised biomasses. They developed it based on the understanding of the behaviour of granular solids within a rotating roller (Yehia, 2007). Roller press densification has the design parameters which play major roles in the quality of the products. The parameters are: diameter of rollers, the roller force, the shape and the width of the die, also the width gap between rollers which rotates in the horizontal axis in the opposite direction (Anukam *et al.*, 2016). The roller press activates solid bridge, chemical bonds, and electrostatic force to form a larger size granular from smaller size granular due to compression and rise in temperature (Yehia, 2007).

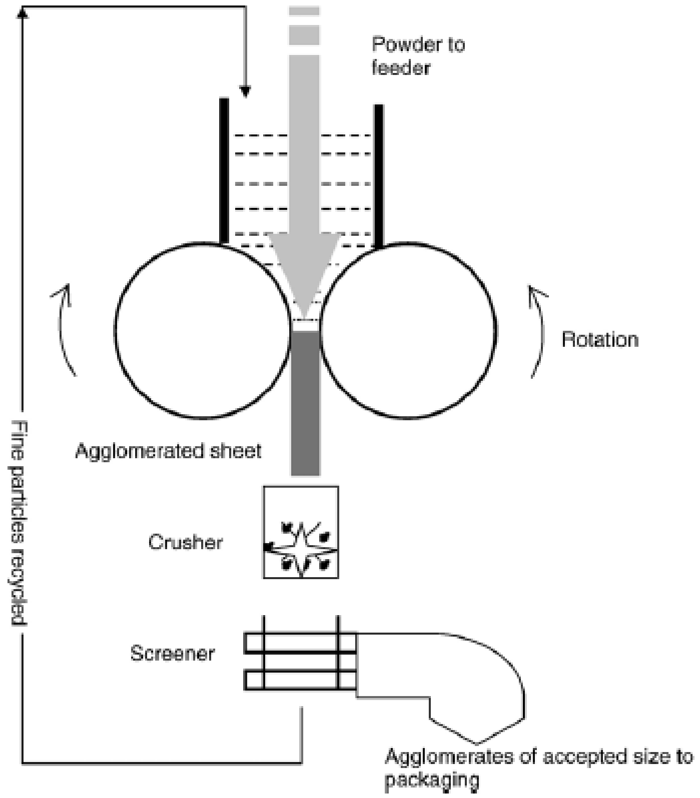

**Figure 2.12 Compression and Agglomeration roller press machine** (Yehia, 2007)

The distance between the rollers (the gap) is determined by the physical and chemical properties of the biomass. Properties such as: type of biomass, the moisture content, the particle size and addition of the binder (Sapariya *et al.*, 2010). During the process, the output sheet product (pillow-shaped briquette) is used for agglomeration and the finer particle are reused back to the feeder only in the case of briquetting (Figure 2.13). Table 2.5 illustrates the magnitude of the moisture content, particle size and type of binder and at what concentration does roller press produces quality agglomerates.

**Figure 2.13 Briquette made from a pallet mill sheet** (Sapariya *et al.*, 2010)

For different densification technologies, different biomass physical characteristics are required by different densification technologies (Table 2.5). Due to different pressure and heating of biomass, several briquette energy properties differ from different biomass densification. Dissimilar in densification technology from different biomasses due to variation in physical properties gives briquettes produced different properties for different energy applications.

**Table 2.5 Comparison of different densification technology on performance** (Anukam *et al.*, 2016)

| **Performance parameters** | **Piston press** | **Screw press** | **Roller press** |
|---|---|---|---|
| Optimum moisture content of material | 10–15% | 8–9% | 10–15% |
| Particle size of material | Larger | Smaller | Larger |
| Wear of contact parts | Low | High | High |
| Output from machine | In strokes | Continuous | Continuous |
| Specific energy consumption (kW h/t) | 37.4–77 | 36.8–150 | 29.91–83.1 |
| Throughputs (t/h) | 2.5 | 0.5 | 5−10 |
| Density of briquettes/pellets | 1000–1200 kg.m$^{-3}$ | 1000–1400 kg.m$^{-3}$ | 600–700 kg.m$^{-3}$ |
| Maintenance | Low | High | Low |
| Combustion performance of briquettes | Moderate | Very good | Moderate |

## 2.7 Properties of Briquettes

Mohammad and Kamruzzaman (2011) highlighted that briquette technology increases volumetric calorific values of the densified loose biomass; which further improves or motivates biomass utilisation as an energy feed stock. But the major densification variables which play significant role are: pressure, die temperature, and die geometry which enhances briquette quality (Shaw, 2008). Briquetting of biomass residue is defined by residue availability, adequate technologies and the market for briquettes (Felfli *et al.*, 2011). For appropriate densification technology to be adopted, the quality attribute used to be evaluated are: density, durability, and heat value of the briquettes for the suitable densification variables. Bagasse briquetting is made from grounded bagasse to increase its inter force (binding strength). However, bagasse can be charred to increase carbon content and reduce moisture and to enhance its heat value. Purchase *et al.* (2014) reported that briquetting is not economically viable for large scale industry since it is very expensive to produce. Tumuluru *et al.* (2010) presented the work of extruded hard and soft wood with its results illustrated in Tables 2.6 and 2.7. Some energy properties are being improved due to briquetting which indicates the importance of briquette technology in waste management, energy security, and for environmental benefits.

**Table 2.6 characteristics of bagasse before and after densification (briquette)**

| **Characteristic** | **Bagasse** | **Bagasse based briquette** | **References** |
|---|---|---|---|
| Calorific Value | 400 Kcal.kg$^{-1}$ | 4080 Kcal.kg$^{-1}$ | (Sapariya *et al.*, 2010) |
| Moisture content (M) | 45-55 % by weight | 5-5 % by weight | (Sapariya *et al.*, 2010) |
| Bulk density | 153 kg.m$^{-3}$ | 258 kg.m$^{-3}$ | (Anukam *et al.*, 2016) |

**Table 2.7 Effect of extruding the bagasse biomass to improve energy properties** (Anukam *et al.*, 2016)

| **Material prior to extrusion** | |
|---|---|
| Moisture content | 8 % by weight |
| Average particle size | 2-6 mm |
| Bulk density | 200 kg.m$^{-3}$ |
| Calorific value | 17.8 MJ.kg$^{-1}$ |
| Ash content | 2-10 % |
| **After extrusion** | |
| Moisture content | 4% |
| Bulk density | 1400 kg.m$^{-3}$ |
| Calorific value | 19.53 MJ.kg$^{-1}$ |
| Ash content | 2-10 % |

## 2.8 Uses of Briquettes

Agro-wastes biomass in their loose condition poses difficulties associated with application as solid or liquid fuel source for domestic and industrial purposes. But when these biomasses are compacted or densified, the resultant solid mass possesses better fuel properties and quality. These are called briquettes. Oladeji (2010) studied the potential of rice-husk and corncob briquettes to be applied as biofuel for heat generation for domestic and industries cottage, the combustion and burning characteristics are presented in (Table 2.8). This was motivated by the drastic increase of gas and kerosene price in the market and so the need to use biomass briquettes was conceived. After the result, the conclusion was made that; both biomasses have the potential to be used as source of heat energy or generation. However, corncob displayed itself as a better fuel than rice husks. Rice-husks and brans have 10 to 23 percent oil content by mass, which makes it a good source of combustion fuel (Yank *et al.*, 2016).

**Table 2.8 Combustion and burning characteristic** (Oladeji, 2010)

| | | Briquettes | |
|---|---|---|---|
| Parameter | Unit | Rice Husk | Corncob |
| Moisture Content | % | 12.67 | 13.47 |
| Compressive strength | kN.m$^{-2}$ | 1.07 | 2.34 |
| The heating value | kJ.kg$^{-1}$ | 13.389 | 20.89 |
| Initial density | Kg.m$^{-3}$ | 138 | 155 |
| Maximum density | Kg.m$^{-3}$ | 524 | 650 |
| Relaxed density | Kg.m$^{-3}$ | 24 | 385 |
| Density ratio | | 0.45 | 0.59 |
| Compaction ratio | | 3.8 | 4.19 |
| Relaxation ratio | | 2.22 | 1.7 |
| After glow time | s | 354 | 370 |
| Flame propagation rate | cm.s$^{-1}$ | 0.1 | 0.12 |

Yank *et al.* (2016) also investigated the use of rice-husks in producing low pressure briquettes with the intention to substitute the use of fuelwood in West Africa. The result indicated the good potential of rice-husks as fuel source. Furthermore, the physical and fuel properties was measured such as; density, moisture content, calorific value, durability, and compressive strength with variation in the type of binder and quantities used. The rice-husk presented a high calorific value of 16.08 $MJ.kg^{-1}$ as cooking fuel. Purohit *et al.* (2006) discuss the economic feasibility of substituting coal based application in industries for energy generation with biomass briquetting technology. The conclusion was made with biomass that; it is not energetically viable to be adopted as industrial source of fuel due to its low energy density as compared to coal and other conventional sources.

But it can be used, however the quantity of biomass briquettes is estimated to be eight times as compared to coal to produce the same amount of energy per unit mass of coal. Bazargan *et al.* (2014) since the palm oil is widely used all over the world as edible oil, its production has increased which produces more waste of palm kernel shells (PKS). PKS has been used as a source of energy for steam and electricity generation (Bazargan *et al.*, 2014). Because of its better heating value (HV) and high heating value (HHV) of 17.4 $MJ.kg^{-1}$ and 23.0 $MJ.kg^{-1}$ respectively as compared to other biomass fuels. The use of PKS is used by a Hong Kong based company through gasification using bubbling bed reactor and the by-product biochars produced through densification. A lot of studies have been conducted on the application of briquettes as a source of energy and as the pre-processing technology of biomass to archive high volumetric heat value, the studies was done by Klock *et al.* (1957);Hart (1977);Baron *et al.* (1982);Lask (1993).

Besides, being used by industries, briquetting can also solve energy problem in households located in rural areas and townships in African countries. Other applications of briquetting technology was presented by Pilusa *et al.* (2013a) on eco-fuel briquetting made up of 32 percent coffee grounds, 23 percent coal fines, 11 percent saw dust, 10 percent waste papers, 18 percent mielie and 10 percent paper pulp. The eco-fuel briquette outcome indicated that it can solve historical lack of access to electricity especially in South African townships, where heating for cooking still comes from conventional sources of energy that are not eco-friendly.

## 2.9 Chapter Summary

From the literature covered in this study, the study has provided informative incursion on sugarcane crop production of high biomass yields per hector and potentials as a rich solar reservoir crop. It has the potential to generate energy at a rate of 0.5 to 2 GJ ha$^{-1}$ from its trash and bagasse after sucrose extraction. Harvesting technique of sugarcane crop in the fields play a significant role in overall biomass (trash and bagasse) generation. Overall, sugarcane biomass has low micro pollutants and particulate emission during thermochemical conversion. However, chemical and physical properties of sugarcane crop vary with: agro industrial processing type of cultivar, geographical location and climatic condition (s). From bagasse biomass fractions, a wide range of particle size and shape gives bagasse heterogeneity. The literature indicated that they are no traditional method employed to determine the particle size of biomass. From its micro and macro structures includes waxes, metallic ions, and acidic substances. Bagasse biomass is not limited only as energy co-generation feedstock, but is also utilized for: pollutant absorbance, improving soil physical and chemical properties. Also, apart from thermo-chemical conversion technology being utilised to quantify energy from biomass its biotechnology is also used. During combustion of bagasse biomass, ash consists of silicon which can be used in construction as the cementing agent is obtained. Ash analysis is important in energy conversion processes and from energy transfer. Biotechnology reduces the formation of ash as the by-product which negatively affects energy quantification and transfer from biomass. Bagasse separation can be mechanical or physical where fibre quality produced depends on the technique(s) employed. Moisture content and quality of depithed fibre as well depends on:

1. Rotational speed
2. Feed rate
3. Flow rate and temperature of blowing air

Physical properties of bagasse biomass are mainly determined by its chemical constituency of carbon, hydrogen, nitrogen, oxygen, and sulphur. For oxidation of bagasse biomass, hydrogen and carbon element is vital for heat generation only in oxygen reduced environment. This brings about lower bulk density and energy density of bagasse biomass as compared to coal. Bagasse biomass has low trace element as compared to forest biomass and short grasses. Energy quantification in biomass can be analysed using an instrument called bomb calorimeter or by the use of equations when elemental analysis information is present. Thermo-chemical conversion through combustion proves to be good for adequate heat supply for sugarcane mill through exothermic reaction. Also, gasification seems like a flexible technology conversion to clean energy. Besides, among densification technologies, briquetting is the most flexible technology for diverse biomass types and properties. Lastly, pre-treatment is vital in biomass energy conversion systems in order to reduce energy requirements and cost of operations.

From the literature, the following gaps have been identified in energy generation using biomass as the feedstock:

1. Utilization of biomass for energy generation has not shown global success from previous years mostly in South Africa.
2. Adoption problem and high investment cost associated with it.
3. High recovery cost for sugarcane biomass in; transportation due to bulkiness, storage, and briquetting for commercial purposes.
4. The high cost of briquetting machines for small and larger scale productions.

In general, the use of biomass as bio energy feedstock can address the energy insecurities in developing nations in Africa. All head of states should begin to invest in the manufacturing of facilities for thermo-chemical conversion technology and also give access to rural communities to afford to buy and utilize the technology. The historical disadvantaged access to electricity in South Africa has not been solved in 25 years of democracy. It has become the major issue even with power uncertainty of the major energy supplier, Eskom and to meet the electricity demand for the exponential population growth in South Africa. Therefore, biomass energy conversion systems and utilization are required to complement the energy need of the country.

# CHAPTER THREE: SUGARCANE ADVANCEMENTS AND PROPERTIES

## 3.1 Sugarcane Industry

### 3.1.1 History

The sugar as an agricultural commodity was first produced from sugarcane (*Saccharum officinarum*) (Ballinger, 1978). Sugarcane is the genus with 37 species and it is a member of the grass family (Santos *et al.*, 2015). Sugarcane was used as a source of food by the natives in its original country, sugarcane originated in the islands of the South Pacific in India in 800 BC (Pandey, 2007;Sahu and Chaudhari, 2015). In India, sugarcane is known as *Iksu,* Aryans knew the crop at a very early times, this evidence is supported by the word *Iksu* which has no differences from other Indo-Aryan language (Pandey, 2007). Galloway (1977) also explained the sugarcane industry evolution for Mediterranean region history. The cultivation of sugarcane in India drew attention to the Greek visitors in India, which they called "reeds that make honey without the agency of bees" (Ballinger, 1978;Pandey, 2007).

After sugarcane has been discovered as a sugar commodity, its spread from South Pacific to South Eastern Asia was supersonic then eastwards to India, the Philippines, Hawaii, northward to China, and to other places of the world. The first production of sugar from sugarcane began in India in the 4th and 6th century AD and from the 7th century, China and Persia had learnt the systematics of sugar processing (Sahu and Chaudhari, 2015). Before the discovery of America, it took a lapse of 2000 years for sugarcane to be processed to sugar, and to spread out of India to the Industry of Africa. The knowledge of sugarcane and sugar in Greece was brought by the invasion of India by Alexander, but it took another thousand years for the Europeans to have the knowledge of sugarcane and sugar. But in the twentieth century, the major sugarcane producing countries is Brazil, China, Mexico, Thailand and Mexico (Pandey, 2007). However, Sahu and Chaudhari (2015) presented the current tonnes produced and area under cultivation for sugarcane from various parts of the world for the year 2012 to 2013.

Table 3.1 illustrate this. In Brazil and India, sugarcane has accelerated pace of rural industrialization with over 553 registered sugar factories in India. But in India and other parts of the world with sugarcane industries, effluents during the crushing season result in negative environmental pollution. The sugarcane industry consumes 1500 to 2000 $dm^3$ of water to generate 1000 dm$^3$ of wastes per tonne of sugarcane crushed (Sahu and Chaudhari, 2015). However, not only influences but also produces solid wastes as by product called bagasse which has a major challenge of handling, conservation and storage. This can be turned to reliability by developing nations such as Africa.

**Table 3.1 The million tons produces and productivity of sugarcane in various part of the world (2011 to 2012**) (Sahu and Chaudhari, 2015)

| **Country** | **Area (million/ha)** | **Production (million/tons)** | **Productivity (Tons/ha)** |
|---|---|---|---|
| Brazil | 3.34 | 386.2 | 72.3 |
| India | 4.61 | 289.6 | 62.8 |
| China | 1.34 | 92.3 | 65.5 |
| Thailand | 0.97 | 64.4 | 66.4 |
| Pakistan | 1.09 | 52 | 47.9 |
| Mexico | 0.64 | 45.1 | 70.6 |
| Colombia | 0.43 | 36.6 | 84.1 |
| Australia | 0.42 | 36 | 85.1 |
| USA | 0.4 | 31.3 | 77.5 |
| Philippines | 0.38 | 25.8 | 67.1 |
| Indonesia | 0.35 | 25.6 | 73.1 |
| Cuba | 0.65 | 22.9 | 35 |
| South Africa | 0.32 | 20.6 | 63.4 |
| Argentina | 0.29 | 19.2 | 65.2 |
| Myanmar | 0.165 | 7.5 | 45.4 |
| Bangladesh | 0.17 | 6.8 | 41.2 |
| WORLD | 20.42 | 1333.2 | 65.2 |

Southern African countries has the great potential for the expansion of sugarcane crop, which are: Malawi, Mozambique and Zambia. But also, Central African countries have the potential for growing sugarcane crop but since the region is under forest cover, it is nearly impossible for commercialisation and energy conversion strategies (Santos *et al.*, 2015).

## 3.2 Sugarcane as a bioenergy crop

After sugarcane has been used as a food resource by sugar extraction, its bio-products and secondary processing products can be harnessed for energy. In the 1920's, Brazil began to produce bioethanol by establishing the institute of sugar and alcohol. Due to the first oil price crises of 1973 which stimulated the drive for developing and improving alternative energy sources viz a viz bioethanol production from sugarcane and other energy crops. In 1978, Brazil redesigned the car engines to use bioethanol and gasoline mixtures as fuels in any form. Between 1980 to 1998, sugarcane production in Brazil blossomed from 73 to 90 tonnes of stems per hectare per year due to double demands (food and bioenergy). Also, the efficiency to extract sugar juice increased from 90 to 96 %, sucrose (sugarcane juice) fraction of the sugarcane crop is only a third of biomass, while bagasse and leaves contribute other two thirds at an accumulation rate of 550 kg.ha$^{-1}$.day$^{-1}$ under rain fed system. Physiology of the crop is vital for energy potential of the crop. To understand the physiology of the crop from the energy point of view, it is important to understand photosynthesis and energy source and sink relationships to effectively link up the utilisation of energy in the biomass fraction for generation using different methods such as biochemical and thermochemical conversion methods. Sugarcane crop is considered as C4 plant. C4 plants operate optimally under high temperature regions with greater water use efficiency, high carbon dioxide exchange and greater biomass yields (Santos *et al.*, 2015). The biomass yields also maximised by employing mechanization form of harvesting of cane in the field. However, without compromising the effect of sucrose concentration, it contributes greatly in driving cogeneration of heat and electricity from cane trash and bagasse after crushing.

## 3.3 How Sugarcane was selected as a Bioenergy Crop

Sugarcane crop was selected based on the typical average of its sucrose, biomass yields, regeneration capacitor and fibre it can produce. Average composition is 24% for sucrose and 14% for fibre. It is estimated that sugarcane cultivars contain 50% of sucrose content of the cane dry mass. It has been proven that, using the energy present in the sugarcane cell wall is expected to increase by 40% for bioethanol based production in few years which also includes bagasse for thermochemical conversion (primary biofuel) (Pandey, 2007). Additionally, due to the high efficiency of solar energy conversion for sugarcane, bagasse is rich as a solar energy reservoir therefore there is high yields of 80 t.ha$^{-1}$ and regeneration capacity of two years in comparison with other agricultural residues, like trees, grasses, and wheats (Canilha *et al.*, 2013). Although electricity and ethanol generation from sugarcane is the main coproduct which draws the attention but they are other commercial products whose market value is likely to grow.

Many household and industrial products such as corrugated boxes and furfural are made from sugarcane fibres. Sugarcane flexibility and its diversity as a renewable energy resource can support industrial development, economic growth and promote poverty reduction in mostly African countries which also qualifies it as a bioenergy crop with substantial sustainability (Grover and Mishra, 1996;de Souza *et al.*, 2014). With most car engines modified to use bioethanol as fuel, the output of the engine is estimated to be between 65 and 80 percent power with high emission reduction as clean fuels as compared to the present ones powered by gasoline (petrol).

## 3.4 Technological Advancement

### 3.4.1 Sugarcane Factory Technology

The technology development in sugarcane industry includes improving cane harvesting and machinery for quicker regrowth in the field, minimising replanting and crushing for batter biomass quality (Pandey, 2007). In biorefinery factories, the new technology development is aimed on improving: (1) Lignocellulosic feedstock, and its pre-treatments for effective separation of lignin, cellulose and hemicellulose, (2) Improvement in chemical, thermal and mechanical processes, (3) development of biological processes, and (4) further combination of biotechnological and chemical processes (Chakraborty *et al.*, 2012).

A complete sugarcane processing infrastructure set-up in industry consist of configuration of ethanol distillery, the cogeneration plant and an co-product facilities if necessary (Santos *et al.*, 2015). Most sugarcane factories were using roller mill for crushing the cane and extracting juice. Alternatively, diffuser is also used were extraction of cane juices are extracted by washing the cane to release sucrose.

Co-generation plant can be installed only if the sugar factory processing capacity is adequate and efficient enough to produce bagasse for heat and electricity. The surplus of heat and electricity generation from sugarcane biomass is mainly dependent on steam economy, energy conservation measures and the instrumentation used. Bagasse cogeneration plant in Africa are still using back pressure turbine which generates ten times less surplus electricity as compared to condensing extraction steam turbine (CEST) which to be transmitted to the grid systems. Countries such as India, Mauritius, Brazil employ condensing extraction steam turbine to export surplus electricity to the grid system during harvesting time (Ensinas *et al.*, 2006a). In Brazil, a total of 2300 MW of electricity is produced from bagasse which is sufficient for energy as a requirement and for in situ application for the sugarcane factories (Ensinas *et al.*, 2006a).

The previously used cogeneration systems were of low efficiency cogeneration steam which operates with a 22 bar of pressure and 300 °C based on stream cycle. The new cogeneration systems having a steam cycle which operates at up to 60 bars of pressure in the industrial configuration layout is illustrated by Figure 3.1. The use of more efficient cogeneration systems confers the benefit of reducing the thermal energy demand in the production systems.

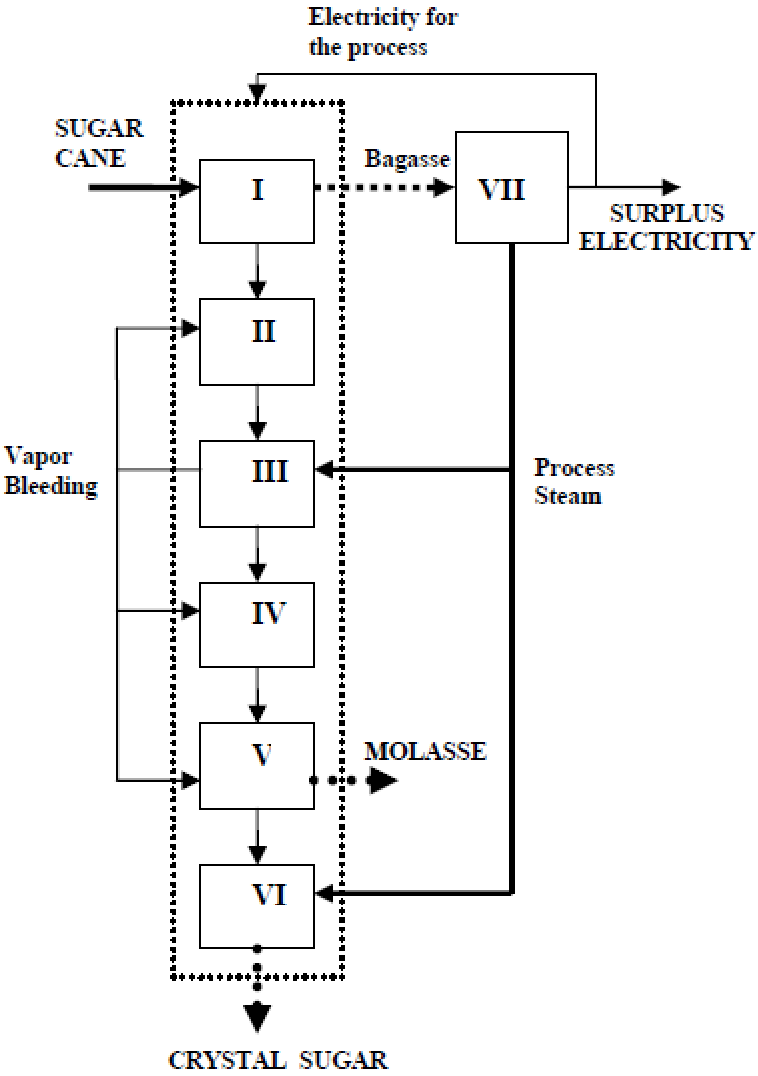

**Figure 3.1 Sugarcane processing layout configuration with a cogeneration plant** (Ensinas *et al.*, 2006b)

The method of reducing stream demand during sugarcane processing was proposed by Ensinas *et al.* (2006a), with the aim of generating sufficient steam and electricity for sugarcane processing in addition to excess electricity generation. Surplus electricity will be sold to the grid systems. The processes that steam demanding in the refinery operations are: during raw juice clarification, evaporation of water from clarified juice, during syrup treatment, boiling, crystallization and centrifugation where molasses are obtained, and also drying of the final crystal sugar. But the effect of reducing the demand steam during the process was archived by introducing new equipment through manipulating and allocating different processes from the four vapour bleeding processes (1st, 2nd, 3rd, and 4th effects of evaporation). The overall result in the two case studies presented in Table 3.2 indicated great improvement from before (case1) and after (case 2) under saturated steam at 210 kPa. Case 1 represent the base average of the typical thermal energy used in sugar production factory which characterised by high steam demand. Case 2 was implemented for steam demand reduction which was archived by introducing new equipment and configuration the detail of configuration is covered by (Ensinas *et al.*, 2007).

**Table 3.2 Process steam demanded from before and after the new techniques and equipment's has been introduced** (Ensinas *et al.*, 2007)

| | Steam demand (kg steam.t$^{-1}$ cane) |
|---|---|
| Case 1 | 470 |
| Case 2 | 335 |

Different vapour bleeding is done on four different configurations that are normally used or that can be used by any sugarcane factory to generate surplus electricity for the grid. The first configuration is the steam cycle with back pressure (Figure 3.2), the steam is produced by the boiler. Configuration 2; Rankine cycle with condense extraction steam turbine (CEST) (Figure 3.3) with a condenser, which offers more options for operations and flexibility for the plant.

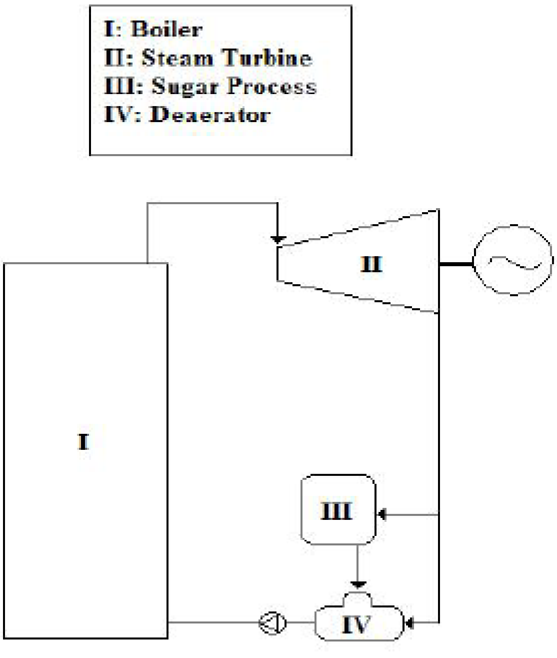

**Figure 3.2 Steam cycle back pressure schematics configuration** (Palacios-Bereche, 2013)

Configuration 3; the gasification of bagasse to syngas which are used as fuel in a gas turbine (Figure 3.3), the thermal energy from the exhaust gases are used to generate steam in a heat recovery steam generator (HRSG).

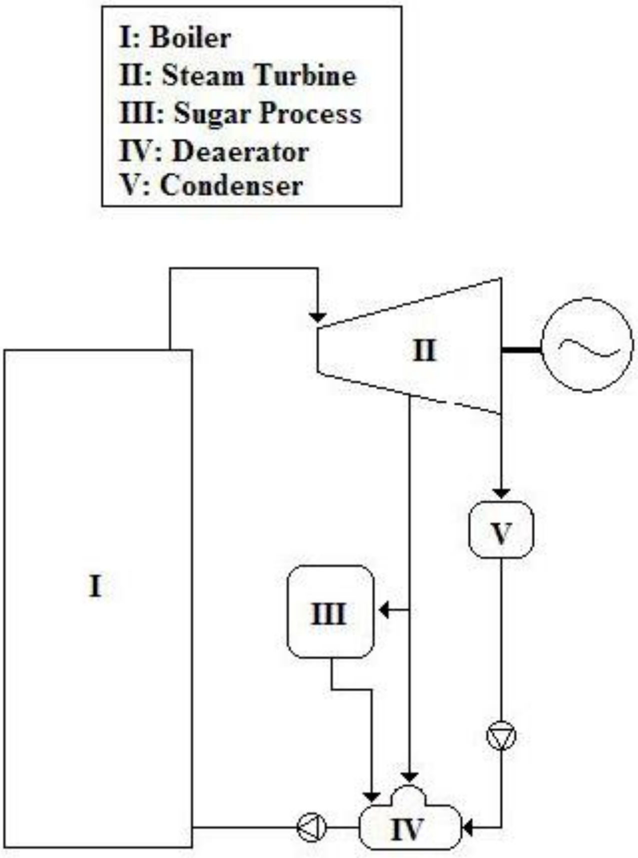

**Figure 3.3 Rankine cycle schematics with CEST configuration** (Palacios-Bereche *et al.*, 2013)

The last configuration, the sugarcane factory can operate with is illustrated in (Figure 3.4 and Figure 3.5), which operates with gasifier bagasse producing fuel for gas turbine. The thermal energy from the exhaust gas are used in two ways, firstly: the lower pressure is used by sugarcane processing, second; used by stream turbine back pressure at a high pressure, with the exhaust steam used in sugarcane processing. The electricity produced by steam and gas turbine is then used by the factory and the surplus sold out to the grid system surplus when attained.

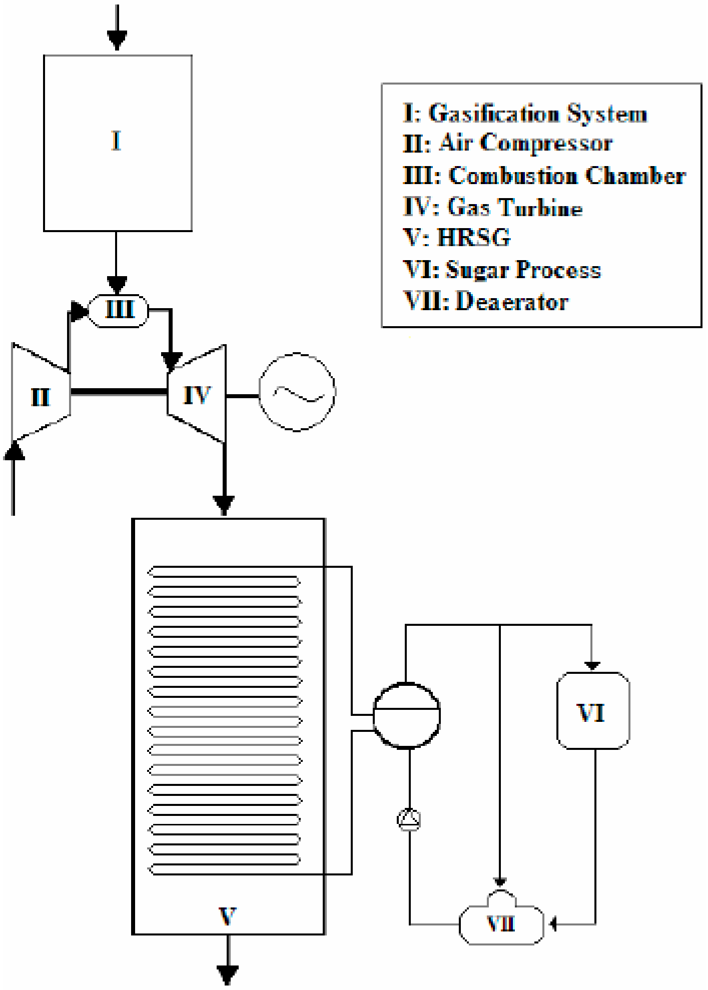

**Figure 3.4 Gasifier turbine schematics configuration** (Palacios-Bereche *et al.*, 2013)

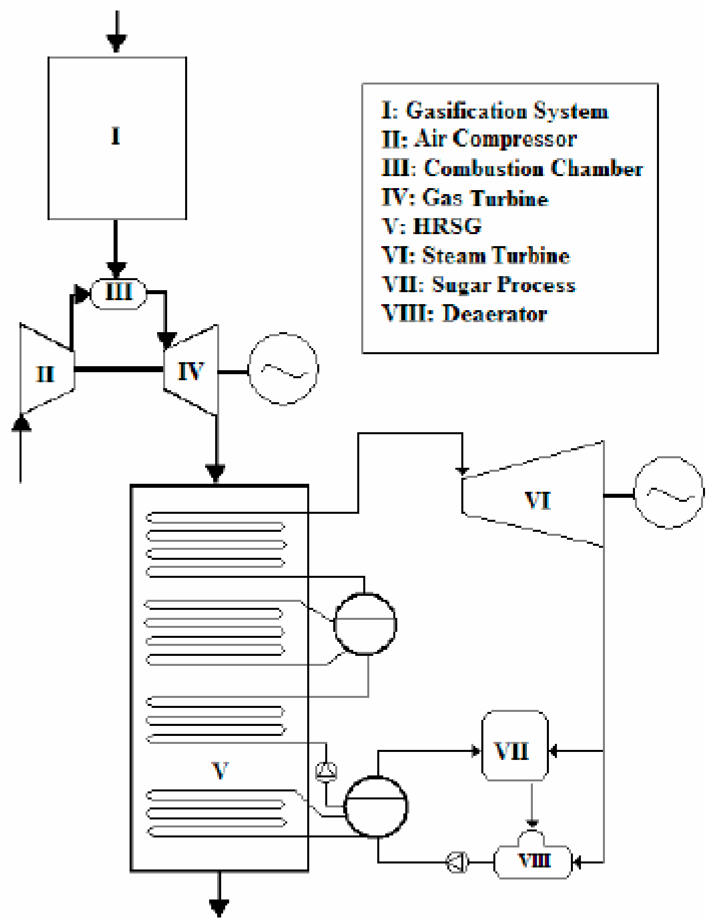

**Figure 3.5 BIG-CC cycle schematics for gasifier turbine** (Palacios-Bereche *et al.*, 2013)

## 3.5 Sugarcane Bagasse Biomass

Sugarcane bagasse biomass is the outer stalk by-product obtained during crushing season for sugar juice extraction through roller mill or diffuser (Ensinas *et al.*, 2006a). Bagasse is the most abundant biomass with good stability, highly compressibility, cost effective, high moisture retention system and low bulk density of 0.1 to 0.2 g.cm$^{-3}$ (Sapariya *et al.*, 2013;Hugot, 2014). Raw bagasse when out from the mill, have 50 - 55% of moisture content, contains 55 - 60% of fibre and the rest fraction being the parenchymatous or pith tissue of 30 - 35% (Lois-Correa, 2012a). Bagasse biomass can be burnt for energy (heat) generation. It is beneficial for use as fuel because of its friendliness with the environment. It can be enhanced as a potential agent of nature and energy conservation. Sugarcane biomass consists of cane trash left on the field after cane harvest in addition to bagasse by-products during crushing in the sugarcane mill.

Sugarcane bagasse constitutes of fibre, a non-soluble solid dispersed in water and lignocellulose. The fibre consists of inorganic substances which are rocks, extraneous materials and soil but this constituency is mainly influenced by the type of agricultural cane processing and cane harvesting techniques applied (Canilha *et al.*, 2013). Lignocellulosic chemical constituency of sugarcane bagasse on the average is composed of 19.1 - 32.4% of lignin, 4.6 - 9.1% of extractives, 38.8 - 45.5% of cellulose, 1.0 - 2.8% of ashes, and 22.7 - 27.0% of hemicellulose in the Brazilian bagasse (Canilha *et al.*, 2013). Table 3.3presents other countries of the world and the chemical constituency of bagasse of dry matter, chemical compositions as differed by different agro-industrial practices and cultivars.

**Table 3.3 Chemical composition (% w/w dry) for Brazil and other countries of the world** (Martin *et al.*, 2007;Canilha *et al.*, 2011)

| **Constituency** | **%** | | |
|---|---|---|---|
| | **Brazil** | **Cube** | **USA** |
| Cellulose | 38.8 | 43.1 | 39.6 |
| Hemicellulose | 25.8 | 31.1 | 29.7 |
| Lignin | 19.1 | 11.4 | 24.7 |
| Ash | 1 | 55 | 4.1 |
| Extractives | 6.8 | | 14.3 |

Biomass yields and their chemical and physical compositions depend on:

- Sugarcane origin
- Different laboratory methods during analysis
- Plant genetics
- Growth environment

### 3.6 Uses and its Application

Bagasse is the main source of all sugar lignocellulosic bioconversions. It is a renewable resource for the manufacture of pulp and paper products, agglomerated boards, building materials and in agricultural operations in nutrients enrichment and in physical soil improvements. It is also the main source of sugarcane juice used for sugar (sucrose) or alcohol (ethanol) production (Canilha *et al.*, 2013). Bagasse biomass being a raw materials for so many things can be used by the adaptation of different processes and reactions to produce valuable products (Sukumaran *et al.*, 2009). Chemical, thermal, mechanical, and biotechnological processes such as saccharification are used for biomass application (Hugot, 2014). Also, further use as a raw material for cultivation of microorganism in fermentative processes is also possible to produce xylitol, ethanol, butanediol, single cell proteins as the value added product (Martin *et al.*, 2007). Since bagasse biomass consist of lignocellulosic material (cellulose, hemicellulose and lignin), it makes it difficult for the production or synthesis other value added products due to successive impurities sometimes (Canilha *et al.*, 2013). Pre-treatment technique is adopted for breaking down hemicellulose-lignin-cellulose complex through delignification and hydrolysis (Martin *et al.*, 2007;Canilha *et al.*, 2013). The popular use of sugarcane bagasse is for energy generation and for secondary generation of bioethanol from its sucrose left behind on the culm after crushing (Brienzo *et al.*, 2009b). However, bagasse biomass is widely used as a source of heat and steam for electricity generation in sugarcane mill (Nassar *et al.*, 1996). Anukam *et al.* (2016) highlighted in their comprehensive review that; using sugarcane bagasse biomass in furnaces and in boilers have shown lower net electricity efficiency of 10 to 20 percent. But its application in gasification as the part of thermochemical conversion for electricity generation has been successful under proper technology.

## 3.7 Synthesis and Characterisations of Bagasse

### 3.7.1 Proximate and Ultimate analysis

Proximate and ultimate analysis during characterisation of biomass determine the potential of the biomass to be used as the fuel or not (Gustafsson, 2011;Anukam *et al.*, 2016). Before the biomass is considered as a source of energy proximate, ultimate and moisture content analysis are important. Proximate analysis gives fuel properties such as: weight, moisture content, fixed carbon content, ash content, and volatile matter.  Fuel properties are obtained when the biomass is subjected to certain ranges of temperature. Temperatures are parameters used to simulate reactions through pyrolysis or devolatilization. Reactions occurs as the biomass decomposes and gives volatile substances which are mainly gases: CO, $CO_2$, and $H_2$ (Jorapur and Rajvanshi, 1997). When proximate and ultimate analysis are performed, moisture is driven out of the biomass, because moisture are water molecules which bind several physio-chemical substances to the biomass. In summary, proximate analysis gives the idea on how easy the biomass can be ignited for different uses such as: gasification or oxidation. Volatiles in the biomass yield liquid products while fixed carbons yield solid products. High volatile matter in the biomass burns to gases and are observed as flame while high fixed carbon burns very slowly with no flame (Mohammad and Kamruzzaman, 2011). Biomass with high volatile matter has the problem of tars and oils which result as by products (Kamruzzaman and Islam, 2011b). The recommendations for biomass with high volatile matters has to be converted using pyrolysis or gasification for energy conversion. With ash content being a problem during energy conversion process, too much or high yield of ash content can result from slagging which negatively affect heat transfer at certain temperature ranges.

Ultimate analysis as opposed to proximate analysis gives elemental compositions of the biomass after complete combustion and the final solid products are analysed. From ultimate analysis, the major product are carbon and oxygen with little traces of hydrogen gas. Ultimate analysis is crucial for evaluating the biomass pollution potentials during energy conversion and in determining the air-fuel ratios of fuels (Mohammad and Kamruzzaman, 2011). Contents of cellulose, hermicellulose and lignin determine the content of carbon and oxygen in the biomass. In bagasse biomass, high carbon and oxygen observed are because of carboxylic and alcohol groups on the bagasse constituency which makes up cellulose, hermicellulose and lignin. However, Mohammad and Kamruzzaman (2011) mentioned that majority of agro-based biomass contains high hydrogen and oxygen than carbon which brings about the calorific values of biomasses. Ignition and reactive stability is mainly determined by cellulose, hermicellulose, and lignin contents. But biomass such as bagasse also consists of inorganic or metal elements of potassium, chlorine, and sulphur. High contents of these inorganics is disadvantageous if the biomass are to be used as fuels. High contents of metal salts also result in high deposition of metals which lowers the heat transfer coefficients and causes the corrosion of equipment (Kamruzzaman and Islam, 2011b).

### 3.7.2 Heating Values

Before any form of energy conversion process of biomass, its energy content has to be measured. The amount of energy released by the biomass under sufficient air during combustion is measured in MJ.kg$^{-1}$ and this is called heating value. They are two forms of heating values; high heating value (HHV) and low heating value (LHV), HHV is the sensible heat produced by the fuel when the moisture within the biomass and the moisture generated during combustion are in steady flow in the condensation form while LHV is the amount of sensible heat extracted from the fuel if the water in the fuel matter and water generated during combustion are in the steady state flow in the gaseous state. LHV can be calculated from HHV and hydrogen content of the biomass in percentage using (Equation 5) The HV of biomass is usually measured using a bomb calorimeter. This can also be determined by calculation where the bomb calorimeter is not available. The two governing equations for these heating values are; Dulong and Boie equations (Equation 3 and Equation 4). To use these two equations, elemental analysis has to be carried out first to determine carbon, hydrogen, oxygen ad sulphur (C, H, O, and S). In the case of sugarcane bagasse, the heating vale (HV) ranges between 17 and 20 MJ.kg$^{-1}$, HV of biomass is mainly affected by the presence of oxygen and carbon (Anukam *et al.*, 2016). Mohammad and Kamruzzaman (2011) on their study determined that the heating values of most biomasses range between 10.56 to 18 MJ.kg$^{-1}$. High oxygen content in the biomass than carbon lowers the HV of biomass per its unit mass. While LHV results in lower energy density which also impacts on the increase logistics cost of biomass as feed stocks. Biomass that have high HV are good for gasification.

$$HV(MJ.kg^{-1}) = 33.823 \times C + 144.250 \left(\frac{H-O}{8}\right) + 9419 \times S \qquad \text{Equation 3}$$

$$HV(MJ.kg^{-1}) = 35.160 \times C + 116.225 \times H - 11.090 \times N + 10.465 \times S \qquad \text{Equation 4}$$

$$LHV = HHV - 53H \qquad \text{Equation 5}$$

### 3.7.3 Bulk Density

Bulk density of biomass affects economically the conversion process of biomass to energy and its efficiency of performance. The bulk density determines transportation cost, storage, and collection/loading. Furthermore, not only does it affect the various properties but also determines the type of design of conversion technologies to be adopted for biomass to energy. Bulk density is defined as the weight per unit mass of the material which scientifically represented is by$\rho_b$. Biomass composition determines the bulk density of the material such as; moisture content (ω), particle size which is determined by length and diameter (*l*, d), shape (ɸ), and the individual particle density ($p_p$) (Mohammad and Kamruzzaman, 2011;Anukam *et al.*, 2016). The bulk density is determined using an oven dry biomass with a moisture content close to zero. The low bulk density of sugarcane bagasse ranges between 75 to 200 kg.m$^{-3}$. Bulk density of the material is calculated using the following equation (Equation 6):

$$\rho_b = \left(\frac{W_2 - W_1}{V}\right) \qquad \text{Equation 6}$$

Where $W_2$ in grams (g) is the mass of the container and biomass, $W_1$ in grams (g) is the mass of the container, and V is the volume of the container in cubic meter (m$^3$). Mohammad and Kamruzzaman (2011) in their work indicated that some other agricultural wastes have bulk density ranging between 11 to 160 kg.m$^{-3}$. Biomass with larger particle size, normally have low bulk density which makes difficult to be used in gasification systems because it does not allow for gravity feeding.

### 3.7.4 Moisture

Since moisture in the biomass is regarded as the water molecules that binds physio-chemical properties together (Anukam *et al.*, 2016). Moisture content after all characterizations is the main factor which determines thermal conversion technology. Low moisture content are suitable for gasification and direct combustion for better heat transfer while high moisture content of biomass is appropriate for biological based processes (Mohammad and Kamruzzaman, 2011). High moisture content also negatively affects heating values and thus thermal efficiencies since more heat will be used for drying. For gasification depending on the type of the reactor used, certain amount of moisture is required for better gas heating. In the case of bagasse biomass, the moisture content ranges between 40 to 60 percent in the mill while other agriculture residues have moisture contents way below 50 percent except water hyacinth which has 52 percent moisture content during harvest.

## 3.8 Separation Properties

Biomass separation in bagasse consists of two components in its constituency, fibre and piths has both industrial and market values for both fractions. The separation of one from the other becomes the important operation for its briquetting process and in subjecting the effective utilisation of bagasse as reliable raw materials. There are two ways in which bagasse separation can be carried out. Mechanical separation which is mostly adopted by the sugarcane milling industries and chemical separation which involves the use of chemicals such as sulphuric acid, hydrogen peroxides, and sodium hydroxides to separate the interested components. Chemical method for separating sugarcane bagasse is not seeming very feasible for industrial scale operations because huge volumes of acids and base disposals are additional critical issues and may pose more costs.

### 3.8.1 Mechanical Separation

Mechanical separation can be through mechanical depithers or manual by hands through beating and uses of vibrating sieves to separate bagasse into piths and fibres. There are different types of depithers namely; S.M Caribe depither, Kimberly KC-4 depither, and Horkel depither amongst others. In comparison, the cost and power of depithing versus non-depithing, Zanuttini (1997) expressed that it is more beneficial to depith bagasse while they are still moisty for better quality and quantity of fibres per ton of bagasse. Different depithers are evaluated in terms of quality, quantity of fibres they can produce and the power consumption during operation. By monitoring the vibration and temperature rise on upper and lower bearings of depithers, the safety of operation is determined as used in the milling factory (Rainey *et al.*, 2013). To obtain pure fibre during depithing, rotating screening is used to improve quality of fibres for the paper industry. The feeding and discharge of pith and fibre at the top and bottom of the depithing machine is through gravity (see Figure 3.6) as depicted.

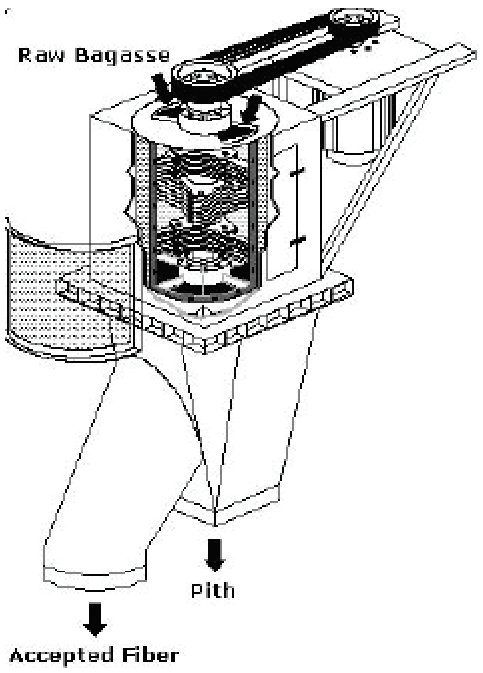

**Figure 3.6 Bagasse depither** (Lois-Correa, 2012b)

Payne *et al.* (1957) in their United States patent of the invention process for the separation of pith and fibre, highlighted the flow process on how pre-treatment of bagasse with sodium hydroxide helps to archive good quality of fibre before it enters a depither. The manual separation of bagasse takes place when the biomass is dried using beating or vibration and passed through 0.7 mm sieve where the piths are obtained. This is achieved because fibres have been classified as being cylinders in shape while piths are essentially spherical in shape which makes screening possible and so the separation process of bagasse into fibres and piths is achieved (Rasul *et al.*, 1999b).

### 3.8.2 Chemical Separation

Fibres can be separated from lignin by using alkali treatment. The characteristics of fibre mainly depends on the concentration of sodium hydroxides but most studies use 0.1M of sodium hydroxides solution (Asagekar and Joshi, 2014). The pith can be removed manually by hands, then the bagasse will then be subjected to hot water treatment at 90 degrees Celsius for an hour.

The bagasse will then be dried in the sunlight for four hours under atmospheric pressure at a boiling temperature of 0.1 M of sodium hydroxides solution at 1: 100 materials to liquor ratio. For effective separation of fibre, the mixture is stirred and dried to obtain the fibres. To determine the quality of fibre produced; crystallinity, morphology, fibre fineness, moisture absorption, tensile properties are evaluated.

### 3.9 Briquetting as a Technology and Briquetting types

Briquetting is the technique of subjecting the loose biomass under heavy mechanical pressure for densification to any shapes, depends on the market and utilisation preferences (Sapariya *et al.*, 2013). Briquetting has the advantage of reducing moisture for thermal efficiency improvement and lower emission of greenhouse gases. It has been estimated that raw bagasse biomass has conversion efficiencies below 40% with particulate emissions exceeding 3000 mg/Nm$^3$ and large portion of unburnt carbonaceous ash (Hugot, 2014). To produce a homogeneous and uniform sized solid piece with a high bulk density which can be used as fuel, three different types of densification processes are adopted. They are:

(i) Densification using a binder
(ii) Densification with no binder
(iii) Pyrolysed densification using a binder

Industrial scale briquetting technology (Figure 3.7) originated in India and evolve to other part of the world. Briquetting technology can be adopted with any agricultural residue, but different densification processes are employed on different types of biomass.

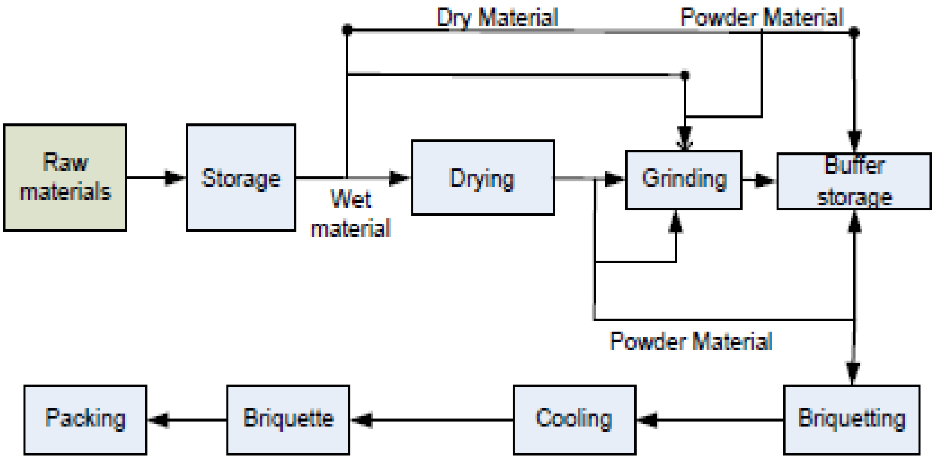

**Figure 3.7 Industrial setup of biomass briquetting technology** (Sapariya *et al.*, 2013)

The densification process of loose biomass involves briquetting machines for heavy mechanical pressure. They are five well known briquetting machines namely; (1) Piston press densification, (2) Screw press densification, (3) Roll press densification, (4) Palletizing, and (5) Low pressure or manual press.

### 3.10 Post Briquetting Applications

Briquettes are made out of different biomass which can be used for various purposes such as for heat, electricity, and steam generation for different needs such as household’s energy needs and in the industries. Briquettes can be pre-processed through gasification for power generation at various temperatures in the gasifier (Yoon *et al.*, 2012). However, in households, there are used for braaiing barbequing  and for cooking, Pilusa *et al.* (2013a) studied the use of hybridised briquettes that can be used by South African townships to replace woods and other conventional energy sources. Wood and coal are not eco-friendly since studies shows that an average township household can use up to 200 kg of coal and 20 kg of wood in one month. This is not sustainable, environmentally unfriendly and uneconomical. Furthermore, a cubic meter of wood generates 61 to 73 kg of carbon dioxide equivalents (Granada *et al.*, 2002). While densification of biomass eliminates all those prevailing problems during combustion of loose biomasses.

### 3.11 Summary

In summary, the literature indicated that sugarcane has 37 species, which originated in India. Sugarcane crop was stimulated to be used as the source of energy due to the 1973 oil crises experienced by the world. The African continent is mostly affected by poor energy security; biomass seems like the solution especially for rural communities. The central African countries may not benefit in the use of bagasse biomass as the energy feedstock for energy generation. The main problem is that central African countries are covered with precious forests. In Brazil, between 1980 to 1998 yields of sugarcane increased from 73 million to 90 million tonnes due to the demand for sugarcane as food and energy crop. Sugarcane crop is imperative for its sucrose content, biomass yield, regeneration capacity, and fibre that it can produce. However, the sugarcane industry is still in need of technology development in order to optimize production.

Since sugarcane has the potential to be used to generate steam and electricity for sugarcane milling operations and other need, the surplus of heat and electricity generated from sugarcane biomass depends on the steam economy, energy conservation approach and instrumentation used. However, African countries do not produce adequate steam and electricity from sugarcane biomass due to inefficient technology such as the use back pressure turbine instead of condensation extraction steam turbine (CEST). Other countries such as India, Mauritius, and Brazil have adopted (CEST) system to produce electricity for their countries and reduce other operational costs. African head of states should consider working closely with private sectors to improve technological advancement since sugarcane can address industrial development, economic growth and promote poverty reduction. Besides, bagasse biomass is not limited only in one sector but it can be used to manufacture pulp and paper, agglomerated board and building materials. But Engineering, technology, and pre-treatment technique remain the barrier to the adoption of the use of sugarcane crop in multiple sectors. The future research should steer the direction on developing cheap technologies which addresses manufacturing of valuable products from agricultural biomass. Also, improve technologies of drying of bagasse from boilers to limit the thermal heat transfer problems from boilers.

## CHAPTER FOUR: MATERIALS AND METHODS

### 4.1 Equipment and Materials

The equipment with models and list of materials employed in this study and their descriptions are listed in Table 4.1. They were used for the experimental analysis and briquetting operations in addition to post-briquetting analysis and quite extensive for the separation of pith and fibre and the exploration of the effects thereof.

**Table 4.1 Material used in the study**

| Material/apparatus | Quantity | Description |
|---|---|---|
| Bagasse | 1.2 kg | Dry |
| Fibre | 1.2 kg | Dry |
| Pith | 2.5 kg | Dry |
| Gas lighter | 1 | N/A |
| Stop watch | 1 | N/A |
| Water bath | 1 | N/A |
| Beakers | 3 x 100 ml | Grass |
| Balance scale | 1 | Adventure |
| Moisture Analyser | 1 | Boeco Germany BM035 |
| Particle laser analyser | 1 | SALD-3101 Laser Diffraction shimadzu |
| Muffle furnace | 1 | Scientific No. 909 |
| Oven | 1 | BINDER APT line |
| Silicon crucibles | 9 | N/a |
| Bunsen burner | 1 | LPG |
| Thermocouple | 2 | N/A |
| Thermometer | 1 | N/A |
| Stainless steel oven | 1 | Triangle |
| Thermogravimetric Analyser | 1 | METTLER TOLEDO |
| Combustion elementary analyser | 1 | Thermo scientific flash 200 |
| Gas emission analyser | 1 | MRU AIR |
| Hydraulic Jack | 1 | 6000 kg capacitor |
| Bucket | 3 x 25 litre | N/A |
| Polyvinyl alcohol (PVA) | 500 g | Mixed with hot water |
| Starch | 500 g | Mixed with hot water |
| Compressive strength machine | 1 | ROHLOFF max capacitor 570 kN |
| Water | 35 litres | Room temperature |
| Desiccator | | N/A |
| Bomb calorimeter | | LECO AC 500 |

## 4.2 Overview

Raw bagasse and its fractions of fibre and pith were collected and transported from Tongaat Hullet Sugar Maidstone Mill, Tongaat, Durban, South Africa. Various stages of preparations were conducted on bagasse and its fractions of fibre and pith in the laboratory as illustrated in Figure 4.1. The wet bags of bagasse samples were cleaned, sun dried and characterised in their raw state. Some parts were separated into pith and fibres and characterised. Each of the samples were thereafter milled and subjected to other characterisations. Each of the component of bagasse, piths and fibres were then briquetted singly and as hybrids with charcoal at different proportions, then dried. Post briquetting analysis in the form of cooking test and emission testing were conducted.

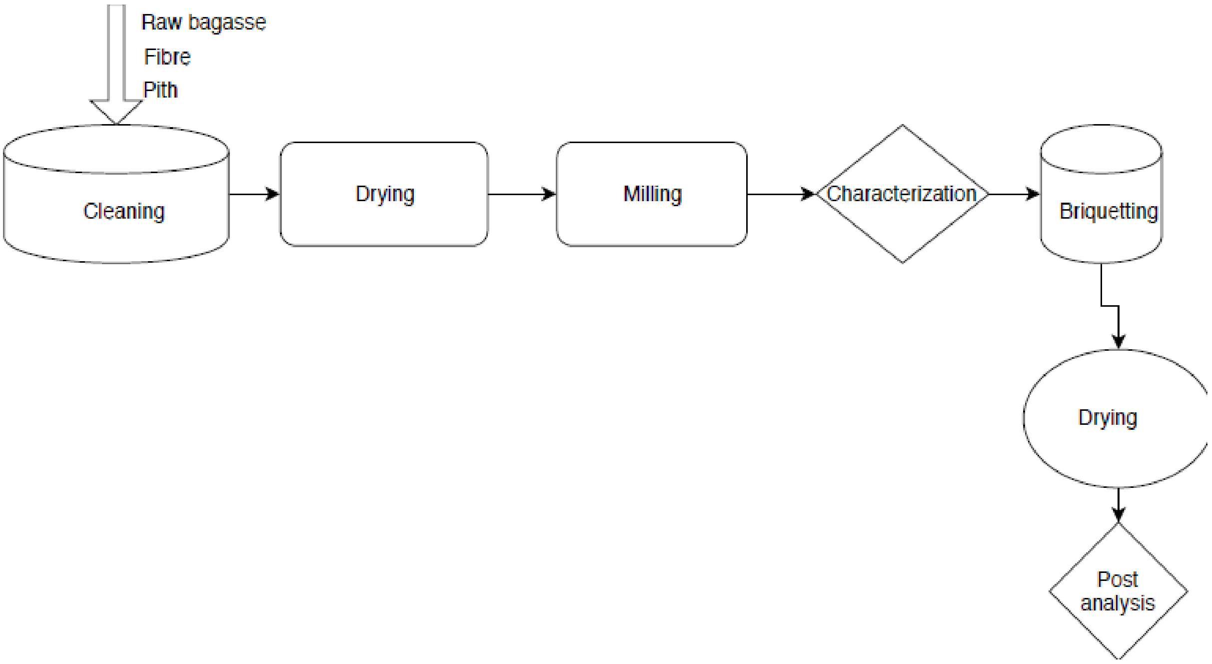

Figure 4.1 Overview summary of the study

## 4.3 Methodology

The following sequence of methodology was adopted for the study. They are:

- Review of literature of the state of the Arts
- Identification and collection of bagasse biomass
- Separation of bagasse into pith and fibre fractions
- Characterization of (raw bagasse, pith, fibre):
    - Proximate analysis
    - Ultimate analysis
    - Energy quantification
    - TGA analysis
    - Particle sizing
    - Chemo-physical properties
- Pre-processing: Milling for briquetting, carbonization, hybridization with charcoal (at varying optimization ratios)
- Actual Briquetting
- Determination of physical and energy properties of briquettes – post briquette and hybrid characterization

## 4.3 Sample Collection and Preparation

In this study bagasse from Tongaat Hullet Sugar Maidstone Mill was collected. The bagasse was collected with approximate 25 percent moisture content. After collection of the sample of bagasse, it was dried in the sun at University of KwaZulu-Natal, chemical engineering. After drying bagasse was separated into it fractions namely: fibre and pith. After drying and separation, the bagasse and fibre was milled using Mobil Polyrex milling machine with 7.5 HP (5.5 kW) output power which was used for production of briquettes. About 200 g of bagasse and fibre were grounded by a blander which was used for proximate and ultimate analysis. In this study bagasse and its fractions of fibre and pith were considered. Figure 4.2 illustrates the samples considered.

### 4.3.1 Separation

Bagasse was separated into fibre and pith fractions by mechanical depither at Tongaat Hullet sugar Maidstone. The depither was feed by gravity with bagasse of approximately 50 percent moisture content, the fibre and pith were collected at the bottom of the depither with the blower separating the pith and fibre into different outlets and transported by carriers. Figure 4.3 illustrates the bottom of the mechanical depither where fibre and pith were collected respectively.


Raw bagasse

Separated Fibres from Bagasse – wet and dry

Separated Pith from Bagasse wet and dry

**Figure2.2 Bagasse biomass and separation of pith, fibre fractions**

**Figure 4.3 Bottom of depither (for piths collection) at the Mill**

#### 4.3.2 Briquetting

Briquetting was carried with the bagasse singly, separated fibres and pith biomasses individually pressurised on several samples using manual piston press of internal diameter 5 cm with the hydraulic jack of 6000 kg capacity (Figure 4.4). Each briquetting sample was treated at different proportions using different binders: starch and PVA and with charcoal to produce hybrids. After the mixture of biomass treatments were made ready, the mixtures were poured onto the cylinder and subjected to compression until its maximum hand capacity was attained at a retention time of 40 seconds to produce the briquettes. The produced briquettes leave the cylinder at a 50 percent moisture level which were then allowed to be air-dried for a week and half to have the final finished products ready for use and for further tests and analysis.

Figure 4.4 Manual hydraulic piston press in operation during briquetting

The briquettes produced after being air dried to reduce moisture content were stored using adsorbent paper materials as shown in Figure 4.5.

Figure 4.5 Briquettes are air dried after production

## 4.4 Ultimate Analysis

### 4.4.1 Moisture Content

To determine the moisture content of the sample tests before and after briquetting, samples of raw bagasse, piths, fibres and briquettes were subjected to a moisture analyser, Model Bocco Germany BM036 (Figure 4.6). Approximately 2 g of each test sample was placed on the moisture analyser, the temperature was set to 105 ℃ for one hour. Percentage moisture (PMC) and dry contents (PDC) were recorded and analysed.

**Figure 4.6 Moisture analyser (Model: Boeco Germany BM035)**

### 4.4.2 Bulk Density

The bulk densities of samples were determined by subjecting them into a cylindrical container (100 ml beaker) as depicted in Figure 4.7. To determine the volume of the beaker, pre-weighed beaker was filled with water until its maximum capacity (at room temperature). The mass of the container plus water was measured using a mass balance scale (Adventure) having a maximum mass of 310 g. The volume of the container was calculated based on the net weight of water and the density of water @ 1000 kg.m$^{-3}$.

A pre-weighed cylindrical container was filled with the test samples of bagasse, fibre, and pith of particle size less than 0.6 mm and dropped from a height of 10 cm on to a horizontal laboratory patch. The sample materials in the container was topped until the maximum capacity was reached, the surplus materials were sheared off. The samples plus the beaker were weighted, and net mass of materials were divided by the volume of container to obtain the bulk density using Equation 7 as indicated:

$$P_b = \frac{F - E}{V} \qquad \text{Equation 7}$$

Where: $p_b$ is the bulk density of the sample in g.cm$^{-3}$, F is the weight of the container and sample (g), E is the weight of the container (g) and V is the volume of the container (cm$^3$).

**Figure 4.7 Mass measurement for bulk density determination**

### 4.4.3 Compressive Strength

A sample of cylindrical biomass briquettes were tested on a 570 kN capacity compression testing machine Ruhloff model (Figure 4.8) at a cleft failure condition. The load was applied at a uniform rate of 0.305 mm.min$^{-1}$ until the briquettes strength internally fails by cracking. The compressive strengths were determined using Equation 8:

$$Compressive\ strength = \frac{2 \times The\ load\ fracture\ point\ (N)}{(\pi DL)} \qquad \text{Equation 8}$$

Where: D is the diameter (cm) of the briquette and L is the length (cm) of the briquettes.

**Figure 4.8 compressive strength test machine (Rohloff)**

### 4.4.4 Shattering Index

Briquettes durability index were determined using coal drop test procedure as detailed by (American Society for Testing and Materials) in ASTM (1998). The following equation was used to compute briquettes shattering index:

$$Shattering\ index = \frac{weight\ of\ briquettes\ retained\ after\ dropping}{weight\ of\ briquettes\ before\ dropping} \qquad \text{Equation 9}$$

## 4.5 Proximate Analysis

Proximate analysis was conducted on the biomass samples and briquettes to determine the weight fractions of volatile ash and fixed carbon contents. To determine the volatile ash, 2 grams of dried samples were taken and placed in a closed silicon crucible (Figure 4.9). The volatile matter was determined by heating the samples at 550 ℃ for 10 minutes in a muffle furnace (Figure 4.9). The weight loss of matter, after free moisture adjustment, was treated as the volatile matter. The mass remaining in the crucible minus the mass of ash, is termed fixed carbon. The ash content was determined by increasing the muffle furnace residence time to 4 hours under 550 ℃ in the air.

### 4.5.1 Percentage volatile matter (PVM)

Exactly 2 g of powdered bagasse, fibres, piths and 2 g of pulverised briquette samples were measured into a crucible was placed in the oven until constant weights were obtained. The samples were then heated in the muffle furnace at a temperature of 550 ℃ for 10 min. Samples were then weighed after cooling in a desiccator. The PVM was calculated using Equation 10:

$$PVM = \frac{A - B}{A} \times 100 \qquad \text{Equation 10}$$

Where: A is the oven dry weight (g) of samples and B is the weight of the samples after 10 min in the muffle furnace at a temperature of 550 ℃.

### 4.5.2 Percentage ash content (PAC)

Exactly 2 g of powdered bagasse, fibres, piths and 2 g of pulverised briquette samples were also heated in the muffle furnace at a temperature of 550 ℃ for 4 hours. The samples were weighed after cooling in a desiccator to obtain the weight of ash. PAC was calculated using Equation 11:

$$PAC = \frac{C}{A} \times 100 \qquad \text{Equation 11}$$

### 4.5.3 Percentage fixed carbon (PFC)

The PFC was calculated by subtracting PVM, PAC and PMC from 100 (percent) as shown in Equation 12.

$$PFC = 100 - (PAC + PMC + PVM) \qquad \text{Equation 12}$$

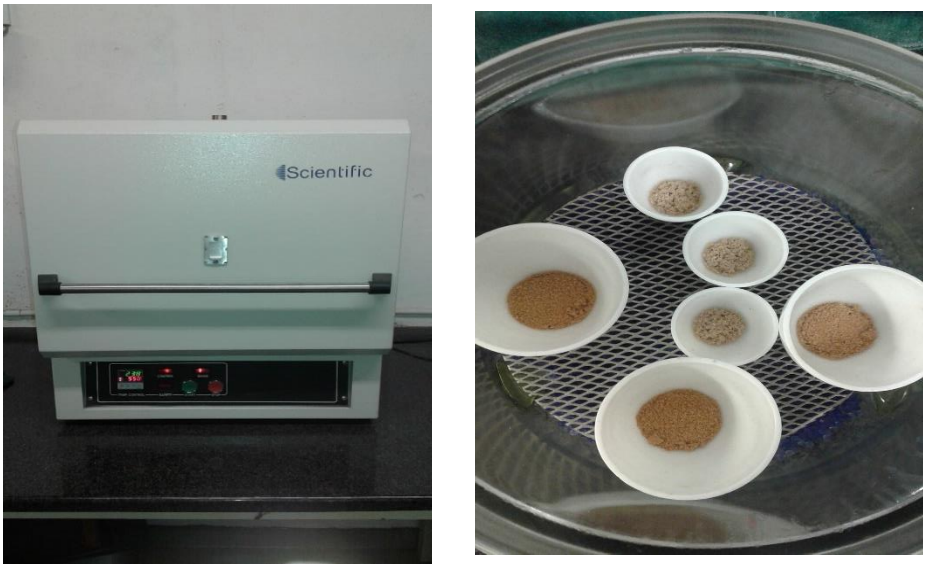

**Figure 4.9 Muffle furnace and crucible used for proximate analysis (Model: Scientific No. 909)**

## 4.6 Measurement of Thermo-Chemical Properties

### 4.6.1 Determination of Higher Heating Values (HHV)

High heating values of the samples of bagasse and it fractions were determined in accordance with the specifications of Jittabut (2015). The heating value was carried out using a using bomb calorimeter (LECO AC 500). Approximately 0.4 g of each sample was burnt in the bomb calorimeter until complete combustion was obtained. The temperature difference was used to compute HHV using Equation 11 for samples the bagasse and all fractions of fibres and piths and briquettes.

$$Q = \frac{(C_{water} + C_{cal})(T_2 + T_1)}{W_f} \qquad \text{Equation 13}$$

Where: Q is the calorific value of bagasse, fibres and piths (MJ/kg)

$C_{water}$ is the heat capacity of water (MJ/kg°C)

$W_f$ is the weight of the biomass material sample (kg)

$C_{cal}$ is the heat capacity of the bomb calorimeter (MJ/kg°C)

$T_2 – T_1$ is the rise in temperature (°C)

### 4.6.2 TGA Analysis

Thermogravimetric Analyzer (TGA) was the instrumentation used to conduct thermalgravimetric analysis of bagasse and its fractions of fibre and pith at the Westville Chemistry laboratory of the university. The TGA unit has a furnace attached with linear heating rate of 10°C.min$^{-1}$ until it reaches a maximum heating of 600°C usually at a holding time of 5 min at 600°C. In this study, Nitrogen gas at a flowrate of 100ml.min$^{-1}$ has been used to create the oxygen free inert atmosphere to avoid combustion of bagasse biomass in the system during analysis.

### 4.6.3 Elemental Analysis

Elemental analysis was carried out using Thermos Scientific Flash 200 (Figure 4.10) elemental analyser. Normally used to measure and determine elemental compositions of carbon C, hydrogen H, nitrogen N, sulphur S, which use combustion at a temperature exceeding 1400℃ following method as prescribed by Jittabut (2015). The oxygen O content is calculated by subtraction of CHNS from 100, using Equation 14:

$$\boldsymbol{O}\% = \mathbf{100} - (\boldsymbol{C}\% + \boldsymbol{H}\% + \boldsymbol{N}\% + \boldsymbol{S}\%) \qquad \text{Equation 14}$$

**Figure 4.10 Elemental analyser (Thermos scientific Flash 2000)**

### 4.6.4 Burning Rate

Burning rate was determined according to Davies and Davies (2013), by arranging the bunsen burner on top of the scale balance while the mass of the bunsen burner was recorded. The known mass of the briquettes was placed on the wire gauze as illustrated by Figure 4.11, the burner was ignited to burn the entire bottom surface of the briquettes, and the ignition time was recorded after the briquettes reach its burning steady state. Also, the mass loss at every 10 seconds through combustion process was recorded using a stop watch. The burning rate through weight loss at specific times was calculated from the following Equation 15:

$$burning\ rate = \frac{total\ weight\ of\ the\ briquette}{tatal\ time\ taken} \qquad \text{Equation 15}$$

**Figure 4.11 Ignition testing techniques of the briquettes**

### 4.6.5 Gas emission analysis

Gas emission analysis was computed using gas emission analyser MRU AIR emission monitoring system with various probes and ancillaries. The briquettes were burnt on the oven chamber where gas analyser probe was connected to. The gas analyser probe was connected to the outlet of the oven as illustrated in Figure 4.12 where gases and smoke exit the chamber. The gas emission analyser was programmed to measure emissions and volatiles from dry wood using analyser (program 1), for gases such as $O_2$, CO, $CO_2$, $CH_4$, $H_2$ and $SO_4$ which were analysed for the briquettes.

**Figure 4.12 gas emission analysis setup**

## 4.7 Experimental design

The experiment has several treatments in triplicates consisting of: bagasse, fiber, and pith as the raw material. Binders (starch and PVA) were used to improve briquette quality (cohesiveness) at 8 percent by weight with the separated and unseparated fractions and hybrids. The sample composition is as follows:

- Unseparated Bagasse + binder (starch or PVA)
- Separated Pith only + binder (starch or PVA)
- Separated Fiber only + binder (starch or PVA)

Each of the binders will be experimented

- Unseparated bagasse without binders
- Separated pith without binder
- Separated fibre without binder

Each of the treatment is without binder

(3) Hybrid and Control briquettes

- Charcoal 100% wt (starch or PVA and without binders) (control)
- Bagasse + Charcoal 50% by Wt + binders (starch or PVA)

- Pith + Charcoal 50% by Wt + binder (starch, or PVA)
- Fiber + Charcoal 50% by Wt + binder (starch or PVA)

Other hybrids

- Bagasse 60% wt + charcoal; Bagasse 70% wt + charcoal; Bagasse 80% wt + charcoal and Bagasse 90% wt + charcoal.
- Pith 60%wt + charcoal; pith 70% wt + charcoal; pith 80% wt + charcoal and pith 90% wt + charcoal
- Fibre 60% wt + charcoal; pith 70% wt + charcoal; fibre 80% wt + charcoal and fibre 90% + charcoal

All treatments (Table 4.2) were prepared to achieve a homogenous mixture before being subjected to the post-briquetting testing. Briquetting procedures and operations were carried out at the briquetting laboratory of ENPROTEC, coal briquetting facility at Middleburg, South Africa.

**Table 4.2 Experimental design of the study**

| **Treatments** | **W% Bagasse** | **W% Fibre** | **W% Pith** | **W% Charcoal** | **W% Binder 1** | **W% Binder 2** |
|---|---|---|---|---|---|---|
| Bagasse+8%starch | 100 | 0 | 0 | 0 | 8 | 0 |
| Fibre + 8%Starch | 0 | 100 | 0 | 0 | 8 | 0 |
| Pith + 8%starch | 0 | 0 | 100 | 0 | 8 | 0 |
| Bagasse+8%PVA | 100 | 0 | 0 | 0 | 0 | 8 |
| Fibre+8%PVA | 0 | 100 | 0 | 0 | 0 | 8 |
| Pith+8%PVA | 0 | 0 | 100 | 0 | 0 | 8 |
| Bagasse+50%charcoal+8%starch | 50 | 0 | 0 | 50 | 8 | 0 |
| Fibre+50%charcoal+8%starch | 0 | 50 | 0 | 50 | 8 | 0 |
| Pith+50%charcoal+8%starch | 0 | 0 | 50 | 50 | 8 | 0 |
| Bagasse+50%charcoal+8%PVA | 50 | 0 | 0 | 50 | 0 | 8 |
| Fibre+50%charcoal+8%PVA | 0 | 50 | 0 | 50 | 0 | 8 |
| Pith+50%charcoal+8%PVA | 0 | 0 | 50 | 50 | 0 | 8 |

# CHAPTER FIVE: RESULTS AND DISCUSSION

## 5.1 Overview

Bagasse biomass was separated into fractions of fibres and piths. At their loose condition, they were characterised for physical, chemical and energy properties and analysed after preparation and air drying. Thereafter, each fraction was milled and briquetted, they were also hybridised with charcoal to produce hybrid briquettes using starch and PVA as binders. Some fractions were briquetted without binders. Low pressure densification process was used for briquetting. Post analysis of physical, chemical and energy properties were carried out and analysed. The result of these activities, analysis and operation with detailed discussions are presented in this chapter.

## 5.2 Pre-physical Characteristics

During characterisation of bagasse and its fraction of fibre and pith, it was found that the maximum bulk densities to be 200, 240 and 80 kg.m$^{-3}$ respectively with a significance difference in their magnitude $P<0.05$ (Appendix 1.11.2). The bulk density analysis for South African bagasse varies between 100 – 200 kg.m$^{-3}$ (Hugo, 2010). However, Garcìa-Pèrez *et al.* (2002) reported a bulk density of pith fraction which is 220 kg.m$^{-3}$ which is much high then found in this study. They are a wide variation on bulk density of bagasse and its fractions reported in literature.

Due to differences in size and shape of the particles gives rise to different in particle and bulk density of the biomass fractions. Since fibre has demonstrated greater bulk density as compared to bagasse and pith which possess the lowest bulk density biomass fraction. Fibre have large length to width ratio as compared to pith which have high voids due to it spouge in nature and spherical particle shape. However, in nature bulk density of bagasse varies with geographical location, extraction of sucrose method from sugar milling, harvesting method, type of cultivar, and the sampling method during analysis. Bagasse in nature has different constituency with different particle size and shape, which gives different bulk density because during storage and drying, different particle size separate (Hugo, 2010). During sampling, particle size reduction of biomass reduces bulk density of biomass due to void ratio reduction (Rhodes and Rhodes, 2008). Among bagasse and fibre in their particle size distribution Table 5.1, there is no significance difference $P>0.05$ (Appendix 1.11.3).

**Table 5.1:Moisture content, Bulk density and particle size of the biomass fractions**

| | | | Particle Size (mm) | | |
|---|---|---|---|---|---|
| **Sugarcane and its fractions** | **Moisture%** | **Bulk Density ($kg.m^{-3}$)** | **25%** | **50%** | **75%** |
| **Bagasse** | 12.24 | 200.00 | 0.39 | 0.42 | 0.48 |
| **Fibre** | 11.93 | 240.00 | 0.39 | 0.42 | 0.48 |
| **Pith** | 12.68 | 80.00 | 0.52 | 0.6 | 0.68 |

## 5.3 Post-physical Analysis

Physical characteristics such as moisture content, bulk density, compressive strength and shattering index are important factors for any biomass with a potential to be used as the fuel. Table 5.2 show the physical characteristics of briquettes manufactured from sugarcane biomass. The moisture content of the dried sugarcane biomass briquettes ranged from 5.66 % (Pith+8%PVA) to 12.71 % (Pith+8%starch). Moisture content of biomass is important for it fuel quality to be selected as the source of energy. Thermal conversion technology requires lower moisture content in biomass especial for oxidation energy conversion. While biomass with high moisture content is suitable for biological based process of energy conversion (Cuiping *et al.*, 2004). It is noted that moisture content of all the investigated briquettes is around 10 % to 12 % which is much suitable to serve as the energy feedstock for energy conversion (Werther *et al.*, 2000).

The increase in biomass moisture content reduces its gross energy value due to high energy required for evaporation. The dry biomass is preferable for combustion with a little moisture content beneficial for gasification (Ghaly *et al.*, 1989). The briquettes manufactured in this study are also suitable for gasification with its little moisture content present. Pith+8%starch briquettes pose high moisture content due to voids present in the briquettes. Due to sponge in nature of pith it absorbs the surrounding moisture, however, pith+8%PVA briquettes have the lowest moisture content because PVA close all the voids between pith particles which prevent absorption of external moisture.

Maximum bulk density was found to be 1106.54 $kg.m^{-3}$ in (fibre+50%charcoal+8%PVA) briquettes. The lowest bulk density was found to be 263.45 $kg.m^{-3}$ in (fibre+8%starch) briquettes (Table 5.2). The density of briquettes increases with the addition of 50 % charcoal and the use of 50 % PVA as a binder. Fibre briquettes have a least bulk density when starch is used as a binder but when PVA is used, the bagasse briquettes have maximum bulk density as compared to fibre and pith. While the pith briquettes have maximum bulk density when starch is used as a binder. Briquettes which have been studied have greater bulk density except briquettes produced from fibre+8%starch (263.45 $kg.m^{-3}$), when it compared with bulk density of charcoal which ranges between 289.0 – 349.0 $kg.m^{-3}$ (Zubairu and Gana, 2014). Also Kamruzzaman *et al.* (2008), reported that densification of agricultural biomass can improve its bulk density to a range of 1080 to 1270 $kg.m^{-3}$. Indeed, the separation of sugarcane bagasse into it fraction of fibre and pith is effective in bulk density of briquettes manufactured since significance was archived $P<0.05$ (Appendix 1.12.2).

It was observed from Table 5.2 and Figure 5.1 that the maximum compressive strength was found to be 1123.47 kPa from (bagasse+8%PVA). The lowest compressive strength was found to be 0kPa from (bagasse+8%starch, fibre+8%starch, bagasse+50%charcoal+8%starch, fibre+50%charcoal+8%starch and pith+50%charcoal+8%starch) briquettes. The result presented in this study demonstrate the effect of PVA binder to improve compressive strength and shattering index as compared to briquettes manufactured from 8% w/w of starch. Due to high surface area of pith particle and PVA improves it cohesive force between particles during compression. This is observed from the result presented in Table 5.2, bagasse and fibre briquettes mixed with charcoal and starch as the binder have lower shattering index as compared to other briquettes treatments. High compacting pressure and high starch binder concentration is required for briquettes with lower shattering index to improve it physical properties for market transportation (Kers *et al.*, 2010).

The effect of bagasse and it fractions of fibre and pith, in two different types of binders and addition of charcoal on the shattering index of the briquettes was conducted as shown in Table 5.2, the mean shattering index ranged between 0.13 (fibre+50%charcoal+8%starch) and 1 (pith+8%PVA) and variation of the values was significant $P<0.05$ (Appendix 1.12.4). It can be concluded that the type of binder used and type of biomass fraction have a significant effect on the durability rating of the briquettes. However, they are no significant difference for shattering index $P>0.05$ on pith briquettes on different binders of starch and PVA. According to Iournals

(2011), briquettes manufactured from bagasse and fibre fraction on this study, were starch is used Table 5.2 , are not falling within the acceptable ranges of DIN51731 for the manufacturing of briquettes for market purposes. This is due to the nature of bagasse which consist fibre as the dominant fraction than pith fraction. Fibre have smooth surface with waxes which give rise to poor cohesiveness when starch is used, since starch is also used as the fat substitute in manufacturing of biodegradable plastics (Jane *et al.*, 1992). Therefore, starch have a nature of wax in their particle surface which make it difficult to cling on other wax surface of fibre. The rest of the briquettes treatments they are in the acceptable range regardless of the binder used, this implies that they are durable, reliable and they can stand mechanical handling and transportation. Compressive strength as show in Table 5.2, indicates that briquettes manufactured from bagasse, fibre fractions in used of starch as the binder they fail to stand for mechanical handling. Since their compressive strength reads 0 kPa.

**Table 5.2 Moisture content, bulk density, compressive strength and shattering index of briquettes treatments**

| Treatments | Moisture content% | Bulk density (kg.m$^{-3}$) | Compressive strength (kPa) | Shattering Index |
|---|---|---|---|---|
| **Bagasse + 8% starch** | 12.61 | 485 | 0 | 0.65 |
| **Fibre + 8%starch** | 11.91 | 263.45 | 0 | 0.96 |
| **Pith + 8%starch** | 12.71 | 583.31 | 32.15 | 0.99 |
| | | | | |
| **Bagasse + 8%PVA** | 5.9 | 1029.46 | 1123.47 | 0.99 |
| **Fibre + 8%PVA** | 5.88 | 928.77 | 544.13 | 0.99 |
| **Pith + 8%PVA** | 5.66 | 670.32 | 291.03 | 1 |
| | | | | |
| **Bagasse + 50%charcoal + 8%starch** | 10.87 | 643.46 | 0 | 0.57 |
| **Fibre+50%charcoal+8%starch** | 11.47 | 484.72 | 0 | 0.13 |
| **Pith + 50%charcoal + 8%starch** | 11.3 | 666.14 | 0 | 0.99 |
| | | | | |
| **Bagasse + 50%charcoal + 8PVA** | 11.41 | 1039.24 | 573.54 | 0.99 |
| **Fibre + 50%charcoal + 8%PVA** | 11.49 | 1106.53 | 578.76 | 0.99 |
| **Pith + 50%charcoal + 8%PVA** | 10.36 | 830.41 | 471.58 | 0.99 |

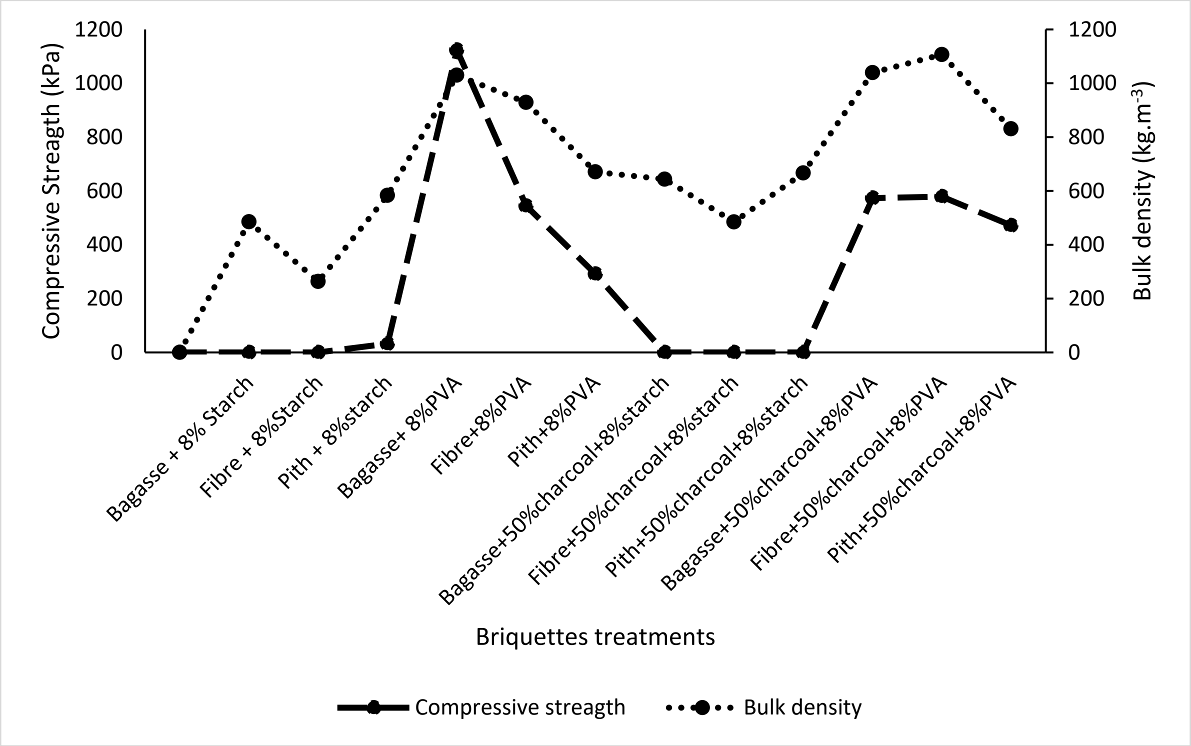

**Figure 5.1: compressive strength and bulk density of briquettes treatments**

## 5.4 Proximate Analysis

The result of proximate analysis is shown in Table 5.3. Volatile matter content of bagasse, fibre and pith are: 80.55%, 89.05% and 76.77% respectively. From the samples tested, fibre fraction contains highest amount of volatile matter (89.05%). Wood charcoal have volatile matter ranges from 20 to 40% (Zubairu and Gana, 2014). Sugarcane biomass fractions have high volatile matter as compared to wood charcoal, lignite coal and bituminous coal (Kamruzzaman and Islam, 2011a). Kamruzzaman (2011), reported that the volatile matter of bagasse biomass varies from 70.6 to 86.3%. The volatile matter content reported in this study is in the same range as reported in the literature. High volatile matter content generates more gases during thermochemical conversion technology. High volatile matter is associated with high hydrogen content in the biomass which suitable for gasification and pyrolysis at lower temperature. From the result of this study, fibre have high volatile matter then the rest of the biomass fractions. Fibre have the great potential to be used in pyrolysis and gasification. However, high ash content decreases the conversion efficiency of the process continuous removal of ash is required (Kamruzzaman, 2011).

Ash is the non-combustible material which result in slagging behaviour which is highly depended on the ash melting temperature. Due to trace element contain within the ash, high ash content biomass is not suitable to be used in thermochemical conversion systems such as boilers. Most literature recommend ash content at a range of 3% to 4% for quality briquette for thermochemical technology (Zubairu and Gana, 2014). However, bagasse and it biomass fractions have high ash content than this set limit. Garivait *et al.* (2006), also reported bagasse ash content of 7.69% which is below from the ash content obtained on this study. However, bagasse ash content can vary with geographic location due to type of soil and climate. Also with cleanliness and particle size of the bagasse biomass and it fraction of fibre. Hugo (2010), reported that ash content of bagasse also varies with particle size of the biomass.

Removal of the finest particle size can reduce ash content produced by biomass. However, it was reported that biomass ash content can vary from 2.29% to 18.76% but depends on the type of the biomass (Kamruzzaman, 2011). Ash content of bagasse, fibre and pith was recorded to be: 8.01%, 1.75% and 18.12% respectively. Pith fraction have higher ash content this could be the result of soil particle present due to difficulties of cleaning pith due to it sponge in nature. However, bagasse has very low ash content which promote it to be used as the energy feed stock for gasification due to it high volatile matter and very low ash content. Among the biomass fractions, they were a significance difference in their ash content $P<0.05$ (Appendix 1.13.2).

Regarding fixed carbon content, bagasse, fibre and pith fixed carbon was found to be: 27%, 12% and 41.35% respectively. The variation in fixed carbon content was significance $P<0.05$ (Appendix 1.13.3) among the biomass fractions. Fibre have a least fixed carbon of 12.0% where pith have high fixed carbon of 41.3% as presented by (Garivait *et al.*, 2006). (Zubairu and Gana, 2014), reported that when bagasse undergoes pyrolysis at a temperature range of 450 – 510℃, its percentage fixed carbon ranges from 70% to 75%. Biomass fraction with high fixed carbon content burn very slowly without a flame and yield solid by-product (Ahiduzzaman and Islam, 2016). It was observed during ignition time and burning rate that pith briquettes have long ignition time and high burning rate compared to fibre and bagasse manufactured briquette (Section 5.6). Therefore, pith fraction is not suitable to be used in gasification and pyrolysis thermochemical conversion technology. But suitable to be used in combustion.

**Table 5.3 Proximate analysis of biomass fractions**

| Sugarcane and its fractions | %V | %Ash | %FC |
|---|---|---|---|
| **Bagasse** | 80.55 | 8.01 | 27.46 |
| **Fibre** | 89.05 | 1.75 | 12.70 |
| **Pith** | 76.77 | 18.12 | 41.35 |

## 5.5 Thermo-chemical Characteristics

The results of gross energy value, thermogravimetric analysis and elementary for three samples of bagasse, fibre and pith are listed in (Table 5.4) with their statistical analysis in (Appendix 1.14).

### 5.5.1 Higher Heating Value

Kamruzzaman and Islam (2011a), reported that the heating value of agriculture biomass ranges from 10.59-18 MJ.kg$^{-1}$. The reported range correspond with the result presented in this study (Table 5.4), which ranges from 15.74, 16.14, and 17.73 MJ.kg$^{-1}$ for pith, bagasse, and fibre respectively. Separation of sugarcane biomass into bagasse, fibre and pith have significant different on higher heating value $P<0.05$ (Appendix 1.14.1). Fibre indicate high heat value as compared to bagasse and pith fraction while pith is the lowest in heat value among bagasse and fibre fraction due to low carbon content. Fibre have high heat value as compared to other fractions because of it rigid structure and high content of carbon and high volatile matter which makes it preferable for gasification at lower temperature (Mansaray and Ghaly, 1997). However, Ahiduzzaman (2011), reported that the removal of ash from the biomass improve biomass heat value. The high heating value follows the trend of carbon content in sugarcane biomass (Section 5.5.3), biomass with high carbon content have high heating value. Which entails why fibre have high heating value.

### 5.5.2 TGA Analysis

The TGA curves of bagasse biomass and its fractions of fibre and pith are presented by Figures (5.2A, 5.2, 5.3A, 5.3 and 5.4A, 5,4). All sugarcane biomass fractions undergo single decomposition at temperature range of 30.98 to 602 °C. Where maximum decomposition and the weight remains occurs at the same temperature ranges of: 250 °C to 500 °C and 500 °C to 600 °C. The bagasse indicated a different trend from the range of 30 °C to 49 °C where gas absorption occurs therefore, the moisture reduction takes place from all three biomasses in the range temperature of 49 °C to 100 °C through vaporisation (drying zone). The temperature reported by Anukam *et al.* (2016), for drying zone is determined mainly by the thermal conductivity of the biomass, the temperature for drying zone reported to be less than 120 °C. The mass remains as the char for all biomass vary from 0 to 14% which is more similar with the char result obtain from proximate analysis with the mass vary from 1 to 18.12%. The similarity in char mass remain from proximate and TG analysis is the mass of the sample weighed and sampling method of biomass fractions used during analysis. The constant mass of char obtained from 500 °C to 600 °C is because there is no change of phase or product yielded out of char since pyrolysis of biomass ends at temperature above 800 °C. The temperature above 600 °C is called the secondary pyrolysis zone, where char can melt and produce CO, $H_2$ and $CO_2$ gas which further increase weight loss remains. Since, pith fraction possess high ash content remain from temperature range of 500 °C to 600 °C, it not good for combustion rather can be used in gasification. This is due to high particle size distribution which reduce it surface area for reaction to ignition or external energy input. Bagasse and fibre undergoes downward endotherm while pith fraction heat flow energy was endotherm up reaction as reported by Kamruzzaman and Islam (2011a). Bagasse and fibre have negative temperature difference while pith have positive temperature difference during endothermic transition.

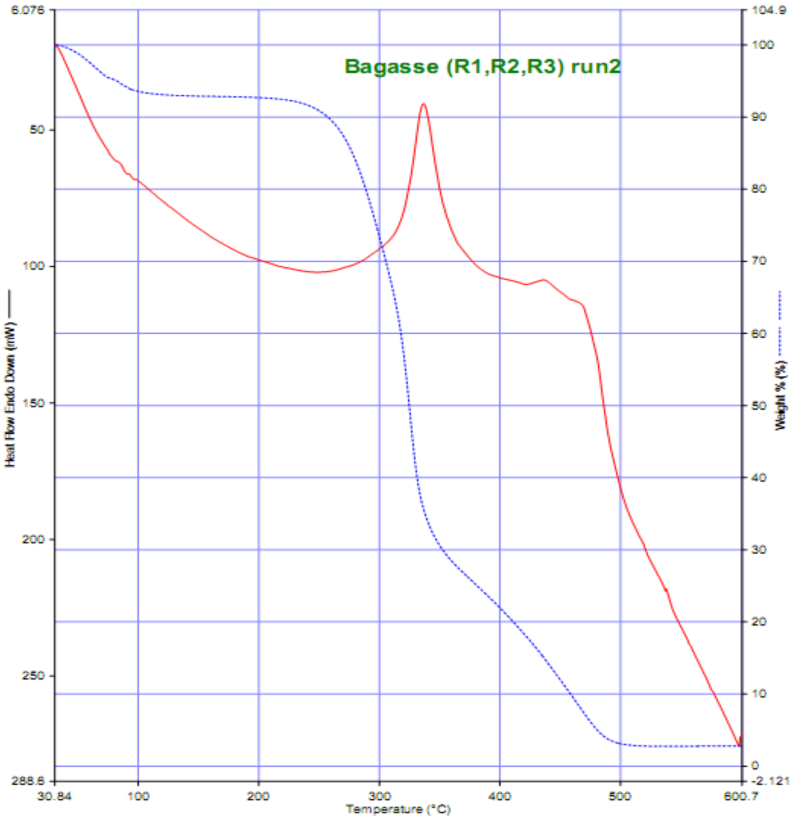

**Figure 5.2 A: Thermogram/mass decomposition from TGA (bagasse)**

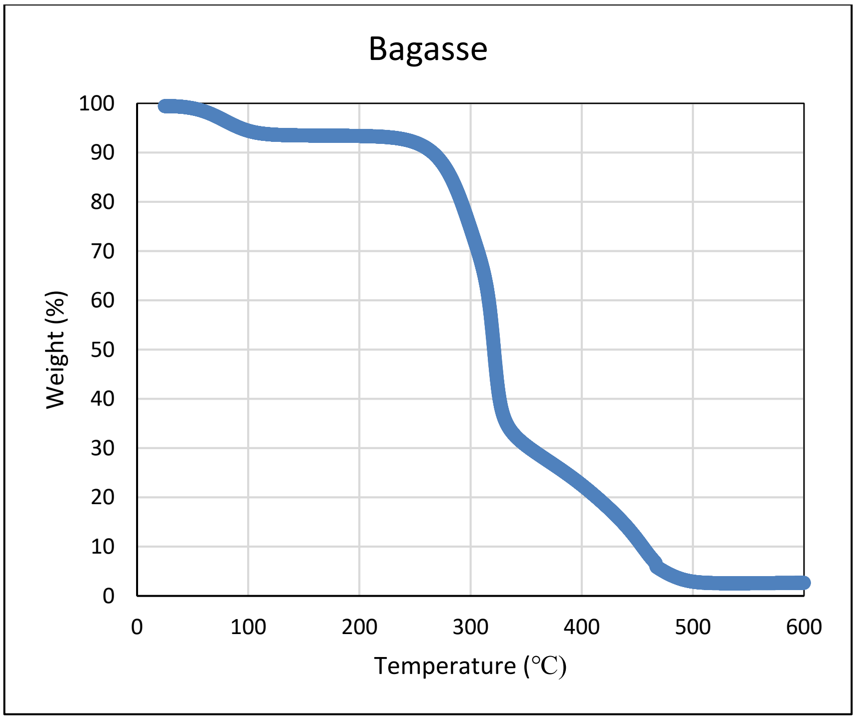

**Figure 5.2: TG curve (Mass vs Temp) for bagasse at 10°C.min$^{-1}$ heating rate in inert medium**

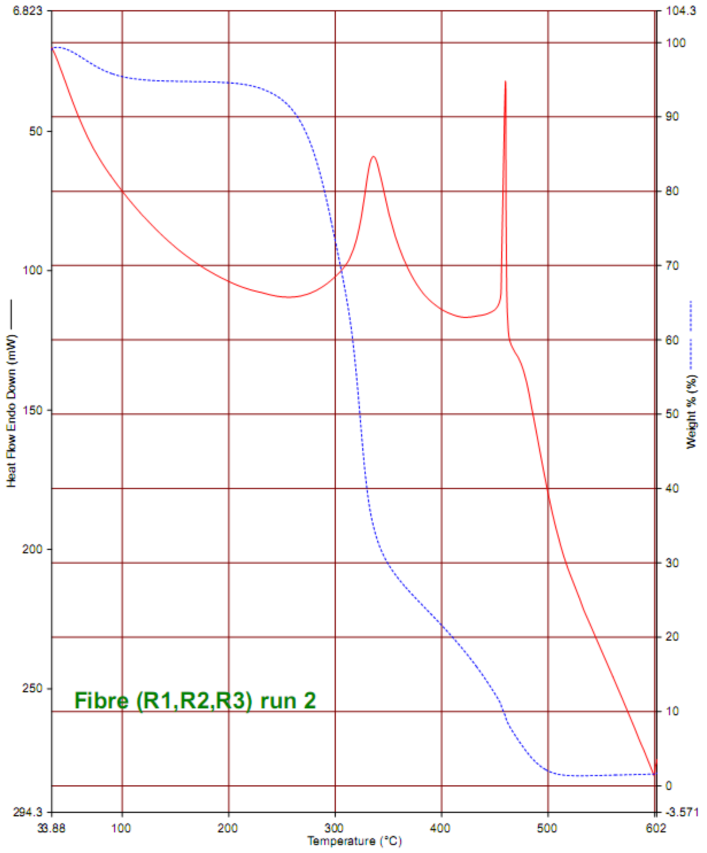

**Figure 5.3 A: Thermogram/mass decomposition from TGA (fibre)**

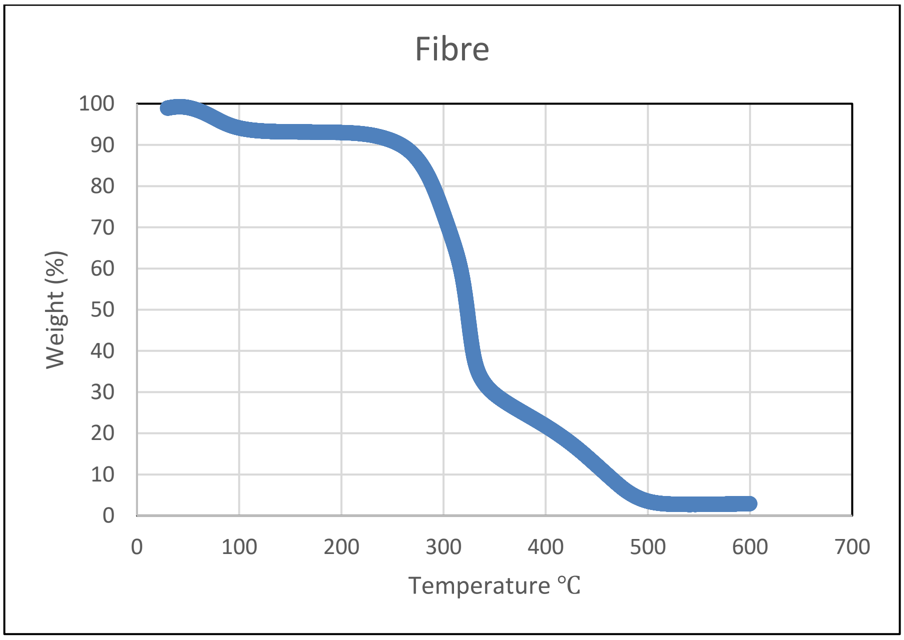

Figure 5.3: TG curve (Mass vs Temp) for fibre at 10°C.min$^{-1}$ heating rate in inert medium

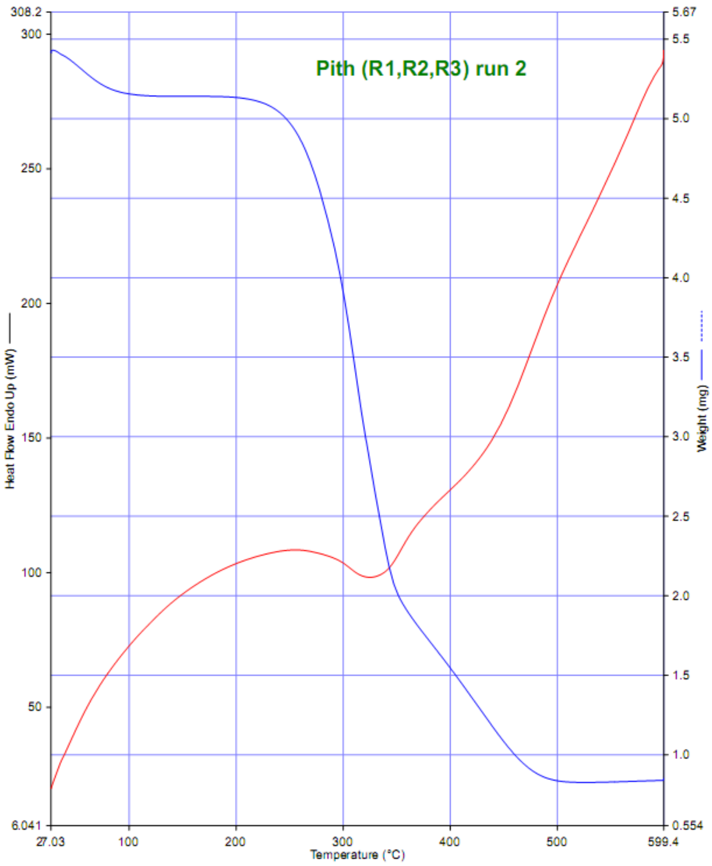

Figure 5.4 A: Thermogram/mass decomposition from TGA (fibre)

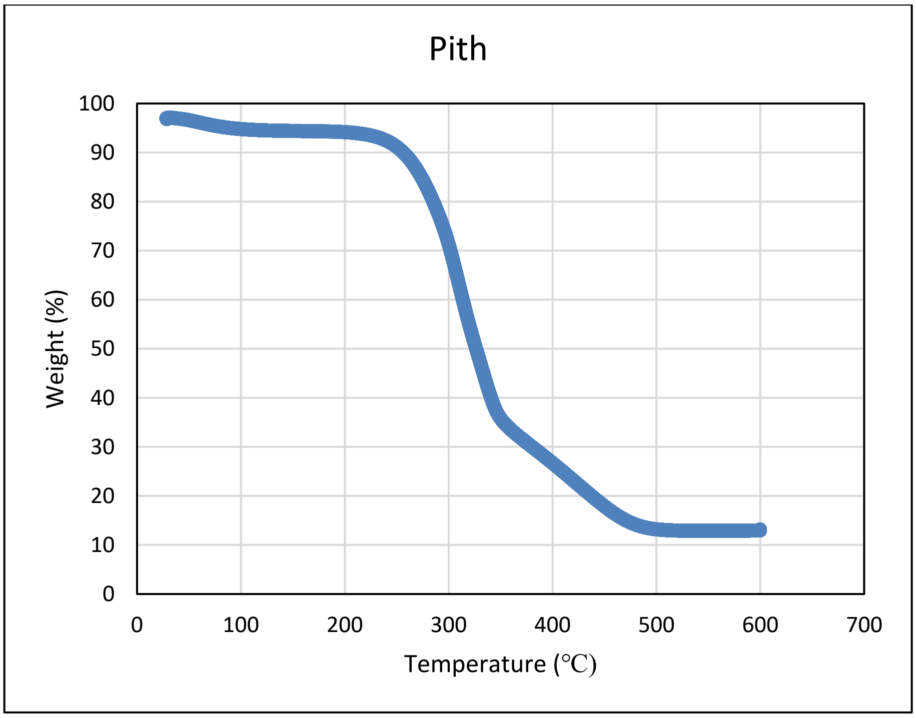

**Figure 5.4: TG curve for pith at 10°C.min$^{-1}$ heating rate in inert medium**

### 5.5.3 Elemental Analysis

Fibre have high carbon content 45.51% as compared to bagasse and pith, followed by bagasse 45.21% and the least is pith of 40.67%. High carbon content in biomass indicate that the biomass has a great use for energy generation through combustion, since carbon enhance long burning time. Bagasse, fibre, and pith demonstrate very low percentage of hydrogen of 5.34, 5.50, and 5.04 respectively also the bagasse and its fraction indicated very low nitrogen percentage of 0.16, 0.16, and 0.35. the result presented in this study are more closely related to the result presented by Garivait *et al.* (2006) in bagasse elemental composition. However, the bagasse and its fractions of fibre and pith have high oxygen proportion as compared to other elements of carbon, hydrogen, nitrogen and sulphur. In addition, bagasse and its fractions have zero percent of sulphur.

Result of bagasse and fibre does not show any significant difference p>0.05 in their elemental analysis (Appendix 1.14.2). Bagasse, fibre have maximum content of carbon, hydrogen, nitrogen, while pith have a low content, but pith have high content of oxygen due to its sponge in nature. Basu (2010) indicated that lower content of sulphur and nitrogen in fuel biomass, contribute positive to the environment. Elemental analysis is very important since it contribute on calorific value of the biomass. Kamruzzaman and Islam (2011a), reported that high proportion of hydrogen and oxygen compared to carbon reduces calorific value. In this study bagasse, fibre, and pith demonstrate very low proportion of hydrogen as compared to carbon, but high proportion of oxygen compared to carbon. The result obtains in this study of elementary and gross calorific value Table 5.4 are closely similar with the result presented in the study by Ismaila *et al.* (2013).

**Table 5.4 Gross calorific value and elementary analysis of biomass fraction**

| Sugarcane and its fractions | Gross calorific value (MJ.kg$^{-1}$) | Carbon % | Hydrogen % | Nitrogen % | Oxygen % | Sulphur % |
|---|---|---|---|---|---|---|
| **Bagasse** | 16.14 | 45.21 | 5.34 | 0.16 | 49.27 | 0.00 |
| **Fibre** | 17.73 | 45.51 | 5.50 | 0.16 | 48.79 | 0.00 |
| **Pith** | 15.74 | 40.67 | 5.04 | 0.35 | 53.92 | 0.00 |

## 5.6 Ignition Time and Burning Rate

Ignition time and burning rate is the key factor attribute in solid fuels. It was demonstrated that they were a significance difference among the briquette treatments $p<0.05$ (Appendix 1.15), for ignition time. Pith with starch briquette have high ignition time of 4.16 minute while pith with charcoal and PVA briquette have very low ignition time of 1.31 minute as compared to another briquette's treatment (Table 5.5). As compared to charcoal which have an ignition time of 2.7 minute, Pith+8%starch and fibre+8%PVA have very high ignition time. Results indicate a trend that, as PVA used as a binder and addition of charcoal, the ignition time decreases (Figure 5.2).

Also, they were a significance difference on burning rate of the briquettes. Burning rate have the same trend as the ignition time (Figure 5.5). Bagasse briquettes with an PVA as a binder have high burning rate (faster consumption during combustion) of 0.0024 kg/min, while bagasse with charcoal and PVA as a binder have a lower burning rate of 0.0010 kg/min as compared to another briquettes treatment. Charcoal have very low burning rate of 0.00095 kg/min as compared to the entire briquettes treatment of the study. However, charcoal briquettes reach its optimum temperature faster during combustion and begin to drop compared to biomass briquettes treatment (Table 5.5).

Charcoal improves both ignition time and burning rate of the briquettes. The improvement of ignition of briquettes with the hybrid of biomass and charcoal is due to the pores that are formed with the particle of charcoal > 0.7 mm and biomass particle. Therefore, the internal biomass caught fire and spread faster within and outside the briquettes. Also, the effect of the type of binder used on ignition time and burning rate. The average ignition time and burning rate of starch briquettes is lower compared to PVA manufactured briquettes. Due to high adhesive force which is contributed by PVA between particle of biomass and it's alcoholic in nature. Closes the poses between the biomass particles which increase the ignition time. In addition, the alcoholic of PVA improves burning rate of biomass briquettes.

**Table 5.5: Ignition time and burning rate of briquettes treatments**

| **Briquette treatments** | **Ignition time(min)** | **Burning rate(kg.min$^{-1}$)** |
|---|---|---|
| Bagasse+8% Starch | 2.13 | 0.0015 |
| Fibre+8%Starch | 2 | 0.0011 |
| Pith+8%starch | 4.16 | 0.0021 |
| Bagasse+8%PVA | 3.46 | 0.0024 |
| Fibre+8%PVA | 4.01 | 0.0013 |
| Pith+8%PVA | 3.88 | 0.0017 |
| Bagasse+50%charcoal+8%starch | 2.85 | 0.0021 |
| Fibre+50%charcoal+8%starch | 1.78 | 0.0011 |
| Pith+50%charcoal+8%starch | 1.66 | 0.0011 |
| Bagasse+50%charcoal+8%PVA | 1.73 | 0.0010 |
| Fibre+50%charcoal+8%PVA | 1.33 | 0.0013 |
| Pith+50%charcoal+8%PVA | 1.31 | 0.0011 |
| Charcoal | 2.7 | 0.00095 |

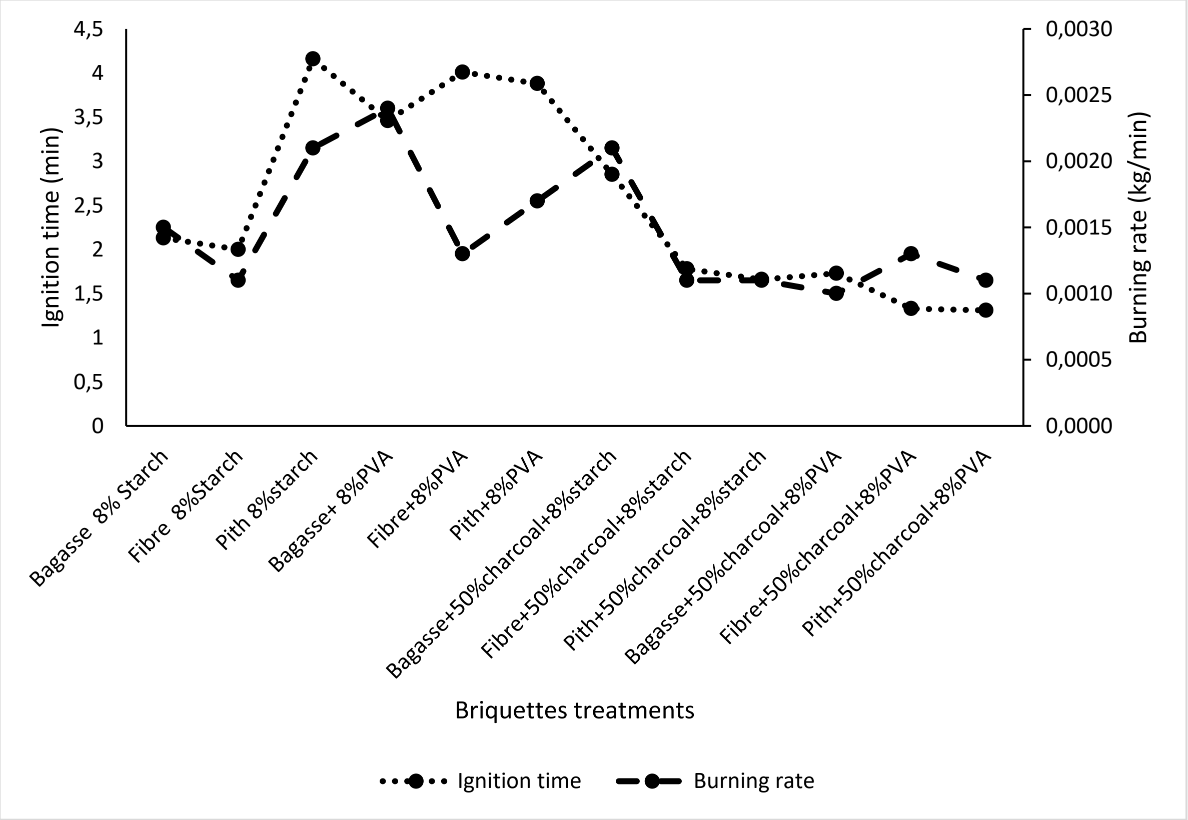

**Figure 5.5 Ignition time and burning rate of briquettes treatments**

## 5.7 Post- Gross Calorific Value and Gas emission analysis

Table 5.6 present the post analysis of gross calorific value and gas emission analysis of the briquettes. They were no significant difference from pre and post gross calorific values of sugarcane fractions briquettes for only starch, PVA and charcoal with starch (Appendix 1.17). However, sugarcane fractions briquettes manufactured with charcoal and PVA as the binder demonstrated a significance different in pre and post gross calorific value and between manufactured briquettes for sugarcane fractions $P<0.05$ (Appendix 1.17). Since starch does not have any fuel value, briquettes manufactured with starch will possible not indicate any improvements in gross calorific value as compared to briquettes manufactured with charcoal plus PVA. Charcoal and PVA has fuel properties which adds some of the gross calorific value from sugarcane fractions in respect of their percentage composition. In addition, the sugarcane biomass briquettes have high gross calorific value as compared to wood charcoal which have gross calorific value ranges between 6.27 to 16 MJ/kg as reported in the literature (Pilusa *et al.*, 2013b;Zubairu and Gana, 2014). However, gross calorific value depends on the type of wood species, geographic location, climate, soil and efficient of pyrolysis process.

According to Occupational Safety and Health Agency (OSHA) standards, all sugarcane briquettes and wood charcoal didn't meet the permissible exposure limit of 8 hours for humans. In Table 5.6, carbon dioxide, carbon monoxide, and sulphur dioxide are regarded as toxic emissions according to (OSHA). The briquettes reached the complete combustion since carbon monoxide is less than the carbon dioxide obtained. During complete combustion carbon dioxide is oxidized to carbon dioxide to reduce the toxicity. Therefore, the manufactured briquettes they combust in the ambient air. Based on the result obtained the briquettes can cause the health issues to be used in households. To prevent the serious illness from using this briquettes, proper ventilation is required (Pilusa *et al.*, 2013b).

**Table 5.6 Gross calorific value and gas emissions of briquettes treatments**

| | **Gross Calorific Value (MJ/kg)** | **Oxygen%** | **Carbon dioxide%** | **Carbon monoxide (ppm)** | **Hydrogen%** | **Methane %** | **Sulphur dioxide (ppm)** |
|---|---|---|---|---|---|---|---|
| Bagasse + 8% Starch | 16.53 | 19.94 | 1.6 | 1720 | 0 | 0.212 | 79 |
| Fibre + 8%Starch | 16.6 | 20.02 | 1.5 | 1391 | 0 | 0.203 | 68 |
| Pith + 8%starch | 14.5 | 20.22 | 0.9 | 1686 | 0 | 0.092 | 83 |
| Bagasse+ 8%PVA | 17.06 | 20.36 | 0.9 | 1430 | 0 | 0.027 | 55 |
| Fibre+8%PVA | 17.73 | 20.62 | 0.8 | 1422 | 0 | 0.022 | 64 |
| Pith+8%PVA | 16.12 | 20.5 | 0.9 | 1549 | 0 | 0.069 | 89 |
| Bagasse+50%charcoal+8%starch | 18.37 | 19.93 | 1.5 | 1619 | 0 | 0.199 | 97 |
| Fibre+50%charcoal+8%starch | 17.86 | 19.69 | 1.4 | 1319 | 0 | 0.015 | 75 |
| Pith+50%charcoal+8%starch | 17.19 | 19.77 | 1.5 | 2298 | 0 | 0.197 | 176 |
| Bagasse+50%charcoal+8%PVA | 19.43 | 20.03 | 1 | 1395 | 0 | 0.05 | 62 |
| Fibre+50%charcoal+8%PVA | 19.57 | 19.99 | 1.1 | 1079 | 0 | 0.02 | 47 |
| Pith+50%charcoal+8%PVA | 18.37 | 20.28 | 1 | 1250 | 0 | 0.04 | 54 |

# CHAPTER SIX: CONCLUSION AND RECOMMENDATION

## 6.1 Conclusion

Based on the result presented in this study in line with the aim and objectives of this study, the findings indicated that bagasse are in effect in terms of chemical, physical and energy properties have huge potential to separate into its fractions of fibre and pith for utilisation as briquette solid fuels. The use of binders and hybridization with other material like charcoal into hybrid biomass briquettes demonstrates an improvement in its physical and energy properties. The conclusions drawn in this study focus are as follows:

1. Briquettes manufactured from sugar cane bagasse biomass are renewable, durable and useable. The heating element is vital during densification to avoid the use of inorganic substances.
2. The presence of pith fraction in bagasse biomass has a negative effect on its energy density and so the need to separate them from fibre is absolutely unquantifiable.
3. Also, pith fraction is not suitable for combustion and to be used in gasification or pyrolysis due to its high activation energy based on thermogravimetric analysis carried out.
4. PVA and charcoal improve the energy density of biomass briquettes, therefore, the use of charcoal as hybrid material or vice versa in briquetting of biomass can reduce deforestation by an estimated 50 percent since in this study 50 percent portion was used.
5. Besides, the use of PVA binder makes packaging and transportation of briquettes more efficient
6. Based on the occupational safety and health agency (OSHA) standards, the briquettes manufactured in this study fell beyond acceptable range in terms of emission profile Therefore, briquettes manufactured are not good to be used in households but they can be used in industries were health safety is a priority for humans.
7. Lastly, the significance demonstrated in the separation of bagasse into its fraction of fibre and pith could help various industries and sectors to use bagasse biomass fractions which is suitable for their production.
8. The findings are an evidence for separation of piths and fibres from bagasse and that sugarcane-milling factories do not waste bagasse by merely burning them in combination, but to employ depithing techniques which to bagasse for energy applications and for other sectors of interest in the production of other value products.

9. Therefore, sugarcane mills can invest in initiatives of developing briquetting facilities in the factory order to manufacture briquettes with potential properties of:

- Low moisture content for better energy and steam generation in boilers.
- The improved energy density of bagasse biomass in the form of briquettes to meet factory energy demand per less quantity of bagasse biomass. If supplies of energy are produced in the form of electricity, it can be sold to the grid system to generate more profits and secure energy security in the country like in Brazil, India, and Mauritius.
- Better storage is necessary due to the reduced bulkiness of bagasse biomass.

## 6.2 Recommendation

Future research should investigate the effect of different binder concentrations, variable densification pressures, and particle size distributions on briquettes thermo-chemical and emission performances. Also, the manufactured briquettes properties should be simulated for performance in boilers in sugarcane milling factories to take the well-informed decision in order to invest in briquetting facilities and efficient cogeneration systems.

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# APPENDIXES

## 1.10 Pre-physical characteristics

### 1.10.1 Moisture content

Table A.1 Statistical table for moisture content

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| | 8 | 249,98 | 31,2475 | 624,16 |
| | 8 | 251,94 | 31,4925 | 607,2644 |
| | 8 | 255,3 | 31,9125 | 599,3813 |
| | | | | |
| Bagasse | 3 | 48,73 | 16,24333 | 0,000633 |
| Fibre | 3 | 171,84 | 57,28 | 0,1323 |
| | 3 | 6 | 2 | 1 |
| Bagasse | 3 | 48,73 | 16,24333 | 0,000633 |
| Pith | 3 | 152,04 | 50,68 | 0 |
| | 3 | 6 | 2 | 1 |
| Fibre | 3 | 171,84 | 57,28 | 0,1323 |
| Pith | 3 | 152,04 | 50,68 | 0 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 1,809733 | 2 | 0,904867 | 4,65398 | 0,028208 | 3,738892 |
| **Columns** | **12812,92** | **7** | **1830,417** | **9414,341** | **1,32E-24** | **2,764199** |
| Error | 2,722 | 14 | 0,194429 | | | |
| | | | | | | |
| Total | 12817,45 | 23 | | | | |

### 1.10.2 Bulk density

### Table A.2 Statistical table for bulk density

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| | 8 | 3,0244 | 0,37805 | 0,1513 |
| | 8 | 5,0386 | 0,62983 | 0,71941 |
| | 8 | 7,0274 | 0,87843 | 1,71884 |
| | | | | |
| Bagasse | 3 | 0,5977 | 0,19923 | 1,8E-06 |
| Fibre | 3 | 0,7175 | 0,23917 | 1,3E-05 |
| | 3 | 6 | 2 | 1 |
| Bagasse | 3 | 0,5977 | 0,19923 | 1,8E-06 |
| Pith | 3 | 0,23 | 0,07667 | 3,3E-07 |
| | 3 | 6 | 2 | 1 |
| Fibre | 3 | 0,7175 | 0,23917 | 1,3E-05 |
| Pith | 3 | 0,23 | 0,07667 | 3,3E-07 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 1,00151 | 2 | 0,50076 | 2,338 | 0,13302 | 3,73889 |
| **Columns** | **15,1283** | **7** | **2,16118** | **10,0904** | **0,00016** | **2,7642** |
| Error | 2,99855 | 14 | 0,21418 | | | |
| | | | | | | |
| Total | 19,1284 | 23 | | | | |

### 1.10.3 Particle size: Table A.3: Statistical table for 25% particle size distribution

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
|  | 8 | 4,62 | 0,5775 | 0,07112 |
|  | 8 | 6,62 | 0,8275 | 0,52684 |
|  |  |  |  |  |
| Bagasse | 2 | 0,788 | 0,394 | 0 |
| Fibre | 2 | 0,788 | 0,394 | 0 |
|  | 2 | 3 | 1,5 | 0,5 |
| Bagasse | 2 | 0,788 | 0,394 | 0 |
| Pith | 2 | 1,044 | 0,522 | 0 |
|  | 2 | 3 | 1,5 | 0,5 |
| Fibre | 2 | 0,788 | 0,394 | 0 |
| Pith | 2 | 1,044 | 0,522 | 0 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 0,25 | 1 | 0,25 | 2,33333 | 0,17047 | 5,59145 |
| **Columns** | **3,43572** | **7** | **0,49082** | **4,58097** | **0,03125** | **3,78704** |
| Error | 0,75 | 7 | 0,10714 |  |  |  |
|  |  |  |  |  |  |  |
| Total | 4,43572 | 15 |  |  |  |  |

### Table A.4 Statistical table for 50% particle size distribution

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
|  | 8 | 4,916 | 0,6145 | 0,06218 |
|  | 8 | 6,916 | 0,8645 | 0,49675 |
|  |  |  |  |  |
| Bagasse | 2 | 0,858 | 0,429 | 0 |
| Fibre | 2 | 0,858 | 0,429 | 0 |
|  | 2 | 3 | 1,5 | 0,5 |
| Bagasse | 2 | 0,858 | 0,429 | 0 |
| Pith | 2 | 1,2 | 0,6 | 0 |
|  | 2 | 3 | 1,5 | 0,5 |
| Fibre | 2 | 0,858 | 0,429 | 0 |
| Pith | 2 | 1,2 | 0,6 | 0 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 0,25 | 1 | 0,25 | 2,33333 | 0,17047 | 5,59145 |
| **Columns** | **3,16256** | **7** | **0,45179** | **4,21675** | **0,03848** | **3,78704** |
| Error | 0,75 | 7 | 0,10714 |  |  |  |
|  |  |  |  |  |  |  |
| Total | 4,16256 | 15 |  |  |  |  |

## Table A.5 Statistical table for 75% particle size distribution

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| | 8 | 5,286 | 0,66075 | 0,05169 |
| | 8 | 7,286 | 0,91075 | 0,45984 |
| | | | | |
| Bagasse | 2 | 0,96 | 0,48 | 0 |
| Fibre | 2 | 0,96 | 0,48 | 0 |
| | 2 | 3 | 1,5 | 0,5 |
| Bagasse | 2 | 0,96 | 0,48 | 0 |
| Pith | 2 | 1,366 | 0,683 | 0 |
| | 2 | 3 | 1,5 | 0,5 |
| Fibre | 2 | 0,96 | 0,48 | 0 |
| Pith | 2 | 1,366 | 0,683 | 0 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 0,25 | 1 | 0,25 | 2,33333 | 0,17047 | 5,59145 |
| **Columns** | **2,83071** | **7** | **0,40439** | **3,77428** | **0,05041** | **3,78704** |
| Error | 0,75 | 7 | 0,10714 | | | |
| | | | | | | |
| Total | 3,83071 | 15 | | | | |

## 1.11 Post-physical analysis

### 1.11.1 Moisture content

**Table A.6 Statistical table for moisture content**

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse + 8% Starch | 2 | 25,22 | 12,61 | 0 |
| Fibre + 8%Starch | 2 | 23,82 | 11,91 | 0 |
| Pith + 8%starch | 2 | 25,42 | 12,71 | 0 |
| Bagasse+ 8%PVA | 2 | 11,8 | 5,9 | 0 |
| Fibre+8%PVA | 2 | 11,76 | 5,88 | 0 |
| Pith+8%PVA | 2 | 11,32 | 5,66 | 0 |
| Bagasse+50%charcoal+8%starch | 2 | 21,74 | 10,87 | 0 |
| Fibre+50%charcoal+8%starch | 2 | 22,94 | 11,47 | 0 |
| Pith+50%charcoal+8%starch | 2 | 22,6 | 11,3 | 0 |
| Bagasse+50%charcoal+8%PVA | 2 | 22,82 | 11,41 | 0 |
| Fibre+50%charcoal+8%PVA | 2 | 22,98 | 11,49 | 0 |
| Pith+50%charcoal+8%PVA | 2 | 20,72 | 10,36 | 0 |
| | | | | |
| 1 | 12 | 121,57 | 10,13083333 | 7,19677197 |
| 2 | 12 | 121,57 | 10,13083333 | 7,19677197 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 158,3289833 | 11 | 14,39354394 | -5,57071E+15 | #NUM! | 2,81793 |
| Columns | 2,84217E-14 | 1 | 2,84217E-14 | -11 | #NUM! | 4,84434 |
| Error | -2,84217E-14 | 11 | -2,58379E-15 | | | |
| | | | | | | |
| Total | 158,3289833 | 23 | | | | |

### 1.11.2 Bulk density

## Table A.7 Statistical table for effect of binding agent on bulk density of briquettes

Anova: Two-Factor Without Replication                    Effect of charcoal in PVA

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse + 8%PVA | 2 | 2,05846 | 1,02923 | 1,1E-07 |
| Fibre + 8%PVA | 2 | 1,85677 | 0,92839 | 3E-07 |
| Pith + 8%PVA | 2 | 1,34133 | 0,67066 | 2,3E-07 |
| Bagasse + 50%charcoal + 8%PVA | 2 | 2,07724 | 1,03862 | 7,7E-07 |
| Fibre + 50%charcoal + 8%PVA | 2 | 2,21353 | 1,10677 | 1,1E-07 |
| Pith + 50%charcoal + 8%PVA | 2 | 1,66142 | 0,83071 | 1,7E-07 |
|  |  |  |  |  |
|  | 6 | 5,60475 | 0,93413 | 0,02605 |
|  | 6 | 5,604 | 0,934 | 0,02592 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Rows** | **0,25982** | **5** | **0,05196** | **159066** | **5,4E-13** | **5,05033** |
| Columns | 4,7E-08 | 1 | 4,7E-08 | 0,14438 | 0,71957 | 6,60789 |
| Error | 1,6E-06 | 5 | 3,3E-07 |  |  |  |
|  |  |  |  |  |  |  |
| Total | 0,25982 | 11 |  |  |  |  |

### 1.11.3 Compressive strength

Anova: Two-Factor Without Replication — Effect of binders on biomass fractions

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse + 8% Starch | 2 | 0 | 0 | 0 |
| Fibre + 8%Starch | 2 | 0 | 0 | 0 |
| Pith + 8%starch | 2 | 64,2635 | 32,1317 | 0,0009445 |
| Bagasse+ 8%PVA | 2 | 2246,88 | 1123,44 | 0,0031833 |
| Fibre+8%PVA | 2 | 1088,26 | 544,128 | 0,0001203 |
| Pith+8%PVA | 2 | 582,135 | 291,067 | 0,0021278 |
| | | | | |
| 1 | 6 | 1990,8 | 331,801 | 196695,12 |
| 2 | 6 | 1990,73 | 331,788 | 196672,68 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Rows** | **1966839** | **5** | **393368** | **331935786** | **2,7E-21** | **5,05033** |
| Columns | 0,00045 | 1 | 0,00045 | 0,3801915 | 0,56449 | 6,60789 |
| Error | 0,00593 | 5 | 0,00119 | | | |
| | | | | | | |
| Total | 1966839 | 11 | | | | |

nova: Two-Factor Without Replication — Effect of charcoal on starch

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse + 8% Starch | 2 | 0 | 0 | 0 |
| Fibre + 8%Starch | 2 | 0 | 0 | 0 |
| Pith + 8%starch | 2 | 64,2635 | 32,1317 | 0,00094 |
| Bagasse+50%charcoal+8%starch | 2 | 0 | 0 | 0 |
| Fibre+50%charcoal+8%starch | 2 | 0 | 0 | 0 |
| Pith+50%charcoal+8%starch | 2 | 0 | 0 | 0 |
| | | | | |
| | 6 | 32,1535 | 5,35891 | 172,308 |
| | 6 | 32,11 | 5,35167 | 171,842 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Rows** | **1720,75** | **5** | **344,149** | **2186291** | **7,7E-16** | **5,05033** |
| Columns | 0,00016 | 1 | 0,00016 | 1 | 0,36322 | 6,60789 |
| Error | 0,00079 | 5 | 0,00016 | | | |
| | | | | | | |
| Total | 1720,75 | 11 | | | | |

Anova: Two-Factor Without Replication

Effect of charcoal in PVA

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse+ 8%PVA | 2 | 2246,88 | 1123,44 | 0,00318333 |
| Fibre+8%PVA | 2 | 1088,26 | 544,128 | 0,0001203 |
| Pith+8%PVA | 2 | 582,135 | 291,067 | 0,0021278 |
| Bagasse+50%charcoal+8%PVA | 2 | 1147,2 | 573,599 | 0,00517736 |
| Fibre+50%charcoal+8%PVA | 2 | 1157,65 | 578,826 | 0,0081515 |
| Pith+50%charcoal+8%PVA | 2 | 942,994 | 471,497 | 0,01515714 |
|  |  |  |  |  |
|  | 6 | 3582,54 | 597,091 | 78040,4088 |
|  | 6 | 3582,57 | 597,095 | 78022,8106 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Rows** | **780316** | **5** | **156063** | **23042469,3** | **2,1E-18** | **5,05033** |
| Columns | 5,3E-05 | 1 | 5,3E-05 | 0,00785296 | 0,93283 | 6,60789 |
| Error | 0,03386 | 5 | 0,00677 |  |  |  |
|  |  |  |  |  |  |  |
| Total | 780316 | 11 |  |  |  |  |

### 1.11.4 Shattering index

Anova: Two-Factor Without Replication Shattering effects of binder

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse + 8% Starch | 2 | 1,342 | 0,671 | 0,00072 |
| Fibre + 8%Starch | 2 | 1,863 | 0,9315 | 0,00198 |
| Pith + 8%starch | 2 | 1,895 | 0,9475 | 0,00451 |
| Bagasse+ 8%PVA | 2 | 1,969 | 0,9845 | 0,00042 |
| Fibre+8%PVA | 2 | 1,979 | 0,9895 | 0,00018 |
| Pith+8%PVA | 2 | 2 | 1 | 0 |
| | | | | |
| 1 | 6 | 5,608 | 0,93467 | 0,01938 |
| 2 | 6 | 5,44 | 0,90667 | 0,01303 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Rows** | **0,15655** | **5** | **0,03131** | **28,6311** | **0,0011** | **5,05033** |
| Columns | 0,00235 | 1 | 0,00235 | 2,15069 | 0,20242 | 6,60789 |
| Error | 0,00547 | 5 | 0,00109 | | | |
| | | | | | | |
| Total | 0,16437 | 11 | | | | |

Anova: Two-Factor Without Replication Effect of charcoal on starch

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse + 8% Starch | 2 | 1,342 | 0,671 | 0,00072 |
| Fibre + 8%Starch | 2 | 1,863 | 0,9315 | 0,00198 |
| Pith + 8%starch | 2 | 1,895 | 0,9475 | 0,00451 |
| Bagasse+50%charcoal+8%starch | 2 | 1,167 | 0,5835 | 8,5E-05 |
| Fibre+50%charcoal+8%starch | 2 | 0,24 | 0,12 | 0,0002 |
| Pith+50%charcoal+8%starch | 2 | 1,915 | 0,9575 | 0,00281 |
| | | | | |
| | 6 | 4,312 | 0,71867 | 0,11669 |
| | 6 | 4,11 | 0,685 | 0,09747 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Rows** | **1,0639** | **5** | **0,21278** | **153,838** | **1,8E-05** | **5,05033** |
| Columns | 0,0034 | 1 | 0,0034 | 2,45843 | 0,17768 | 6,60789 |
| Error | 0,00692 | 5 | 0,00138 | | | |
| | | | | | | |
| Total | 1,07421 | 11 | | | | |

Anova: Two-Factor Without Replication

Shattering effect of charcoal on PVA as binder

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse+ 8%PVA | 2 | 1,969 | 0,9845 | 0,00042 |
| Fibre+8%PVA | 2 | 1,979 | 0,9895 | 0,00018 |
| Pith+8%PVA | 2 | 2 | 1 | 0 |
| Bagasse+50%charcoal+8%PVA | 2 | 1,979 | 0,9895 | 0,00018 |
| Fibre+50%charcoal+8%PVA | 2 | 1,909 | 0,9545 | 0,00396 |
| Pith+50%charcoal+8%PVA | 2 | 1,92958 | 0,96479 | 0,00242 |
| | | | | |
| | 6 | 5,99558 | 0,99926 | 1,8E-07 |
| | 6 | 5,77 | 0,96167 | 0,00118 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Rows** | **0,00296** | **5** | **0,00059** | **1,01367** | **0,49424** | **5,05033** |
| Columns | 0,00424 | 1 | 0,00424 | 7,25581 | 0,04311 | 6,60789 |
| Error | 0,00292 | 5 | 0,00058 | | | |
| | | | | | | |
| Total | 0,01012 | 11 | | | | |

## 1.12 Proximate analysis

### 1.12.1 Volatile matter

Anova: Two-Factor Without Replication

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| 1 | 8 | 488,742 | 61,0928 | 1403,64 |
| 2 | 8 | 497,29 | 62,1612 | 1402,33 |
| 3 | 8 | 504,237 | 63,0296 | 1391,24 |
| | | | | |
| Bagasse | 3 | 241,657 | 80,5523 | 5,74543 |
| Fibre | 3 | 267,168 | 89,056 | 0,00751 |
| | 3 | 6 | 2 | 1 |
| Bagasse | 3 | 241,657 | 80,5523 | 5,74543 |
| Pith | 3 | 230,31 | 76,77 | 0,637 |
| | 3 | 6 | 2 | 1 |
| Fibre | 3 | 267,168 | 89,056 | 0,00751 |
| Pith | 3 | 230,31 | 76,77 | 0,637 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 15,0592 | 2 | 7,52958 | 7,26965 | 0,006835874 | 3,73889 |
| **Columns** | **29366** | **7** | **4195,14** | **4050,32** | **4,82111E-22** | **2,7642** |
| Error | 14,5006 | 14 | 1,03576 | | | |
| | | | | | | |
| Total | 29395,5 | 23 | | | | |

### 1.12.2 Ash content

Anova: Two-Factor Without Replication

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| 1 | 8 | 63,235 | 7,90437 | 58,6628 |
| 2 | 8 | 58,5474 | 7,31842 | 53,1114 |
| 3 | 8 | 57,6303 | 7,20378 | 42,0643 |
| | | | | |
| Bagasse | 3 | 24,0475 | 8,01583 | 3,40768 |
| Fibre | 3 | 5,27313 | 1,75771 | 0,00282 |
| | 3 | 6 | 2 | 1 |
| Bagasse | 3 | 24,0475 | 8,01583 | 3,40768 |
| Pith | 3 | 54,3857 | 18,1286 | 0,69109 |
| | 3 | 6 | 2 | 1 |
| Fibre | 3 | 5,27313 | 1,75771 | 0,00282 |
| Pith | 3 | 54,3857 | 18,1286 | 0,69109 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 2,25948 | 2 | 1,12974 | 0,87158 | 0,4398 | 3,73889 |
| Columns | 1058,72 | 7 | 151,246 | 116,684 | 2,5E-11 | 2,7642 |
| Error | 18,1469 | 14 | 1,29621 | | | |
| | | | | | | |
| Total | 1079,13 | 23 | | | | |

### 1.12.3 Fixed carbon content

Anova: Two-Factor Without Replication

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| 1 | 8 | 176,493 | 22,0616 | 298,828 |
| 2 | 8 | 165,257 | 20,6572 | 258,214 |
| 3 | 8 | 159,393 | 19,9241 | 211,996 |
| | | | | |
| Bagasse | 3 | 82,3907 | 27,4636 | 17,8096 |
| Fibre | 3 | 38,1053 | 12,7018 | 0,00153 |
| | 3 | 6 | 2 | 1 |
| Bagasse | 3 | 82,3907 | 27,4636 | 17,8096 |
| Pith | 3 | 124,076 | 41,3586 | 2,64494 |
| | 3 | 6 | 2 | 1 |
| Fibre | 3 | 38,1053 | 12,7018 | 0,00153 |
| Pith | 3 | 124,076 | 41,3586 | 2,64494 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 18,8758 | 2 | 9,43792 | 1,97362 | 0,17576 | 3,73889 |
| **Columns** | **5316,32** | **7** | **759,474** | **158,818** | **3E-12** | **2,7642** |
| Error | 66,9486 | 14 | 4,78204 | | | |
| | | | | | | |
| Total | 5402,14 | 23 | | | | |

## 1.13 Thermo-chemical characteristics

### 1.13.1 High heating value

Anova: Two-Factor Without Replication

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| | 8 | 102,18 | 12,7725 | 53,5286 |
| | 8 | 103,88 | 12,985 | 46,5446 |
| | 8 | 103,64 | 12,955 | 38,4792 |
| | | | | |
| Bagassse | 3 | 48,43 | 16,1433 | 0,35083 |
| Fibre | 3 | 53,2 | 17,7333 | 0,03063 |
| | 3 | 6 | 2 | 1 |
| Bagassse | 3 | 48,43 | 16,1433 | 0,35083 |
| Pith | 3 | 47,22 | 15,74 | 0,0043 |
| | 3 | 6 | 2 | 1 |
| Fibre | 3 | 53,2 | 17,7333 | 0,03063 |
| Pith | 3 | 47,22 | 15,74 | 0,0043 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 0,21163 | 2 | 0,10582 | 0,27787 | 0,761477661 | 3,73889 |
| **Columns** | **964,535** | **7** | **137,791** | **361,83** | **1,01396E-14** | **2,7642** |
| Error | 5,33143 | 14 | 0,38082 | | | |
| | | | | | | |
| Total | 970,078 | 23 | | | | |

### 1.13.2 Elemental analysis

Anova: Two-Factor Without Replication for

**Carbon percentage**

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| | 8 | 261,236 | 32,6545 | 385,909 |
| | 8 | 269,438 | 33,6798 | 386,331 |
| | 8 | 269,788 | 33,7235 | 364,133 |
| | | | | |
| Bagasse | 3 | 135,657 | 45,219 | 0,04248 |
| Fibre | 3 | 136,544 | 45,5147 | 0,72494 |
| | 3 | 6 | 2 | 1 |
| Bagasse | 3 | 135,657 | 45,219 | 0,04248 |
| Pith | 3 | 122,03 | 40,6767 | 0,31782 |
| | 3 | 6 | 2 | 1 |
| Fibre | 3 | 136,544 | 45,5147 | 0,72494 |
| Pith | 3 | 122,03 | 40,6767 | 0,31782 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 5,8555 | 2 | 2,92775 | 16,4913 | 0,00021 | 3,73889 |
| **Columns** | **7952,13** | **7** | **1136,02** | **6398,91** | **2E-23** | **2,7642** |
| Error | 2,48546 | 14 | 0,17753 | | | |
| | | | | | | |
| Total | 7960,47 | 23 | | | | |

Anova: Two-Factor Without Replication for **Hydrogen percentage**

| SUMMARY | Count | Sum | Average | Variance |
|---|---|---|---|---|
| | 8 | 33,168 | 4,146 | 3,80576 |
| | 8 | 36,19 | 4,52375 | 2,44706 |
| | 8 | 38,028 | 4,7535 | 1,20982 |
| | | | | |
| Bagasse | 3 | 16,034 | 5,34467 | 0,0084 |
| Fibre | 3 | 16,511 | 5,50367 | 0,00903 |
| | 3 | 6 | 2 | 1 |
| Bagasse | 3 | 16,034 | 5,34467 | 0,0084 |
| Pith | 3 | 15,148 | 5,04933 | 0,01361 |
| | 3 | 6 | 2 | 1 |
| Fibre | 3 | 16,511 | 5,50367 | 0,00903 |
| Pith | 3 | 15,148 | 5,04933 | 0,01361 |

ANOVA

| Source of Variation | SS | df | MS | F | P-value | F crit |
|---|---|---|---|---|---|---|
| Rows | 1,50543 | 2 | 0,75272 | 4,02408 | 0,04162 | 3,73889 |
| **Columns** | **49,6197** | **7** | **7,08854** | **37,8959** | **4,8E-08** | **2,7642** |
| Error | 2,61874 | 14 | 0,18705 | | | |
| | | | | | | |
| Total | 53,7439 | 23 | | | | |

Anova: Two-Factor Without Replication for

**Nitrogen percentage**

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| | 8 | 2,9 | 0,3625 | 0,15626 |
| | 8 | 5,57 | 0,69625 | 0,66294 |
| | 8 | 7,64 | 0,955 | 1,60212 |
| | | | | |
| Bagasse | 3 | 0,509 | 0,16967 | 0,00345 |
| Fibre | 3 | 0,48 | 0,16 | 0,00144 |
| | 3 | 6 | 2 | 1 |
| Bagasse | 3 | 0,509 | 0,16967 | 0,00345 |
| Pith | 3 | 1,066 | 0,35533 | 0,01783 |
| | 3 | 6 | 2 | 1 |
| Fibre | 3 | 0,48 | 0,16 | 0,00144 |
| Pith | 3 | 1,066 | 0,35533 | 0,01783 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 1,41173 | 2 | 0,70586 | 3,68847 | 0,05167 | 3,73889 |
| **Columns** | **14,2701** | **7** | **2,03858** | **10,6525** | **0,00012** | **2,7642** |
| Error | 2,67918 | 14 | 0,19137 | | | |
| | | | | | | |
| Total | 18,361 | 23 | | | | |

Anova: Two-Factor Without Replication for **Oxygen percentage**

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| | 8 | 310,696 | 38,837 | 550,172 |
| | 8 | 304,802 | 38,1003 | 500,554 |
| | 8 | 308,372 | 38,5465 | 486,377 |
| | | | | |
| Bagasse | 3 | 147,8 | 49,2667 | 0,1232 |
| Fibre | 3 | 146,379 | 48,793 | 0,92741 |
| | 3 | 6 | 2 | 1 |
| Bagasse | 3 | 147,8 | 49,2667 | 0,1232 |
| Pith | 3 | 161,756 | 53,9187 | 0,65207 |
| | 3 | 6 | 2 | 1 |
| Fibre | 3 | 146,379 | 48,793 | 0,92741 |
| Pith | 3 | 161,756 | 53,9187 | 0,65207 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 2,20355 | 2 | 1,10177 | 1,79209 | 0,20279 | 3,73889 |
| **Columns** | **10751,1** | **7** | **1535,87** | **2498,18** | **1,4E-20** | **2,7642** |
| Error | 8,60717 | 14 | 0,6148 | | | |
| | | | | | | |
| Total | 10761,9 | 23 | | | | |

## 1.14 Ignition time

Anova: Two-Factor Without Replication **Ignition stat binder effect**

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse 8% Starch | 2 | 4,13 | 2,065 | 0,00845 |
| Fibre 8%Starch | 2 | 4,1 | 2,05 | 0,005 |
| Pith 8%starch | 2 | 8,34 | 4,17 | 0,0002 |
| Bagasse+ 8%PVA | 2 | 6,77 | 3,385 | 0,01125 |
| Fibre+8%PVA | 2 | 8,12 | 4,06 | 0,005 |
| Pith+8%PVA | 2 | 7,78 | 3,89 | 0,0002 |
| 1 | 6 | 19,64 | 3,27333 | 0,93207 |
| 2 | 6 | 19,6 | 3,26667 | 0,98279 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Rows** | **9,5443** | **5** | **1,90886** | **318,497** | **2,96738E-06** | **5,05033** |
| Columns | 0,00013 | 1 | 0,00013 | 0,02225 | 0,887261395 | 6,60789 |
| Error | 0,02997 | 5 | 0,00599 | | | |
| Total | 9,5744 | 11 | | | | |

Anova: Two-Factor Without Replication **Ignition stat charcoal effect on starch**

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse 8% Starch | 2 | 4,13 | 2,065 | 0,00845 |
| Fibre 8%Starch | 2 | 4,1 | 2,05 | 0,005 |
| Pith 8%starch | 2 | 8,34 | 4,17 | 0,0002 |
| Bagasse+50%charcoal+8%starch | 2 | 5,26 | 2,63 | 0,0968 |
| Fibre+50%charcoal+8%starch | 2 | 3,28 | 1,64 | 0,0392 |
| Pith+50%charcoal+8%starch | 2 | 2,86 | 1,43 | 0,1058 |
| | 6 | 14,58 | 2,43 | 0,89192 |
| | 6 | 13,39 | 2,23167 | 1,0997 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Rows** | **9,82064** | **5** | **1,96413** | **71,4532** | **0,00012** | **5,05033** |
| Columns | 0,11801 | 1 | 0,11801 | 4,29303 | 0,09301 | 6,60789 |
| Error | 0,13744 | 5 | 0,02749 | | | |
| Total | 10,0761 | 11 | | | | |

Anova: Two-Factor Without Replication **Ignition stat charcoal effect PVA**

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse+ 8%PVA | 2 | 6,77 | 3,385 | 0,01125 |
| Fibre+8%PVA | 2 | 8,12 | 4,06 | 0,005 |
| Pith+8%PVA | 2 | 7,78 | 3,89 | 0,0002 |
| Bagasse+50%charcoal+8%PVA | 2 | 3,23 | 1,615 | 0,02645 |
| Fibre+50%charcoal+8%PVA | 2 | 2,43 | 1,215 | 0,02645 |
| Pith+50%charcoal+8%PVA | 2 | 2,42 | 1,21 | 0,02 |
| | 6 | 15,72 | 2,62 | 1,67952 |
| | 6 | 15,03 | 2,505 | 2,02003 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Rows** | **18,4481** | **5** | **3,68962** | **371,375** | **2E-06** | **5,05033** |
| Columns | 0,03967 | 1 | 0,03967 | 3,99346 | 0,10215 | 6,60789 |
| Error | 0,04968 | 5 | 0,00994 | | | |
| Total | 18,5374 | 11 | | | | |

**Charcoal on starch binder**

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse + 8% Starch | 2 | 0,0028 | 0,0014 | 2E-08 |
| Fibre + 8%Starch | 2 | 0,0021 | 0,00105 | 5E-09 |
| Pith + 8%starch | 2 | 0,0044 | 0,0022 | 2E-08 |
| Bagasse+50%charcoal+8%starch | 2 | 0,0043 | 0,00215 | 5E-09 |
| Fibre+50%charcoal+8%starch | 2 | 0,0023 | 0,00115 | 5E-09 |
| Pith+50%charcoal+8%starch | 2 | 0,0024 | 0,0012 | 2E-08 |
| | | | | |
| | 6 | 0,009 | 0,0015 | 2,4E-07 |
| | 6 | 0,0093 | 0,00155 | 3,1E-07 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Rows** | **2,6675E-06** | **5** | **5,335E-07** | **39,5185** | **0,00051** | **5,05033** |
| Columns | 7,5E-09 | 1 | 7,5E-09 | 0,55556 | 0,48959 | 6,60789 |
| Error | 6,75E-08 | 5 | 1,35E-08 | | | |
| | | | | | | |
| Total | 2,7425E-06 | 11 | | | | |

## 1.15 Burning Rate

### Burning rate binder effect

Anova: Two-Factor Without Replication

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse + 8% Starch | 2 | 0,0028 | 0,0014 | 2E-08 |
| Fibre + 8%Starch | 2 | 0,0021 | 0,00105 | 5E-09 |
| Pith + 8%starch | 2 | 0,0044 | 0,0022 | 2E-08 |
| Bagasse+ 8%PVA | 2 | 0,0049 | 0,00245 | 5E-09 |
| Fibre+8%PVA | 2 | 0,0029 | 0,00145 | 4,5E-08 |
| Pith+8%PVA | 2 | 0,0036 | 0,0018 | 2E-08 |
| | | | | |
| 1 | 6 | 0,0101 | 0,0016833 | 2,4E-07 |
| 2 | 6 | 0,0106 | 0,0017667 | 3,3E-07 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Rows** | **2,7875E-06** | **5** | **5,575E-07** | **29,6018** | **0,00101** | **5,05033** |
| Columns | 2,0833E-08 | 1 | 2,083E-08 | 1,10619 | 0,34106 | 6,60789 |
| Error | 9,4167E-08 | 5 | 1,883E-08 | | | |
| | | | | | | |
| Total | 2,9025E-06 | 11 | | | | |

### Effect of charcoal on PVA binder

Anova: Two-Factor Without Replication

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse+ 8%PVA | 2 | 0,0049 | 0,00245 | 5E-09 |
| Fibre+8%PVA | 2 | 0,0029 | 0,00145 | 4,5E-08 |
| Pith+8%PVA | 2 | 0,0036 | 0,0018 | 2E-08 |
| Bagasse+50%charcoal+8%PVA | 2 | 0,002 | 0,001 | 0 |
| Fibre+50%charcoal+8%PVA | 2 | 0,0028 | 0,0014 | 2E-08 |
| Pith+50%charcoal+8%PVA | 2 | 0,0024 | 0,0012 | 2E-08 |
| | | | | |
| | 6 | 0,0088 | 0,001466667 | 2,7E-07 |
| | 6 | 0,0098 | 0,001633333 | 2,7E-07 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Rows** | **0,00000266** | **5** | **0,000000532** | **99,75** | **5,27536E-05** | **5,05033** |
| Columns | 8,3333E-08 | 1 | 8,33333E-08 | 15,625 | 0,010819897 | 6,60789 |
| Error | 2,6667E-08 | 5 | 5,33333E-09 | | | |
| | | | | | | |
| Total | 0,00000277 | 11 | | | | |

## 1.16 Post-gross calorific value

Anova: Two-Factor Without Replication

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse+8% Starch vs Bagasse | 2 | 32,67 | 16,335 | 0,07605 |
| Fibre+8%Starch vs Fibre | 2 | 34,33 | 17,165 | 0,63845 |
| Pith+8%starch vs Pith | 2 | 30,24 | 15,12 | 0,7688 |
| | | | | |
| Post Calorific value | 3 | 47,63 | 15,8767 | 1,42263 |
| Pre Calorific value | 3 | 49,61 | 16,5367 | 1,10803 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 4,23143 | 2 | 2,11572 | 5,09873 | 0,16397 | 19 |
| **Columns** | **0,6534** | **1** | **0,6534** | **1,57465** | **0,3363** | **18,5128** |
| Error | 0,8299 | 2 | 0,41495 | | | |
| | | | | | | |
| Total | 5,71473 | 5 | | | | |

Anova: Two-Factor Without Replication

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse+8%PVA vs Bagasse | 2 | 33,2 | 16,6 | 0,4232 |
| Fibre+8%PVA vs Fibre | 2 | 35,46 | 17,73 | 0 |
| Pith+8%PVA vs Pith | 2 | 31,86 | 15,93 | 0,0722 |
| | | | | |
| Post Calorific value | 3 | 50,91 | 16,97 | 0,6541 |
| Pre Calorific value | 3 | 49,61 | 16,5367 | 1,10803 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 3,31053 | 2 | 1,65527 | 15,4891 | 0,06065 | 19 |
| **Columns** | **0,28167** | **1** | **0,28167** | **2,63568** | **0,24597** | **18,5128** |
| Error | 0,21373 | 2 | 0,10687 | | | |
| | | | | | | |
| Total | 3,80593 | 5 | | | | |

Anova: Two-Factor Without Replication

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse+50%charcoal+8%starch vs Bagasse | 2 | 34,51 | 17,255 | 2,48645 |
| Fibre+50%charcoal+8%starch vs Fibre | 2 | 35,59 | 17,795 | 0,00845 |
| Pith+50%charcoal+8%starch vs Pith | 2 | 32,93 | 16,465 | 1,05125 |
| | | | | |
| Post Calorific value | 3 | 53,42 | 17,8067 | 0,35023 |
| Pre Calorific value | 3 | 49,61 | 16,5367 | 1,10803 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 1,78973 | 2 | 0,89487 | 1,58833 | 0,38635 | 19 |
| **Columns** | **2,41935** | **1** | **2,41935** | **4,2942** | **0,17402** | **18,5128** |
| Error | 1,1268 | 2 | 0,5634 | | | |
| | | | | | | |
| Total | 5,33588 | 5 | | | | |

Anova: Two-Factor Without Replication

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse+50%charcoal+8%PVA vs Bagasse | 2 | 35,57 | 17,785 | 5,41205 |
| Fibre+50%charcoal+8%PVA vs Fibre | 2 | 37,3 | 18,65 | 1,6928 |
| Pith+50%charcoal+8%PVA vs Pith | 2 | 34,11 | 17,055 | 3,45845 |
| | | | | |
| Post Calorific value | 3 | 57,37 | 19,1233 | 0,43053 |
| Pre Calorific value | 3 | 49,61 | 16,5367 | 1,10803 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Rows | 2,5501 | 2 | 1,27505 | 4,83859 | 0,17127 | 19 |
| **Columns** | **10,0363** | **1** | **10,0363** | **38,0859** | **0,02527** | **18,5128** |
| Error | 0,52703 | 2 | 0,26352 | | | |
| | | | | | | |
| Total | 13,1134 | 5 | | | | |

## Gross calorific value comprehensive statistic

Anova: Two-Factor Without Replication

| *SUMMARY* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Bagasse + 8% Starch | 2 | 33,05 | 16,525 | 5E-05 |
| Fibre + 8%Starch | 2 | 33,21 | 16,605 | 5E-05 |
| Pith + 8%starch | 2 | 29,01 | 14,505 | 5E-05 |
| Bagasse+ 8%PVA | 2 | 34,11 | 17,055 | 5E-05 |
| Fibre+8%PVA | 2 | 35,45 | 17,725 | 5E-05 |
| Pith+8%PVA | 2 | 32,24 | 16,12 | 0 |
| Bagasse+50%charcoal+8%starch | 2 | 36,74 | 18,37 | 0 |
| Fibre+50%charcoal+8%starch | 2 | 35,72 | 17,86 | 0 |
| Pith+50%charcoal+8%starch | 2 | 34,38 | 17,19 | 0 |
| Bagasse+50%charcoal+8%PVA | 2 | 38,85 | 19,425 | 5E-05 |
| Fibre+50%charcoal+8%PVA | 2 | 39,14 | 19,57 | 0 |
| Pith+50%charcoal+8%PVA | 2 | 36,75 | 18,375 | 5E-05 |
| | | | | |
| Replicate 1 | 12 | 209,33 | 17,4442 | 2,05579 |
| Replicate 2 | 12 | 209,32 | 17,4433 | 2,04888 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Rows** | **45,151** | **11** | **4,10464** | **130557** | **1,8E-26** | **2,81793** |
| Columns | 4,2E-06 | 1 | 4,2E-06 | 0,13253 | 0,72272 | 4,84434 |
| Error | 0,00035 | 11 | 3,1E-05 | | | |
| | | | | | | |
| Total | 45,1514 | 23 | | | | |