

**INVESTIGATION ON *TRADESCANTIA ZEBRINE* (WANDERING JEW) AS A
RESOURCE FOR BIOMASS ENERGY PRODUCTION**

BY

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DECLARATION

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DEDICATION

This thesis is dedicated to my dear parents Joseph Charana and Martha Mogere, my fiancé Doricah, my dear sisters Josephine Saringi, Jane Kemuma, Jackline Nyandoche, Janet, and Mary, my brothers John Kennedy-JK, George, Ongwae and Dr. Ondigo and to everybody who stood by me for their support in all areas of my life throughout my studies.

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ABSTRACT

Tradescantiazebrina (TRZE) is readily available and grows rapidly in agricultural farms. It grows well along with other agricultural crops like tea bushes, maize and coffee; however, it is a weed demanding its continuous removal from farms whenever encountered by farmers. This research investigated the potential of *Tradescantiazebrina* (TRZE) weed plant for bio-fuel energy production. TRZE analysis had the following specific objectives; to harvest, roll, dry, mill and produce pellets from TRZE; determine the energy content in the material; and thirdly, determine the combustion characteristics of TRZE material that form a combustible material. To achieve the stated objectives, TRZE was harvested, sorted, cleaned, rolled, dried, milled, screened, blended and pelletized for combustion property analysis. The combustion characteristics of TRZE were analyzed in an oven and the following data were obtained. Moisture content in (% wt.) of the material from the source had 14.20% with a heating value of 4.49MJ/Kg (using a ballistic bomb calorimeter) while an average of 18.10MJ/Kg was obtained after fitting in energy models from data obtained after oven combustion of compressed pellet particles. The average percentage concentrations by weight of nitrogen, carbon, volatile matter, fixed carbon, ash and moisture content in the TRZE indicates 1.42 (using Kjeldahl method), 50.37, 54.30, 19.22, 16.03 and 10.45 respectively. The values of VM and FC are averagely high, an indication that TRZE material produces heat. The results of moisture content shows that TRZE is within range of other combustible biomass material like coconut shell - 13.95, rice husks - 12.67 and paddy husks - 10.79 (Oladeji, 2010). Determined angle of repose ranged from 30⁰ to 50⁰ at varying particle sizes. The general stoichiometric formula of CH_{1.17}O_{0.64} and A/F ratio of 4.63 was determined. For a pellet with an average mass of 15.30grams, the compression ratio ($l/2r$) decreased as follows 0.54, 0.52, 0.51 and 0.50 over pressure loads of 0.0, 6.89bars, 13.78bars and 20.68bars respectively. In the experiments of durability indices determination by Tumbler method (Oveisi, 2011), 2.0mm particle sizes achieved durability index of 80% for no binder condition at 13.79 bars while other particle sizes obtained maximum indices of 50% at 13.79 bars for 0.6 mm, 10% at 6.86 bars for 1.18 mm and a no value for 2.36 mm particle sizes at all pressure loads. Only 2.0mm particle sizes obtained 85% durability index at 13.79bars for water bound pellets. Cane molasses bound pellets achieved a durability index of 83% at 20.68 bars for 0.6 mm, 95% at 6.86 bars, 13.79 bars and 20.68 bars for both 1.18 mm and 2mm, while 2.36mm particle sizes achieved 90% index at 6.86 bars, 13.79 bars and 20.68 bars. Comparatively, cane molasses binder produced high quality pellets followed by water binder and least quality pellets when no binder was used. Averagely, 2.00mm particle size performed well in all the three conditioning parameters in a range of 6.86bars to 20.68bars pressure loads. In density versus pressure load experiment, molasses bound pellets' density were above 700kg/m³ for all pressure loads applied while the no binder and water bound states achieved density values below 600kg/m³. Nevertheless, compressibility study curves using Jones (1960) model revealed that 2.36mm particle sizes are more easily compressed than 1.18mm particle sizes which were least compressible when cane molasses was used as a binder. The TRZE C/N ratio (34.47) was out of the optimum range (20-30) for biogas production. Thus, if *Tradescantiazebrina* is properly exploited and processed, it could be a good quality and readily available biomass feedstock for heat energy production.

Keywords

Tradescantiazebrina, heating value, pellets, C/N ratio, biomass.

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ABBREVIATIONS AND ACRONYMS

AD	Anaerobic Digestion
TRZE	<i>Tradescantiazebrina</i>
C	Elemental Carbon
CV	Calorific Value
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
DM	Dry Matter
EREC	European Renewable Energy Council
FC	Fixed Carbon
GIS	Geographical Information System
GoK	Government of Kenya
HV	Heating Value
HS	High Solids
IIED	Institute of International Economic Development
IWM	Institute of Water Management
LBECs	Lignocellulose-Based Energy Crops
LS	Low Solids
m	Percentage moisture content
MC	Moisture Content
MS	Medium Solids
MSW	Municipal Solid Wastes
N	Percentage nitrogen content
OECD	Organization for Economic Cooperation and Development
OLR	Organic Loading Rate
p.s.	Particle size
TGA	Thermo-gravimetric Analysis
UNEP	United Nations Environmental Programme
V	Percentage volatile matter
VM	Volatile Matter
VS	Volatile Solids

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Problem

Though there are significant progress in increasing energy supply, access to low-cost, clean and reliable sources of energy is still prevalent. Energy is an important input for economic growth, social development and for improving the quality of life. Adequate access to source of energy is a major factor that determines living standards in the modern world for both rural and urban inhabitants. The availability of energy at affordable prices to the rural people is a major factor that determines a whole array of other productive activities that lead to economic growth (Upali, 2001). Further research works indicate that renewable energies create more jobs than fossil fuels per unit of output (UNEP, 2008; Energy Institute, 2009; Greenpeace and EREC, 2010).

In 2008, the European Renewable Energy Council (EREC) passed an EU directive with ambitious and engaging aims to substitute 20% of the world's energy demand by renewable energies (Binneret *al.*, 2011). Biomass energy, in comparison with traditional fossil fuels, receives more attention for providing almost CO₂ neutral emission during utilization and renewable contribution. On February 16th 2005, when the Kyoto protocol formally went into effect, the conference members raised the development and utilization of renewable energy to a higher level and conversion of biomass to higher quality energy products became a hot topic (UNEP, 2008).

Biomass, in principle, can provide a renewable source of indigenous energy (Omuterema, 2003). Biomass energy is energy produced from organic material grown, collected or harvested for energy use. Biomass production entails using garbage, municipal solid wastes (MSW), agricultural residues and other renewable like corn and vegetation to generate heat energy. During the decomposition of organic materials like vegetation, pipes capture and transport methane gas produced for combustion to produce heat energy. Vegetation can further burn directly to generate electricity.

Biomass fuels such as wood can help developing countries move towards green economies in which the poor benefit from producing sustainable clean energy (Mangat, 2011). Though it may seem beneficial to use renewable plant materials for bio-fuels, the use of crop residues and other biomass for bio-fuels raises major concern about energy balance, food security and environmental problems.

1.1.1 Global energy situation

Through the ages, people have relied on more than 10,000 plant species for food. No longer, barely 150 are now cultivated and only 12 provide 80 per cent of all humanity's supply (UNEP, 2009). Thirteen per cent (13%) of primary energy consumption for the Organization for Economic Cooperation and Development (OECD) countries is from renewable energy. These include water, wind, solar and biomass renewable energies. All these renewable sources are sustainable and available (May, 2010).

Worldwide, biomass is the fourth largest energy resource after coal, oil and natural gas and it is estimated at about fourteen per cent (14%) of global primary energy and much higher in many developing countries (Kurchania *et al.*, 2010). Since the industrial

revolution of 1850's the total rate of energy use from all sources has been growing even faster than the world population growth. From 1970 to 1995, energy use increased at a rate of 2.5% per year, which is, doubling after every 30 years compared with the worldwide population growth of 1.7% per year that doubles every 40 to 60 years (Pimentel, 2009). Pimentel, (2009) further notes that during the year of 1700, abundant fossil fuel energy supplies made it possible to augment agricultural production to feed an increasing number of human population. For example, energy availability has made possible the purification and transport of water, reduced human diseases and generally enhanced the quality of human life.

The study on biomass report released by the Institute of International Economic Development (IIED) in 2011 indicated that reliance on biomass is set to triple from 10 per cent to 30 per cent of global energy consumption by 2050 (Macqueen, 2011). Developed nations such as India and China are taking this seriously and investing in new technology to capitalize on biomass fuels. In Austria, 80 per cent of new homes are equipped with wood-pellet boilers. Denmark plans to double its use of biomass energy in its bid to become carbon neutral by 2050. In the United Kingdom, building all the planned biomass-to-electricity power station would expand demand for biomass from 1 million tonnes to 50 million- 60 million tons (Mangat, 2011).

The installed capacity of biomass power generation worldwide is about 35,000MW, with about 7,000MW in the US derived from forest-product-industry and agricultural residues. In the US, biomass provides about 3-4% of primary energy for heating and cooking (Kurchania *et al.*, 2010). In Germany, biogas is one of the most efficient technologies and most beneficial to the environment. The number of biogas plants in Germany rose from

2,010 plants in 2004 to 3,280 plants in 2006, which further contributed to nearly quadrupling of installed electrical power from 247MWel (megawatt, electrical) to 950MWel (Binneret *et al.*, 2011).

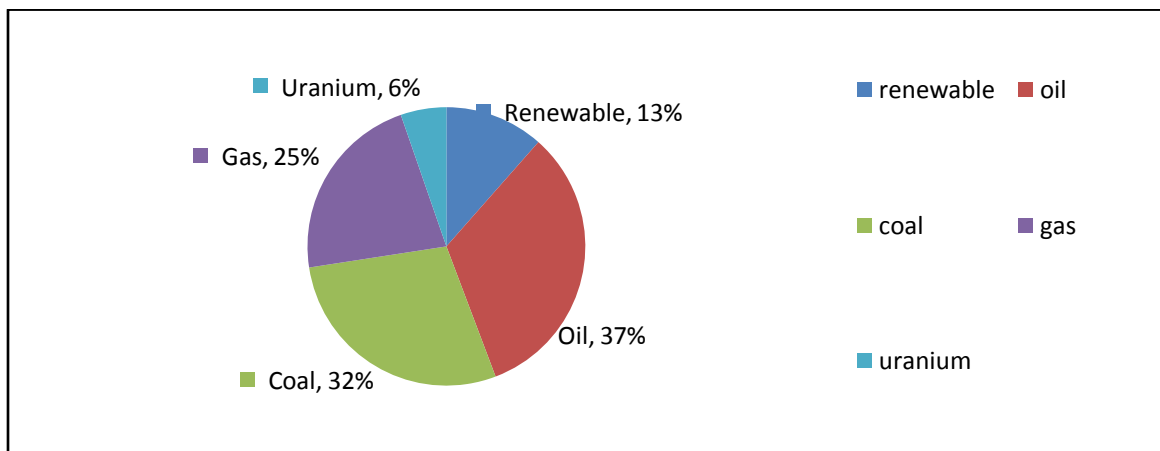


Figure 1.1: Shares of global energy demand in 2007. (Source: May, 2010)

1.1.2 Energy demand and supply in Kenya

Biomass energy provides about 68% of Kenya's national energy requirement (Macqueen, 2011). According to the government report of March 2003, 67% of households in Kenya depended on wood fuel to meet their energy requirements. Consumption of 35 million tonnes of woody biomass in the year 2000 surpassed the sustainable supply figure of only 15 million tonnes (Mangat, 2011). Reports according to the Government of Kenya (GoK) development plan for the period of 2002-2008 indicated that biomass energy provided about 68% of the total energy requirements, petroleum 20% and electricity 10% other alternative sources 2% in terms of energy supply. There is high expectation for rapid growth of energy demand in the next few years. Constraints in conventional sources of electricity, unsuitable physical supply of petroleum fuel and its escalating prices require exploration of alternatives such as biomass based gasification (Omuterema, 2008).

Renewable fuel is wasted if not utilized and waste fuel like TRZE, an agricultural farm weed is renewable and sustainable though a weed as known to agricultural scientists. Energy recovery from waste, specifically residuals and weeds related to agriculture (crop production) provide significant energy, are largely untapped. In the same vein, cascading biomass to produce material first, then recovering the energy content of the resulting waste, can maximize CO₂ mitigation potential of biomass (UNEP, 2009). Substitution of fossil fuels by renewable resources comes more and more into focus for the rapidly growing energy demand. Biogas plays a major role with regard to replacement of fossil fuels for production of heat and power. Biogas is most beneficial to the environment for bio-energy production (Binneret *al.* 2011).

It is on this background that this research sets out to make an investigation of biomass energy resource from TRZE weed plant with a view to exploiting its potential in areas of distribution.

1.2 Statement of the Problem

Wandering jew, *Tradescantiazebrina*, a weed plant in agricultural farms, abundantly grows well along with crops. It intertwines within the roots and stems of most agricultural crops. Currently, the farmer uproots and disposes the plant from farms once encountered. Disposal of the plant is a menace to farmers; it resists wilting when placed over crags, scree, boulders or even inside ravines unless burnt down. In comparison to other biomass materials like wood, crop residues and wastes, TRZE's growth is rapid. The characteristic abundance, rapid growth and cheap in cost, makes it ideal source of biomass. However, as the country is experiencing depletion and scarcity of non-

renewable energy resources, there is need for research on this plant material to investigate its suitability as a biomass energy resource. Thus, this study determined the basic characteristics of the material that are considered necessary in evaluating the biomass' pellet suitability for transportation, storage and energy value produced after combustion and its suitability as a feedstock for AD synthesis.

1.3 Objectives of the Study

1.3.1 General objectives

A central objective of this work is to investigate the potential of *Tradescantiazebrina* (TRZE) weed plant for bio-fuel production.

1.3.2 Specific objectives

The specific objectives of this study are;

1. To harvest, roll, mill and produce pellets from TRZE.
2. To determine the energy content of *Tradescantiazebrina* weed plant.
3. To determine the physical and chemical characteristics of the TRZE weed plant that form a combustible material.

1.4 Scope of the Study

The study is limited to agricultural weed specifically *Trades cantiazebrina* as the main research material. Additives such as binders are used to facilitate bonding for easier study. TRZE is a weed plant found in agricultural farms.

1.5 Conceptual Framework

Any woody biomass has some certain amount of fluids in them no matter how dry they can be. *Tradescantiazebrina* exists as a fleshy succulent plant in farms. For utilization of any biomass material for combustion purposes, drying by airing removes some moisture content. Extraction principle applies for the case of large amount of water in the material. The extracted fluid-component can be disposed of or kept for further analysis. Likewise, combustion characteristics of the fibers remaining after extraction are analyzed through an oven furnace. Further, the fine fibers are milled and mixed with a starchy binding agent to produce pellets through which other physical characteristics are investigated.

The researcher conceptualizes in this study that densification of *Tradescantiazebrina* can be achieved and its properties studied after the weed has undergone all the indicated transforming processes that include harvesting, sorting, cleaning, rolling, milling, conditioning and pelletizing as shown in the conceptualized flow chart diagram in Fig. 1.2.

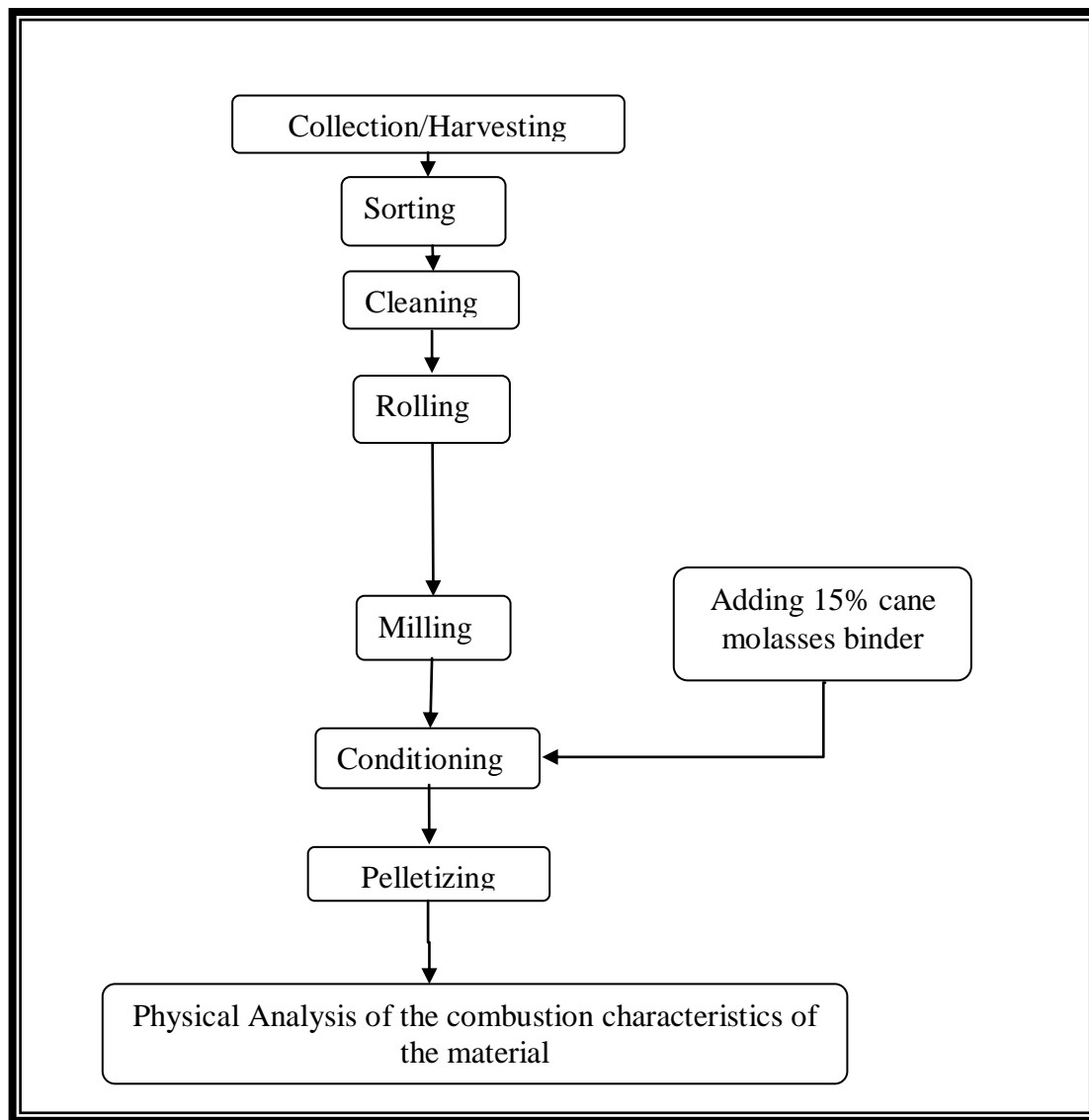


Figure 1.2. Conceptual framework

1.6 Limitations of the Study

This study was limited by the following setbacks;

1. There was lack of finances to enable the researcher obtain some of the required materials. This led to delay in data collection and study programme. Most

experienced delays occurred during procuring of a bomb calorimeter and a roller machine.

2. This research work lacked technical expertise to device the equipment required for the experimental work. Designing and producing a die and plunger relied heavily on the existent of a metal pipe with the required dimensions. This prompted the researcher to loafer from his destined area of research in search of the equipment, thus taking time in data collection.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

This chapter reviews previous materials and studies on biomass research. The aim is first to review TRZE location, identification, moisture content and material storage. Secondly, studies on densification technologies and models for determining the heating values for other biomass materials are reviewed. Thirdly, the chapter reviews the pellet formation influencing parameters like durability, density, pressures, press channels and particle sizes. Further reviews on biomass combustion characteristics are studied as mathematical models get considered for densification, compressing and evaluation of energy values.

The properties of good fuel depend upon its physical and chemical properties. Two technical criteria are generally used to select fuels; their combustion characteristics and their suitability for handling and storage. The first characteristic depends upon the type and moisture content of raw material. The latter criterion depends on the durability of the pellet formed.

2.2 TRZE Location and Identification

The data found showed mass distribution to exist in the Gulf Coast region of Eastern Mexico (Tropicos.org. 2009). In Kenya, TRZE is found in tropical regions, highlands, areas with soils of pH ranging from mildly acidic (6.1) to mildly alkaline (7.8) (Source: <http://davesgarden.com/guides/pf/go/596>) and all other regions where tea, maize, banana, coffee, sugarcane and wheat are grown as primary cash crops. Most importantly, the

environment under which these cash crops grow supports the thriving of TRZE. For example, tea performs well at an optimal pH value of 5.6 (Source: www.teaboard.or.ke/industry/growing_production.html) at a range of 4.5 to 7.0, banana at a range of 5.5 to 6.5 (source: www.homeguides.sfgate.com/ph-requirements-growing-bananas-30130.html), sugarcane at a range of 5.0–8.5 (www.sugarcane crops.com/soil_requirement), and maize at a range of 5.8 to 7.0 (Espinoza & Jeremy, n.d.). From the above pH ranges, TRZE thrives in and along every crop. Scientifically, TRZE is the researcher-initialized botanical name form for wandering jew derived from genus and species name of the plant that is *Tradescantia* as genus name and *zebrina* as the species name. The common English name is wandering jew. Locally, various dialects refer to it *Rikongiyo* by Gusii people, *Loplopitiet* by Nandi/Kalenjin community, *Tarino* by the Keiyo people and *Ang'ayo* by Luo people.

Weeds are a major hindrance to agricultural plant growth. They favorably compete with crops by consuming the most of nutrients provided by applied fertilizers and foods that crops require for growth. Most notable agricultural farms that face the axe of this competition include; sugar cane farm, banana plantation, tea plantation farms and maize farms. These weeds have a high benefit in heat generation.

2.3 Moisture Content of a Biomass Material

The moisture content of a solid biomass material is expressed as the quantity of water per unit mass of the dry solid. Under wet basis, percent moisture content is the ratio of the total mass of moisture in the original sample to the original wet mass of the sample. This is given by the equation proposed by Jain (2013) shown below.

$$MC = \left[\frac{\text{wet weight} - \text{dry weight}}{\text{wet weight}} \right] \times 100 \quad (2.1)$$

Also, Darra, (1999) proposed the following formula (2.2) for determination of moisture content;

$$\text{moisture content, (\%Wb)} = \frac{w_2 - w_3}{w_2 - w_1} \times 100 \quad (2.2)$$

%Wb = is the percentage by weight, w_1 = weight of crucible, g; w_2 = weight of crucible + sample, g; w_3 = weight of crucible + sample, after heating.

Moisture content in any biomass material exists in three different forms; inherent, surface and decomposed. Commonly, moisture content that is normally referred to is inherent plus surface moisture content (Jain, 2013). According to Jain, inherent moisture content is the moisture that a biomass fuel material can hold within the capillaries when in equilibrium with the atmosphere while surface moisture content is the forms on the surface of the biomass material. Decomposed moisture content is determined stoichiometrically and is normally found to range between 450 to 600 grams of water for every kilogram of biomass material during thermal decomposition reactions. This is the moisture that normally forms on organic compounds of biomass during thermal decomposition reactions.

A combustible biomass may have humidity ranging from 5% to 35% (Mani *et al.*, 2006). Humidity and temperature are a factor to variation in moisture content of a biomass material.

Moisture content can be determined by two different methods. The conventional method or standard oven method for determination of moisture is drying it in an oven to constant

weight at 105⁰C (DIN EN 14774-2, 2009, Jain, 2013). The drying time required to achieve constant mass will vary depending on the type, quantity, size and condition of the material. Large clay lumps may require significantly longer drying periods. Constant mass has been achieved when less than 0.1% of the test sample wet mass is lost during an additional exposure to the drying process. Subsequent drying periods to verify constant mass shall be of at least 1 hour (California Test 226, 1999). At temperatures in excess of 100⁰C the water content is removed and converted into vapor. Optimal humidity level in biomass fuels must reach drying phase. Care must be taken, because prolonged drying in the oven can result in loss of volatile constituents due to decomposition, distillation or oxidation of the biomass.

Secondly, moisture content can be measured by use of moisture meter analyzer. The meter has two extending probes that are inserted into a combustible material and the moisture content is shown digitally on the screen. This meter uses dry cell power to perform the analysis.

Arbon, (2002) found that conveying and storing of high moisture fuel is a problem, more so in bunker choking and bed temperature maintenance. Moisture content can vary during handling. Very dry biomass materials are hygroscopic. The study conducted by Stahl *et al.*, (2002-2006) on chemical characteristics of wheat and rice straws (0.12mm particle size) found the mass of dried samples increased from 0% to 3-4% as they were being handled. Thus, dried materials have to be carefully stored in closed vessels. Correct handling is a precondition for reliable analytical results.

2.4 Material Storage and Angle of Repose

The angle of repose expressed in degrees, is the angle made by the pile diagonal side to the horizontal base under free fall conditions. It is determined by filling a large open ended tube with oven dried biomass material and then lifting the pipe to let the material form a pile on the ground. The angle of repose is then calculated as the angle between the diagonal of pile and the horizontal base (Jain, 2013). It is affected by particle size and moisture content of the material. The angle of repose helps in determining the angle of fuel hopper, fuel transportation in the furnace. As thermo-chemical conversion process changes, the angle of repose varies as well. Jain (2013), notes that when the angle of repose is closer to 90 degrees or more, the fuel tends to bridge and becomes free to flow at lower angles.

2.5 Biomass Densification Technologies for Energy Application

Biomass densification technologies include; pelleting, extrusion, agglomeration and briquetting.

2.5.1 Pelleting

Pelleting is the process of compressing or molding a material into the shape of a pellet. Verena and Marina, (2011) defined pelletizing as the compression of loose organic waste materials such as sawdust or rice husks or coffee husks to a more compact form (briquette) that makes the waste into a marketable product as a substitute for fuel wood or coal. Verena and Marina, (2011) found that pelletizing process is based on the principle of agglomeration, a mechanism of particle bonding. During agglomeration, many

particles of solid matter tighten to each other and form a particle composite. Summer (1999), notes that pellets are porous and consist of three distinct phases, namely; solids, liquids and air which interact with each other to form structural integrity. Verena and Marina further found that the tightening process can be caused by different mechanisms, namely;

- i. Solid-body bonds build between the particles when melting, caused by heating, takes place.
- ii. When very small particles are used, different forces like Van der Waals' forces cause bonds between them.
- iii. Bonds form due to locking of single particles, in case of fibrous materials.
- iv. Liquids within the pore space between particles induce bonds between particles out of tightening between liquid and particles on both sides of a liquid element or drop.

Pelletizing a material of 6-8mm particle size with 10-20% powdery component gives the best results. It is desirable to crush larger particles to get a random distribution of particle sizes so that adequate amounts of small particles are present for embedding into larger particles (Grover & Mishra, 1996). The presence of different size particles improves the packing dynamics and contributes to high static strength (Grover & Mishra, 1996). Pelletizing is implemented pressurized agglomeration. The bonding mechanism takes place under known pressurized conditions and in a given geometrical shape. When entering the pelletizing process, the material is dried to predefined moisture content. The dried material is milled to a particle size crucial for the pelletizing process as found by Verena and Marina, (2011).

Pelletization leads to an improvement in flow ability, appearance and mixing properties thus avoiding generation of excessive dust and reducing segregation. It further eliminates undesirable properties and improves the physical and chemical properties of fine powders.

2.5.2 Extrusion

In extrusion, smaller particles are brought closer by forces acting on them to provide a stronger densified bulk material. The material is put at the hopper, and by help of a rotating screw, the material moves from the hopper through the barrel against the die resulting to a significant pressure gradient and friction due to the biomass shearing. Biomass material is heated as it is extruded, due to the combined effects of wall friction at the barrel, internal friction in the material and high rotational speed of the screw. This material is further forced through the extrusion die to form the briquette/pellets with the required shape (Tumuluru *et al.*, 2010c). If heat generated is not enough for the material to achieve pseudo-plastic state for smooth extrusion, heat is provided externally to the extruders by using either band or tape heaters as found by Grover and Mishra, (1996). However, processing of biomass using screw compaction involves the following mechanisms (Grover & Mishra, 1996).

Maximum energy is recommended to overcome particle friction and compress the material to ground biomass before the material reaches compression zone. Secondly, at the compression zone, the biomass material becomes soft as temperature increases from 200⁰C to 250⁰C during which the material loses its elastic nature resulting to an increased area of inter-particle contact. Consequently, local bridges due to particles coming closer

are formed and interlocking of particles result. At this zone, biomass absorbs energy from friction for uniform heating and mixing through its mass. In the third stage, biomass enters a tapered die where moisture is evaporated due to prevailing temperatures of 280⁰C, further moistening and increasing compression on the biomass material. Finally, steam removal and compaction are simultaneous and pressure normalizes resulting in a uniform extruded log.

The merits of screw compaction according to Grover & Mishra, (1996) include the formation of uniformly sized briquettes, the production of partially carbonized outer surface that facilitate ignition, combustion and protection against ambient moisture and increased surface area for combustion due to the concentric hole created. However, screw compaction requires high power compared to piston press.

2.5.3 Agglomeration

Agglomeration is a method of increasing particle size by gluing powder particles together (Tumuluru *et al.*, 2010a). It is normally applied to variety of powders such as hydrated lime, pulverized coal, iron ore, fly ash and cement. Literature on agglomeration of agricultural or woody biomass is scarce. In principle, biomass agglomeration process consists of the following steps (Tumuluru *et al.*, 2010b);

- i. Biomass grinding
- ii. Agglomeration of the powder with a binder, and
- iii. Briquette drying

The efficiency of agglomeration is improved by mixing biomass powder separately and feeding it into the agglomerate. Mani (2008) proposed the following mechanism for pellet/ granules formation;

- i. Attraction forces between solid particles
- ii. Interfacial forces and capillary pressure in movable liquid surfaces
- iii. Adhesion and cohesion forces in non-freely movable binder bridges
- iv. Mechanical interlocking and
- v. Solid bridges

2.5.4 Briquetting

Briquetting is the densification of loose and smaller biomass waste using a briquette press in order to utilize biomass for fuel applications. It is performed using hydraulic, mechanical or roller presses (Tumuluru *et al.*, 2010a). Briquettes range from 900-1300kg/m³ in density. Briquettes made from biofuels are clean and are green fuels that can be used in furnaces, boilers or open fires (Tumuluru *et al.*, 2010a).

Briquetting machines handle large-sized particles and wider moisture contents without addition of binders. During biomass briquetting process, the material is compressed under high pressure and temperature in which the particles of biomass self-bond to form a briquette by thermoplastic flow. This is the plasticizing of protein and starch rich in densified material which acts as a binding agent. For example, at high temperature and pressure, lignin, a natural binder softens and improves binding ability and thus forms high-density briquettes (Tumuluru *et al.*, 2010a). The main advantage of using biomass briquette/ pellets in industrial furnaces is ash slagging due to the alkali content in

briquette made from biomass. Other advantages are; briquettes have the ease of charging the furnace; have increased heating value; improved combustion characteristics; reduced entrained particulate emissions and have uniform size and shape (Tumuluru *et al.*, 2010b).

2.6 Heating Value of Biomass Material

The heating value of biomass represents the energy possessed by the feedstock as potential fuels (Mark *et al.*, 2008). Heating value is the quantity of heat evolved per unit weight of fuel measured in joules per gram (J/g) or in Mega joules per kilogram (MJ/Kg). Different plants belong to different classification, thus different species contain varying heating energy value. Bowman and Wilson (1988) indicated that the heating values range from a low of 16.23MJ/Kg for animal grass, sorghum intrans to a high of 22.47MJ/Kg in the dead foliage of the woody species, leguminous ironwood (*Erythrophleumchloroystachys*). Over 34 species studied, it was found that the energy content for fresh foliage was similar to that of dead foliage in all species except for northern cypress pine (*Callitrisintratropica*) as noted by Bowman and Panton, (1993) in which dead foliage was found to have a substantially lower heating value than the fresh material. The findings proves essential for this study since *TRZE* often exists in fresh states even after being uprooted or weeded from agricultural farms.

During densification, Tumuluru *et al.*, (2010b) found that the heating value of pellets depended upon process conditions like temperature, particle size and in-feed pretreatment. Pellets with higher density have higher heating value. For example table 2.1 shows the change in heating value due to impact of processing condition.

Table 2.1. Change of HV due to pelletizing process

Process	Type of pellets	HV	References
Torrefaction and steam explosion at 200-300 °C	Wood pellets	17-18MJ/Kg	Tumuluru <i>et al.</i> ,2010b
	Straw based pellets	17-18MJ/Kg	Satyanavayana <i>et al.</i> , 2010
Torrefaction at 200-300°C	Corn stover&miscanthus	Increased by 20%	Tumuluru <i>et al.</i> ,2010b

2.6.1 Combustion models

Jain, (2013) proposed models for predicting the heating value, stoichiometric formula and air fuel ratio.

i. Heating value models

This model utilizes ash, ultimate values and the heating value data in predicting LCV and HCV. These models include;

$$\text{Model 1. LCV} = 17.89 - 0.21A \quad (2.3)$$

$$\text{Model 2. HCV} = 19.24 - 0.22A \quad (2.4)$$

$$\text{Model 3. LCV} = 0.19C + 0.38365H + 0.217O - 3.4363 \quad (2.5)$$

Where LCV and HCV are lower and higher heating values in (MJ/kg) whereas A, C, O, and H are percentage ash, carbon, oxygen and hydrogen of biomass on dry weight basis respectively. The models, (Eqns. 2.3 to 2.4) correlates to lower and higher heating values with ash content of biomass material with the assumption that heating value of ash free biomass is constant and is a linear function of ash content (Jain, 2013). Jain further notes that the model, (Eqn. 2.5) is appropriate for predicting lower heating value for known values of carbon, hydrogen and oxygen.

Adetogun and other writers (2014) also proposed the following formulae for heating value calculation.

$$HV = 2.326(147.6C + 144V) \text{kJ/Kg} \quad (2.6)$$

Where HV= heating value; C= percentage fixed carbon content; and V = the percentage volatile matter.

ii. Stoichiometric formula model

Elemental analysis provides the necessary ground for determining the stoichiometric formula of a biomass material. This formula gives the atomic composition of carbon, hydrogen and oxygen in a biomass material. The stoichiometric formula, for any biomass material, is represented by CH_xO_y , (Jain, 2013). Where x and y are atomic ratios of hydrogen and oxygen determined from the following expressions;

$$x = H/(C/12) \quad (2.7)$$

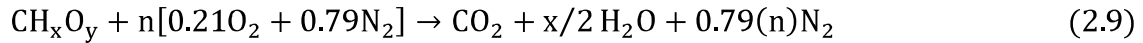
$$y = (O/16)/(C/12) \quad (2.8)$$

For biomass material $x=1.4$ and $y = 0.6$ while for coal, $x = 0.9$ and $y = 0.1$. The evaluation of stoichiometric formula enables molecular weight and stoichiometric air fuel ratio to be calculated.

iii. Stoichiometric air fuel ratio

The stoichiometric air fuel ratio represents the theoretical air required for complete oxidation for a unit weight of biomass. The ratio is important in determining the amount of air required in combustion chambers and in designing air/ gas handling systems (Jain, 2013). The air to fuel ratio should not be excess nor should it be too little. When too little air is provided, the combustion becomes incomplete and subsequent pollution occurs

whereas when too much of the air is supplied, there is a loss of energy through the induction fan and the reaction is inefficient. For a balanced combustion of any biomass material, (Eqn. 2.9), applies.



In this equation, air is assumed to have a molecular composition of 21% in the relation $\text{O}_2 : \text{N}_2 :: 21 : 79$ and represents the number of moles of air in the reaction.

2.6.2 Oxygen bomb calorimeter method

Darra, (1999) proposes, (Eqn. 2.10) of using Oxygen Bomb Calorimeter method for determining the Heating value for any biomass material.

$$\text{Heating Value} \left(\frac{\text{MJ}}{\text{kg}} \right) = \frac{(W + w) \times (T_1 - T_2)}{X} \quad (2.10)$$

Where, W = weight of water in calorimeter (kg); w = water equivalent of apparatus, T_1 = initial temperature of water ($^{\circ}\text{C}$); T_2 = final temperature of water ($^{\circ}\text{C}$); X = weight of fuel sample taken (kg).

2.7 Pellet Formation Influencing Parameters

2.7.1 Pellet durability

According to Oveisi (2011), pellet durability has been defined as the ability of the pellet to withstand wear, tear, decay and loss of material through continual use; it is also the resistance to change from original appearance; the ability to resist weathering action or chemical attack. Measured durability for pellets varies depending on the methods used for measurements. The strength of the pellet depends on the durability of the pellet. A

durability measurement is a test for compressive, impact and water resistance. These tests are indicative of the maximum force or stress the formed pellet can withstand. Durability is computed as a percentage of pellets mass remaining on the sieve screen after tumbling over total mass. Durability measurement is a key towards quality control in a manufacturing process. Durability can as well assessed on resistance to particle breakages. Slow compression, abrasion and impact crushing are the methods employed in determining particle breakages.

The following formula is appropriate when determining the durability of a substance;

$$\text{Durability test (\%)} = \frac{\text{mass of material left on the screen}}{\text{mass of original mass}} \times 100 \quad (2.11)$$

Mechanical durability is the ability of densified biofuels to remain intact when handled. It is determined through shock or friction application on the densified material. Various methods brought forward in determining durability of biomass materials are; Tumbler, Dural test, Ligno tester, Holmen tester and Drop test.

i. Tumbler test;

It is a durability test unit made of a rectangular stainless steel container with inner dimension of 300mm x 125mm (Oveisi, 2011). One baffle is placed inside the container to enforce the tumbling effect. The rotation speed is adjusted to 50rpm and the rotation time is 10minutes. The percentage of pellets remained unbroken to total sample weight is reported as a durability index. The treated sample is sieved using round screen holes of 3.15mm. This unit is used in North America and Europe.

ii. Dural tester;

The equipment consists of a grinder that produces and applies a consistent impact and shear to the pellets. It is small, light and portable. A mass of 100g with a testing time of 30s can be used for any typical test.

iii. Ligno tester;

In this tester, pellets are exposed to shocks caused by air stream that induces the particles to collide against each other and against the walls of the equipment. The best box has a four-sided pyramid form and air stream comes from below the box. During the procedure, fines are removed from the sample by sieving. 100g of the sample is placed in the box and air stream of 70mbar is blown for 60s into the ligno tester. The dust produced is removed and the remaining pellets are weighed and durability is calculated.

iv. Holmen tester;

This is pneumatic system which simulates a more rigorous treatment of pellets. A 100g sieved sample of pellets is introduced in a stream of air. Feed pellets are conveyed around in a closed circuit at an air of 20m/s velocity for 0.5-2minutes standard time based on the pellet diameter. The air and pellets are circulated through right angled bends, impinging repeatedly on hard surfaces. After treatment, the samples are sieved again with a sieve having an opening of about 80% of the pellet diameter.

v. Drop test;

Drop test is used to test the durability of bulk materials, including coal, ore and pellets. A substance is dropped from different heights depending on the pellet size of the pellet. Drop test measures the amount of dust in a situation close to reality. The dust produced from the drop is removed and remaining unbroken pellets is weighed to determine the percentage breakage. Samples may be dropped singular or a number of pellets all together.

2.7.2 Density as a material variables

Classification of density falls into two categories; true density (specific density) and bulk density. True density is the weight per unit volume of a single biomass piece (Jain, 2013). It depends on biomass moisture content but has a constant value on dry weight basis. For fast growing wood trees like *Acacia*, *Albizia*, *Eucalyptus*, *Derrisindica*, *Leucaena*, *Lecocephala*, *Arjunat* their true density vary from 600 to 820kg/m³ (Jain, 2013). Bulk density is the weight of bulk biomass material divided by the volume occupied. It depends on size, shape and level of compaction. Determining bulk density is crucial in evaluating the cost of transportation and storage space for biomass. Bulk and true densities of certain fuel materials are shown in appendix XII.

2.7.3 Other material variables

i. Moisture content

The optimum moisture content for wood species is reported to be between 5-10% (wt) in beech 6-10% (wt) Nielsen *et al.*, (2009), spruce about 10% (wt), and pine 6-8% (wt) Nielsen *et al.*, (2009). The optimum moisture contents for the pelletization of grasses are

significantly higher. For unspecified straw in general is 10-15% (wt), barley straw 19-23% (wt), wheat straw at about 15% (wt), and corn stover about 10% (wt). Increasing moisture content above the optimum have a negative influence on the pellets mechanical properties and reduce pellet density. The moisture content of a material influences densification process. Mani *et al.*, (2006) observes that pellets formed with initial material having moisture content of above 15% and pellets formed with less than 5% moisture content leads to crack formation and breakages during storage and transportation respectively.

Verena and Marina, (2011) further notes good quality pellet are produced at 17.1% moisture content for no binder and 17.3% moisture content with a binder of potato starch, 4% moisture content. For stability and good quality achievement, the materials are conditioned with water or cane molasses binding agent (Verena and Marina, 2011).

Andreiko and Grochowicz, (2007), concluded from their studies that the energy consumption to compact ground lupine seeds into pellets was dependent on moisture content. They found out that the energy input necessary to compact the ground seeds to a constant volume decreased with increasing moisture content within the range of 9.5% to 15.0% (wt). Nielsen *et al.*, (2009) have shown that an increasing moisture content for pine and beech results in a decrease of the energy requirement for different components of the pelletizing process.

ii. Particle Size

Different studies made about the impact of particle size on the compaction properties of biomass show that friction in the press channel of a pellet mill increase with decreasing

particle size for beech particle (Stelteet *al.*, 2011). Kaliyan and Morey (2009a) have found out that decreasing particle size from corn stover grinds results in an increased briquette density. Similar results were observed by Mani *et al.*, (2006) who found that particle size significantly affects the pellet density for pellets made from barley straw, corn stover and switch grass, but not in the case of wheat straw. Verena and Marina (2011) note that for successful production of pellets and with right amounts of conditioning agents, a die of 4-6mm channel diameter and channel length of 20.0mm is required. Further studies indicate a die of 30.0mm channel diameter and channel lengths of 6-8mm are necessary.

2.7.4 Compressing pressure as a process variables

The pressure biomass exposes to during pelletizing and briquetting process has a significant impact on the product density and durability as well as on the process energy consumption (Stelteet *al.*, 2011; Mani *et al.*, 2006). Studies conducted on the straws of wheat, barley, canola, alfalfa and oat. When these residues are compacted at different pressures and resulting product density, mechanical properties or energy content are compared. The studies shows that pellet and briquette density increases with an increasing pressure and the dependency between pressure and density follows a saturation curve indicating that the plant cell wall density is the upper limit that can be reached (Stelte, 2011). Generally, pellet density increases only incrementally at pressures above 50MPa to 100MPa (Stelteet *al.*, 2011; Mani *et al.*, 2006). The mechanical properties, compressive strength and durability improve with increasing pressure and follow a saturation curve. Tabilet *al.*, (2011) studied the relationship between compression ratio and the compaction pressure. They tested the impact of the

compression ratio on the pelletizing pressure of straw. Their data showed an exponential correlation between compression ratio and the pelletizing pressure.

Other process variables

i. Temperature

Stelteet *et al.*, (2011) indicates that generated heat during pelletization is due to friction between biomass and the press channels of the pellet mill. Serrano *et al.*, (2011) study found out in her study of heat distribution, that the temperature of a die under operation at stable conditions is about 90⁰C while the temperature of the biomass is just about 70⁰C and cools quickly once it passes through the die. Smith *et al.*, (1977) study on effects of temperature on biomass densification showed that the density increased with temperature until it reached 90⁰C for a range of 60–140⁰C, while further increase did not result in density increase. Increase in temperature enhances stability as the thin layers of waxes around the stem (cuticula) melt and solidify during this process and serve as an adhesive between individual straws fibers (Stelte, 2011).

Several studies (Stelteet *et al.*, 2011 and Gilbert *et al.*, 2009) have suggested that lignin glass transition and subsequent flow and hardening result in an inter-penetration of polymer chain from adjacent particles and thus in enhanced secondary bonding and high mechanical properties of pellet. This scenario of increasing mechanical properties of the pellets with increasing temperature were reported for spruce, corn stover, switch grass, pine (Nielsen *et al.*, 2009), olive, beech (Nielsen *et al.*, 2009) and wheat straw. Furthermore, reports indicate that an increasing temperature reduces the friction in the

press channel of a pellet mill and lowers the energy requirement for different component of the pelletizing process (Nielsen *et al.*, 2009).

ii. Retention or Holding Time

Retention or hold times of a material in the die affect significantly the quality of briquette or pellets produced (Tumuluru *et al.*, 2010b). Various studies have shown that a hold time between 5–20 seconds have no effect on the durability and stability of the pellet produced at high pressures unlike at low pressures. A hold time of more than 40 seconds brings negligible effect on the density of the pellet but increases by 5% at 10 seconds hold time.

iii. Relaxation time

Relaxation time has great effect on the density of the material. The final relaxed density of a briquetted fuel and relaxation behavior after removal from the die depend on; die geometry, the magnitude and mode of compression, type and properties of the feed material and storage conditions (Tumuluru *et al.*, 2010a). Studies further indicate that removal of densified material from the die, the density of briquetted material decreases with time to a final relaxed density.

2.7.5 Other influencing parameters

2.7.6 Biomass composition

Feedstock composition is one of the major variables that contribute significantly to the quality of the densified materials (Tumuluru *et al.*, 2010b). Plant biomass has both low molecular weight and high molecular compositions. Low molecular weight substances include organic matter and inorganic matter, while macromolecular substances include

cellulose, hemi-cellulose and lignin (Tumuluru *et al.*, 2010b). The effect of biomass constituents on the strength and durability of feed pellets have recently been reviewed by Kaliyan and Morey (2009b), who focused on the influence of starch, protein, fiber, fat and extractives on the biomass bonding properties. In the case of fuel pellets from biomass, high extractives content lower the friction in the press channel of a pellet mill (Stelte *et al.*, 2011) and that high concentration of extractives on the biomass particle surface can reduce the mechanical strength of densified biomass products.

Process variables, during densification of biomass material like temperature, pressure, die geometry and densification mechanisms bring about significant transitions in the chemical compositions of the biomass by interaction reaction mechanism (Tumuluru *et al.*, 2010a). For example, starch granules at higher temperatures and moisture contents gelatinize and significantly influence the textural properties of many foods and feeds. Protein that is heated during the densification process undergo denaturalization leading to the formation of new bonds and structures with other proteins, lipids, starch available in biomass and improves the binding capacity (Thomas *et al.*, 1998).

2.7.7 Press channel dimensions

The diameter of a press channel varies according to the desired product diameter by usually between 6-25mm (Alakangas, 2010). The press channel length and the ratio between length and diameter (compression ratio) are studied. Tabilet *et al.*, (2011) studied the relationship between compression ratio and the compaction pressure. They tested the impact of the compression ratio on the pelletizing pressure of straw. Their data showed an exponential correlation between compression ratio and the pelletizing pressure.

(Colovic *et al.*, 2010) studied the impact of the press channel length on the physical qualities of cattle feed pellets and they concluded that an increasing press channel length resulted in higher mechanical properties of the pellets by use of pellet hardness test.

2.7.8 Biomass additives

Additives improve the pellets mechanical properties such as increasing density and strength improve the pelletizing process (throughput) or improve moisture resistance. They also improve the combustion properties such as ash melting point, slugging and corrosion. Binders in liquid or solid form, improves inter-particle bonding. Protein content increases pellet durability. Raw protein improves the physical quantities of the pellets than denatured proteins (Tumuluru *et al.*, 2010b). Thomas *et al.*, (1998) further found that increasing throughput and reducing pelletizing pressure lipids/ fats added to the biomass acts as a lubricant during pelletization.

Liquid pellet binders, improves pellet quality and durability because of their cohesive properties. Pelletizing animal feeds results into pellets of 1.2mm in shrimp feeds, 3-4mm in poultry feeds and 8-10mm in stock feeds. The pelletizing of stock feeds is done with a pellet mill machine in a feed mill.

Conditioning of TRZE involves sprinkling a known amount of the binding agent. Binding agents like potato starch, molasses or wheat flour are added to form solid body bridges. In order to achieve the required material compatibility to the pelletizing process, production of specified finished pellet size, shape requirements and physical characteristics of the pellets, a specified binder should be well selected. Selection of binders is based on the compatibility of the binder with the material being pelletized,

capability of the binder to perform the required enhancements to the pellets and the best cost performance criteria.

Osman and Arol, (2010) found out that binder additive improve the green, dry, pre-heated and fired pellet strength, enabling the production of good quality pellets to be attained at lower temperatures; leads towards production of a more durable product; they further help reduce wear in production equipment and increase abrasion-resistance of the fuel (Tumuluru *et al.*, 2010b). The most commonly used pellet binders include the following; Proteferm is a liquid binder that is used in capillary type binding in adhesive and cohesive forces as well (Summer, 1999). Ammonium lignin sulphonate is cellulose based organic component of trees that comes as a by-product of the paper making industry. It is generated by a chemical pulping process and is a non-toxic fluid with levels of dissolved or suspended solids. Lignins from the sulphite pulping process are lignosulphonates and dissolves in water. Wood fibers are sulphonated in closed vessels by which the lignin derivatives become soluble and separate from the cellulose fibers. According to Veverka & Hinkle, (2001) dry matter analysis for Ammonium Lignin Sulphonate indicates 50.0% moisture content and lignin of 24.0% that is necessary for binding. At high temperature and pressure lignin naturally binds the material. High moisture content facilitates starch gelatinization, protein denaturalization and fiber solubilization process during extrusion, pelleting and briquetting. Addition of heat enhances significant particle bonding resulting in improved densification quality (Tumuluru *et al.*, 2010a).

Water used for binding is ordinary tap water at room temperature. When water is used as a binding agent, it is sprinkled on the material evenly then through continuous churning

of the material makes the material soaked and mixed well. Water, forms interfacial forces and capillary pressures that increases particle bonding (Tumuluru *et al.*, 2010a). Various models have been put forward to describe how water distributes within particle elements. These models are; pendular, funicular, capillary and liquid-droplet states. The pendular model occurs when void spaces are filled with liquid to form lens-like rings at the point of contact and air forms a continuous phase. The bond strength achieved is due to negative capillary pressure and surface tension of the liquid. The funicular state model occurs when the liquid content is increased resulting in lower pore volume and coalescence of the liquid rings and in the formation of a continuous network and trapping of the air phase. At decreased liquid content the pore volume becomes higher with poor coalescence of liquid rings. Finally, in the capillary and liquid droplet state, the agglomerate is completely enveloped by the liquid and the primary particles are held by the surface tension of the droplet.

Cane molasses is an organic by-product of cane or beet sugar refining. It is residual heavy syrup left after crystallization process. Cane molasses is derived as a by-product from fermentation industries of cane molasses or from the production of alcohol, yeast, citric acid or other fermentation products. Molasses has high viscosity which allows particle granules to stick together during pelletizing process and produce pellets that are less likely to break down during transportation and passage through feeding equipment (Blair, 2007). Cane molasses contains about 5.7% of protein. Protein content in biomass affects densification process. Whereas protein has about 20% of moisture content, any available amount of moisture content improves binding by gelatinizing starch. The 5.7% protein

content in cane molasses contains about 20% moisture that enables biomass to bind (Sokhansanjet *et al.*, 2005).

Molex is a technology used to extract sucrose from beet molasses, while sucrose (a reducing sugar compound of beet molasses) is produced in sufficient quantities to be an option for major agglomeration application. Sucrose is composed of moisture, sugar, carbohydrate and protein content with values 40.0, 15.0, 17.0 and 12.0 in percentage by volume respectively. These components of sucrose have a binding characteristics of starch based on the amylase-to-amylpectin ratio. During gelatinization of the starch granule, amylase immediately form double helical bonds that aggregate (hydrogen bonds) to each other creating semi-crystalline regions and helping in binding (Tumuluru *et al.*, 2010a).

Collagen CH₂ results from the alkaline hydrolysis of leather waste, chrome shavings and trimmings. In this process leather waste is digested into two fractions. The trivalent chrome is recycled for tanning use and the collagen is reduced to polypeptides.

TAC is a commercial name in tanning industry referring to residual vegetable tannin from the process of tanning animal hides to make sole leather. Though in solid form, it also exists in liquid form but with 35-40% solid content.

Brewex is a liquid modified starch material derived from the mashing and brewing process; which transforms malt corn and rice into a fermentable substance from which beer is produced. Mash blends are processed in the brew kettle where this material called wort is adjusted for sugar content suitable for fermentation into beer. The solids derived

from screening grain residuals in the mash tubs and brew kettle are collected and centrifuged to separate brewer's grains from brewer are soluble. Further processing to increase solids content from 12% to 50% in a multi-effect evaporator leads to formation of Brewex. Blends are blends of molasses, whey and lignin (Veverka& Hinkle, 2001).

Generally, proteins, lignin, moisture content, calcium liginosulphonate, colloids, calcium hydroxide and glucose provide the binding effect to the pellets. For example, proteins that is heated during densification process undergoes denaturalization leading to the formation of new bonds and structures with other proteins, lipids and starch available in the biomass and improves the binding capacity (Thomas *et al.*, 1998). The lignin molecule in a plant acts as a glue to the cellulose fibers, it helps to form pellets without binders (Tumuluru *et al.*, 2010a). Lignin exhibits thermosetting properties at temperatures greater than 140⁰C and acts as an intrinsic resin in binder less board production.

2.8 Biomass Combustion Characteristics

The literature undertaken reviewed previous works on combustion of materials in the oven/ furnace. Studies carried out on briquetting process of maize cob, maize cob + coal particles, groundnut and melon shells (Oladeji, 2010), rice husk (Oladeji, 2010), waste paper + admixture of coconut husk (Olorunnisola, 2007) and banana peels indicate that fuel briquettes produced under different conditions (channel diameter, temperature, pressure, moisture content, relaxation and hold times) have different handling (density and strength) characteristics. Besides, raw materials strongly affect these characteristics. Pellet density is one of the most important properties that bear on the combustion characteristics, handling characteristics including the ignition behavior of pellets, die pressure and bulkiness.

Information of the properties of biomass materials is useful in order to evaluate its suitability as a feedstock in different heating processes. It also enables efficient and rational use of biomass briquette fuels (Oladeji, 2010). In analyzing combustion of feedstock, the following characteristics are useful; moisture content, thermo-chemical behavior (proximate), ultimate (elemental composition) analysis, ash analysis, angle of repose, air fuel ratio and density. These analyses provides relevant information on; gasifier design combustion chamber, flow behavior of biomass material, storage capacity of fuel charging hopper, size of furnace, gasifier or other biomass conversion device, evaluation of transportation cost and storage space for biomass fuel and in the design and analysis of biomass conversion process, volatility and elemental analysis of the feedstock. Analysis of element is important in evaluating possible technical problems like pollution and its effect on the reactor chamber (Oladeji, 2010).

2.8.1 Proximate analysis of typical agro-residues

The proximate analysis indicates the percentage by weight of the moisture content (MC), volatile matter (VM), fixed carbon (FC) and ash in a fuel material. Proximate characteristics of biomass materials vary from one species to other due to type of soil, mineral content, variety of crops grown, sampling techniques etc.

Table 2.2. Proximate analysis of typical agro residues. (Source: Bureau of Energy Efficiency; Oladeji, (2010) & Anhwange et al., (2009))

	Deoiled Bran	Paddy Husk	Saw dust	Banana Peels	Coconut shell	Rice Husk	Corn cob
Moisture	7.11	10.79	37.98	6.70	13.95	12.67	13.47
Ash	18.46	16.73	1.63	8.50	3.52	18.6	1.40
Volatile matter	59.81	56.46	81.22	-	61.91	67.98	86.53
Fixed carbon	14.62	16.02	17.15	-	20.62	13.4	12.07

Volatile matter of any substance is the fraction that is driven off by heating the sample to a specific time and temperature (Jain, 2013). The commonly adopted procedure for proximate analysis of coal outlined in BS 1016 part 3 and 4, 1973, are in use for the proximate analysis of biomass as well. The biomass material is placed in a muffle furnace at 915⁰C for 7minutes in a covered platinum crucible. The moisture and volatile matter are driven off and the residue left after 7minutes is the fixed carbon and ash (Jain, 2013).

The amounts of fixed carbon and combustible volatile matter directly contribute to the heating value of TRZE. FC acts as a main heat generator during burning. High volatile matter content indicate easy ignition of fuel. The ash content is important in the design of the furnace grate, combustion volume, pollution control equipment and ash handling system of a furnace. Ash is the mineral content in the fuels that remain in oxidized form after combustion and has a major impact on the operation of a furnace.

2.8.2 Ultimate Analysis of typical agro residues

Table 2.3.Ultimate analysis of typical agro residues.(Source: Bureau of Energy Efficiency, (n.d.) &Oladeji, (2010))

	Deoiled Bran	Paddy Husk	Saw dust	Coconut shell	Rice Husk	Corn cob
Moisture	7.11	10.79	37.98	13.95	12.67	13.47
Mineral Matter	19.77	16.73	1.63	3.52		
Carbon	36.59	33.95	48.55	44.95	42.1	19.72
Hydrogen	4.15	5.01	6.99	4.99	5.8	15.56
Nitrogen	0.82	0.91	0.80	0.56	0.38	0.38
Sulphur	0.54	0.09	0.10	0.08	0.05	0.82
Oxygen	31.02	32.52	41.93	31.94	51.67	62.12
GCV (MJ/Kg)	13.19	14.93	20.10	19.11	-	-

The ultimate analysis gives the elemental composition of the biomass in weight percentage of carbon (C), hydrogen (H), nitrogen (N), sulphur (S) and oxygen (O) are

determined by difference in the solid fuel, where once an element is determined it is eliminated from the rest and the next element determined. In determining the percentage contents of C, H and N, the following proposed formula by Bureau of Energy Efficiency is applied.

Table 2.4. Analytical determination of C, H and N. (Source: Bureau of Energy Efficiency, n.d.)

	%C	=	$0.97C + 0.7(\text{VM} - 0.1A) - M(0.6 - 0.01M)$
	%H	=	$0.036C + 0.086(\text{VM} - 0.1A) - 0.0035M^2 (1 - 0.02M)$
	%N ₂	=	$2.10 - 0.020\text{VM}$
Where	C	=	% of fixed carbon
	%C	=	Elemental carbon
	A	=	% of ash
	VM	=	% of volatile matter
	M	=	% of moisture content

The ultimate analysis is better performed and reported on dry basis; otherwise, moisture is indicated as additional hydrogen and oxygen (Stahl *et al.*, 2002-2006).

2.8.3 Fixed carbon

Adetogun and other writers (2014), in their work while determining the combustion properties of briquettes produced from cob of different particle sizes adopted the following formulae in calculating the percentage fixed carbon.

$$\text{Percentage FC} = 100 - (\%V + \%A)$$

Where %V= percentage volatile matter and % A= percentage ash content

The results indicated that the fixed carbon of the briquettes ranged from 5.75-8.28% depending on the particle sizes. However, there were no significant difference ($P>0.05$) in the percentage fixed carbon content of the briquettes produced from 2.30mm, 4.75mm and 6.30mm particle sizes that were studied.

2.8.4 Ash content of a biomass material

Ash refers to the inorganic residue remaining after the water and organic matter have been completely oxidized in a sample. Ash content represents the total mineral content in plant materials. Dry ashing, wet ashing and low temperature plasma dry ashing are the three methods in existence. The method chosen depends on the reason for carrying out the analysis; the type of material being analyzed and the equipment available.

In dry ashing, a high temperature range muffle furnace capable of maintaining 500-600°C for 24hours is used (Mc Clements, 2005). The furnace is set at 600°C and the sample weighed placed in a crucible put inside the furnace. After 24hours, the sample is removed from the oven furnace and weighed to determine the concentration of ash present. The percentage concentration of ash is determined by Equation (2.12).

$$\% \text{ Ash (dry basis)} = \frac{M_{\text{ASH}}}{M_{\text{DRY}}} \times 100 \quad (2.12)$$

$$\% \text{ Ash (wet basis)} = \frac{M_{\text{ASH}}}{M_{\text{WET}}} \times 100 \quad (2.13)$$

Where M_{ASH} refers to the mass of the ashed sample, M_{DRY} refers to the original mass of the dried sample and M_{WET} is the original mass of the wet sample.

Wet ashing is primarily used in the preparation of samples for subsequent analysis of specific minerals. The material is broken down by removing the organic matrix surrounding the minerals so that they are left in aqueous solution. A dried ground sample is weighed into a flask containing strong acids and oxidizing agents such as nitric acid, sulphuric acids then heated. Heating continues until the organic matter is completely digested leaving only mineral oxides in solution (Mc Clements, 2005). Temperature and time used depend on the type of acids and oxidizing agents used. For example, digestion taken from 10minutes to few hours at temperatures of about 350°C results to a solution analyzed for specific minerals.

In low temperature plasma ashing, a sample is placed into a glass chamber, which is evacuated using a vacuum pump. A small amount of oxygen is pumped into the chamber and broken down to nascent oxygen $\text{O}_2\text{-}2\text{O}$ by application of an electromagnetic radio frequency field. The organic matter in the sample is rapidly oxidized by the nascent oxygen and the moisture is evaporated because of the elevated temperatures (Mc Clements, 2005).

Conclusively, dry ashing procedure is simple to carry out; it is not labour intensive, requires no expensive chemicals and can be used to analyze many samples simultaneously. However, the procedure is time consuming and volatile minerals may be lost at high temperature used. Wet ashing and low temperature plasma ashing are more rapid and cause less loss of volatile minerals because samples are heated to lower temperatures. Nevertheless, the wet ashing procedure requires the use of hazardous

chemicals and is labour intensive while the plasma method requires expensive equipment and has a low sample throughput.

It is noted that 95% of ash particles are minerals. Some of the common constituents of ash include SiO_2 , Al_2O_3 , Fe_2O_3 , TiO_2 , CaO , MgO , Na_2O , K_2O and SO_3 (Jain, 2013). SiO_2 , Na_2O and K_2O are notorious when found in ash. If these particles exceed 50% then there are high chances of problems within the handling systems of combustion devices. At high temperatures exceeding 1200°C the minerals undergoes fusion which lead to plugging of boiler tubes and gas channels.

2.8.5 Reviews on single particle combustion

Drying, de-volatilization and char combustion

Yang and other researchers (2007) in their experimental studies of combustion of small single particles of solid fuels have been undertaken. In this case, three cases are considered. And these includes; thermo gravimetric analysis (TGA); entrained particle combustion in a supporting flame and suspended particle combustion.

In thermo gravimetric analysis, experiments of particles are in the form of a distributed bed and the particle size ranges between $20\mu\text{m}$ and $200\mu\text{m}$ in diameter. The particles are considered to be isothermal since the heating rate is low and the mass is small. However, TGA finds limited application in determination of kinetic data arising from secondary reactions especially in the larger particles (Yang *et al.*, 2007). Kinetic data is necessary in all applications especially in pulverized biomass flame because most of the biomass components are released as volatiles and the correct kinetic parameter are a composite of the fundamental reaction kinetics and the secondary cracking and condensation reactions.

Particle combustion in a flame involves placing particles of willow coppice in a methane-air flat flame using high speed video photography. In this method, the rate of burn out could be observed as well as phenomena such as particles accelerated by a jet of volatiles and particle rotation. Particles could be captured for investigation by scanning electron microscopy. The effects of particle size and temperature are marked and particle temperature and devolatilization rates are dictated by particle size.

In suspended particle combustion, the particles undergoes through stages of heating-up, ignition, devolatilization, char-burn out and disintegration of the residual ash (Yang *et al.*, 2007). The devolatilization equation is shown;



Moisture in biomass occurs in two forms; free water and bound water. Moisture content above the fiber saturation point (FSP) is free water, exists in liquid form in pores and cells. Below the FSP, moisture is bound water, that is, exists as moisture physically or chemically bound to surface sites or as hydrated species (Lu *et al.*, 2008). Free moisture vaporizes from both the internal and external surface at a rate determined by the surface saturated vapour pressure, the partial pressure of vapour in the gas phase. Bound water does not vapourize in a manner similar to free moisture but rather is released because of chemical reactions releasing bound hydrates under similar processes.

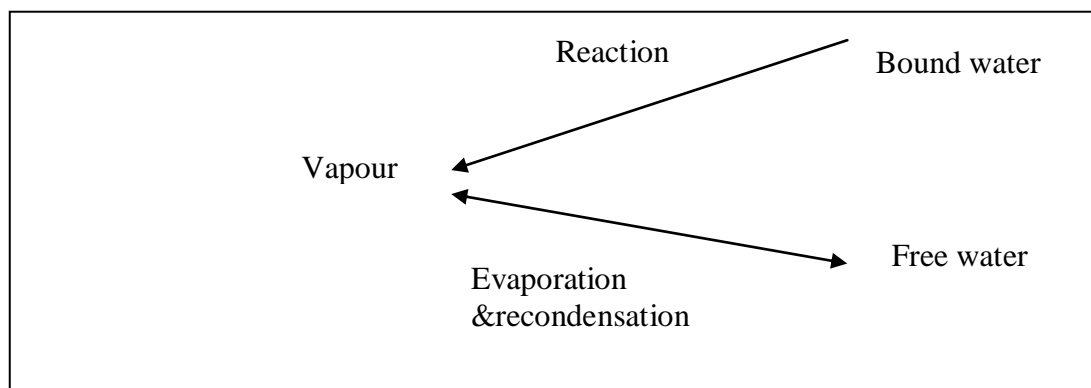
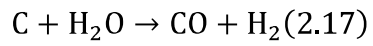


Figure 2.1. Moisture drying scheme; Source: Lu *et al.*, (2008)

Devolatilization involves heating of raw biomass components/ organic materials in the absence of oxidizer, thermal degradation of the biomass component and mass transport of the devolatilization products by advection and diffusion and escape of products at the surface of the particle. Pyrolysis and devolatilization are defined differently by various authors; with devolatilization assumed to occur in a neutral or reducing environment and pyrolysis occurring at an oxidizing environment. Particles decompose with a volatile cloud, which is a reducing environment, even when the overall environment is oxidizing. Pyrolysis product distribution depends strongly on reactor temperature, heating rate, residence time, mass velocity and pressure.

Devolatilization consists of a series of complex chemical reactions, which lead to decomposition and breakage of the organic matter and separation of different compounds into individual gases (Siagiet *al.*, 2000). A study done by Lu *et al.*, (2008) on poplar wood indicates that volatiles yield from pyrolysis a complex mixture of over 100 hydrocarbons. These include mainly CO, CO₂, H₂O, H₂, light hydrocarbons and heavy hydrocarbons. The first five are a representative of light gas and the last as tar. Char

gasification and oxidation includes five classical heterogeneous and homogeneous reactions as shown below;



Tar is a major product of the devolatilization process.

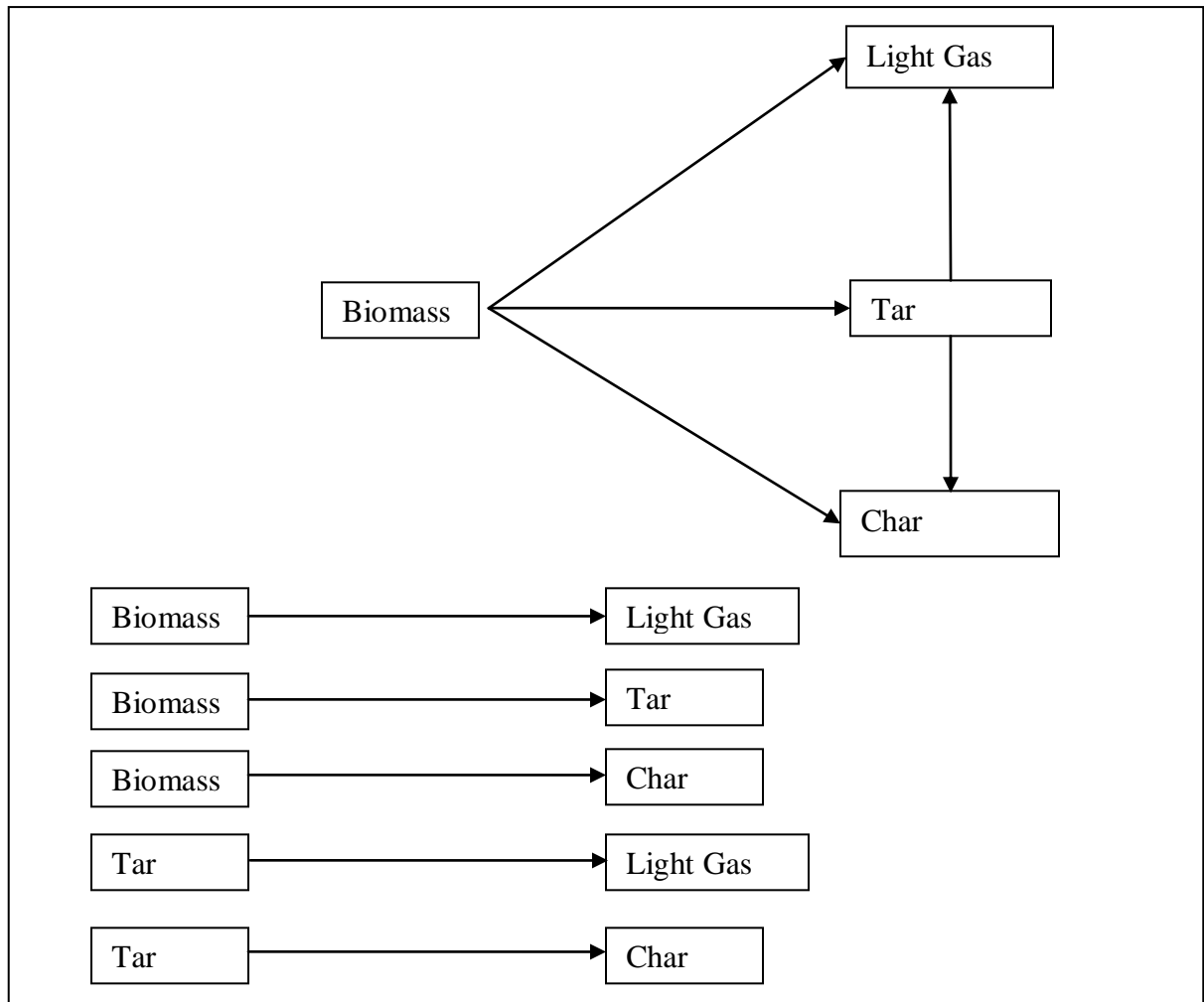


Figure 2.2: Pyrolysis kinetics for a two-stage wood model; (Source: Luet *al.*, 2008)

The combustion characteristics of any biomass are best understood through the following aspects (Siagiet *al.*, 2000).

- The temperature at which devolatilization and char combustion begins
- The influence of drying on the devolatilization process
- The composition of devolatilization products
- The effects of volatile release and combustion on the overall combustion process

The moisture content of a fuel heavily influences particle heating. It increases the energy required for heating and drying, delays the volatile release and affects the combustion rates.

In figure 2.3, the graph represents data for a near-spherical particle ($d_p=11\text{mm}$) with aspect ratio of 1.0 and moisture content of 6.0wt% including mass loss, center and surface temperature during pyrolysis appear with model predictions. The nominal condition of this experiment includes a reactor wall temperature of 1273K and gas temperature of 1050K. The particle mass loss and particle surface temperature predictions agree with experimental data except the measured particle center temperature increases faster than the model predictions at the beginning. This variation discrepancy is attributed to thermal conduction through the thermocouple wire. In principle, the centre particle temperature should equal surface temperature at the end of the pyrolysis experiment. The variation can exist due to differences in thermocouple bead size and shape and ash coating on the center temperature bead.

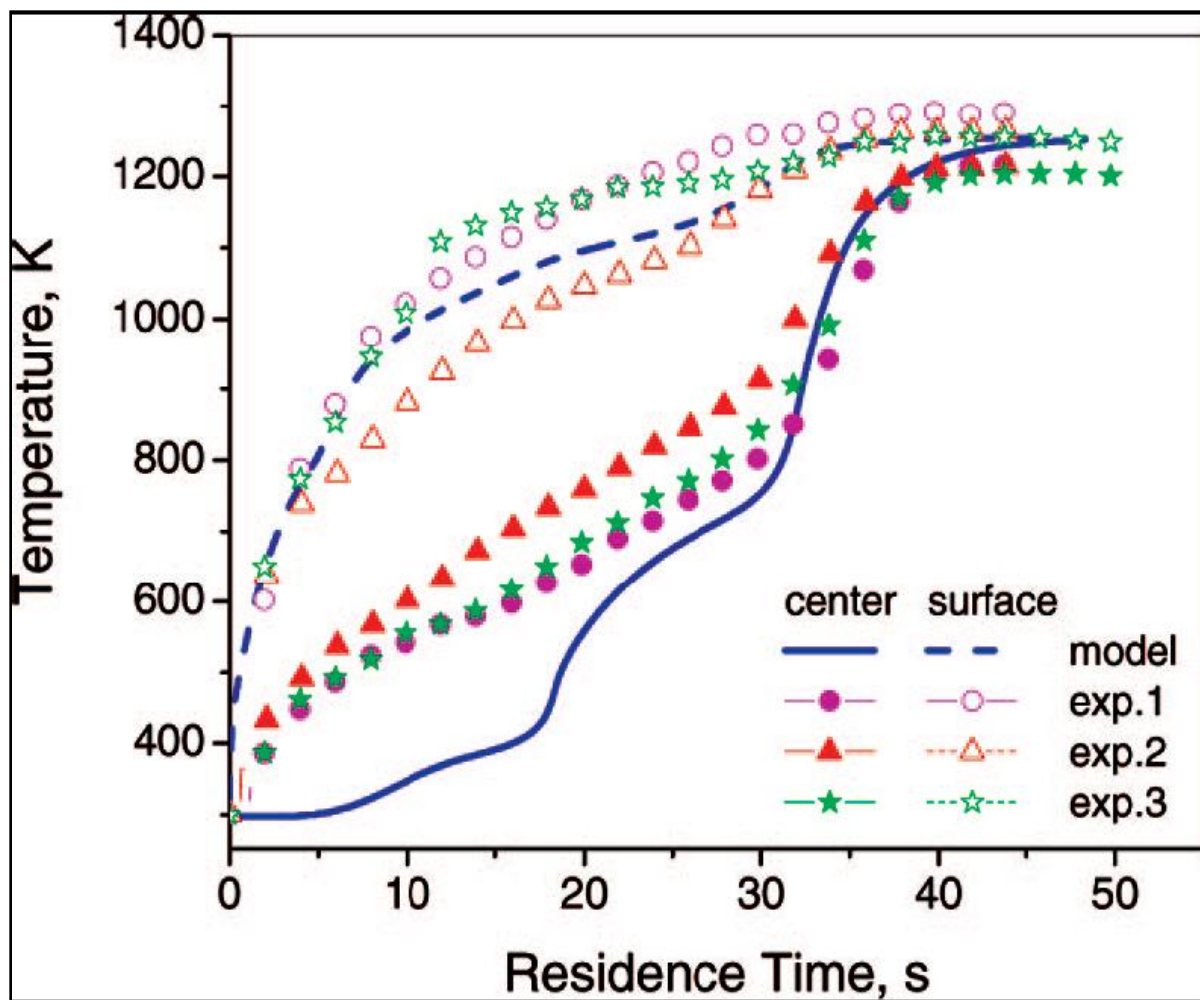


Figure 2.3. Temperature profile of near-spherical biomass particle during pyrolysis

2.8.6 Anaerobic digestion of biomass

Energy crops can be grown and then used for biogas production in anaerobic digestion. In this case, the aim is to produce biogas. Anaerobic digestion involves four stages; pre-treatment, digestion, gas upgrading and digestate treatment. The level of pre-treatment depends on the type of feedstock for example, manure is mixed with other organic materials, whereas MSW are sorted and shredded. The digestion stage takes place in the digester. The biogas produced during digestion stage is upgraded because it contains impurities that can damage engines and gas tubes. Such impurities include hydrogen

sulphide (H_2S), water and carbon dioxide. Anaerobic digestion is a naturally occurring process of decomposition and decay, by which organic matter is broken down to its simpler chemical components under anaerobic conditions. Anaerobic microorganisms digest the organic materials, in the absence of oxygen, to produce methane and carbon dioxide as end products under ideal conditions.

The complex scientific underlying AD process involves; hydrolysis, acidogenesis, and methanogenesis. During hydrolysis, the fermentative bacteria convert the insoluble complex organic matter, such as cellulose into soluble molecules such as fatty acids, amino acids and sugars. The complex polymeric matter is hydrolyzed to monomers like cellulose to sugars or alcohols.

In acidogenesis the acetogenic bacteria acid formers convert the products from the first state into simple organic acids, carbon dioxide and hydrogen. The principal acids produced are acetic acids, butyric acid, propionic acid and ethanol. Finally, methane is produced during methanogenesis by bacteria called methane formers in two ways; by means of cleavage of two acetic acid molecules to generate carbon dioxide and methane or by reduction of carbon dioxide with hydrogen. Presence of lignin in the material remains undigested.

2.8.7 Variables affecting anaerobic digestion

Any process requires optimized parameters for efficient operation. Thus, the following conditions are applied in order to obtain a proper breakdown of the organic compounds.

- i. Total Solid content: increasing total solid content decreases the volume of the digester due to lower water requirements. They exist in three categories; low solids (LS) AD system that has less than 10% TS, medium solids (MS) that range between 15-20% and high solid systems (HS) that range from 22-40%.
- ii. Temperature: the optimum temperature of digestion varies depending on feedstock composition and type of digester, but requires to be maintained relatively constant to sustain gas production rate. AD occur under two main temperature ranges; 20-45⁰C usually 35⁰C that is mesophilic condition and between 50-65⁰C usually 55⁰C that is thermophilic condition.
- iii. Retention time: this is the time needed to achieve the complete degradation of the organic matter. The retention time varies with process parameter such as process temperature and waste composition. The retention time for waste treated in mesophilic digester ranges from 15 to 30 days and 12 to 14 days for thermophilic digester (AD of farm and food processing residues).
- iv. pH: during acidogenesis, acetic, lactic and propionic acids are formed and thus pH falls. Low pH can inhibit acidogenesis and pH below 6.4 can be toxic for methane forming bacteria hence the optimal range for methanogenesis is between 6.6 and 7. An optimal pH range for all is between 6.4 and 7.2.
- v. Carbon to Nitrogen ratio (C/N): the relationship between the amount of carbon and nitrogen present in organic materials is represented by the C/N ratio. Optimum C/N ratios in anaerobic digesters are between 20 and 30. A high C/N ratio is an indication of rapid consumption of nitrogen by the methanogens and results in a lower gas production. A lower C/N ratio causes ammonia

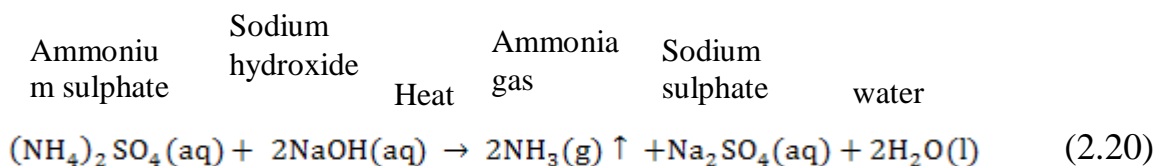
accumulation and pH values exceeding 8.5, which is toxic to methanogenbacteria. Optimum C/N ratio of the feedstock materials can be achieved by mixing waste of low and high C/N ratio that is organic solids waste mixed with sewage or animal manure. The materials can be selected from raw materials as tabulated in appendix XIV.

- vi. **Mixing:** mixing within the digester improves the contact between the microorganisms and substrates that improves the bacterial population's ability to obtain nutrients. Mixing prevents the formation of scum and the development of temperature gradients within the digester. Slow mixing is preferred as excessive mixing can disrupt the microorganisms. In addition, feedstocks should be mixed before entering the digester to ensure a sufficient homogeneity.
- vii. **Organic Loading Rate (OLR)/ Volatile Solids (VS):** OLR is a measure of the biological conversion capacity of the AD system. Feeding the AD system it is sustainable OLR, results in low biogas yield due to accumulation of inhibiting substances in the digester slurry such as fatty acids. Feeding rate need to be reduced. OLR is expressed in kilogram Chemical Oxygen Demand (COD) or Volatile Solids (VS) per cubic meter of reactor. It is linked with retention time for any particular feedstock and anaerobic reactor volume. Volatile solids (VS) represents the organic matter in a sample measured as solid content minus ash content, as obtained by complete combustion of the feed wastes. VS comprise the biodegradable VS (BVS) fraction and the refractory VS (RVS). High VS content with low RVS is more suitable for AD (Themelis and Verma, 2004).

2.8.8 Reviews on nitrogen determination

Nitrogen determination is the most commonly used procedure for a protein assay and it has been the basis for various official and conventional methods currently in use for expressing total protein content of organic matters. Nitrogen (N) determination methods commonly used are; Kjeldahl, Dumas and Combustion, Kjeldahl method is widely used whereas Dumas and combustion methods offer shorter analysis time and no requirement of hazardous chemicals.

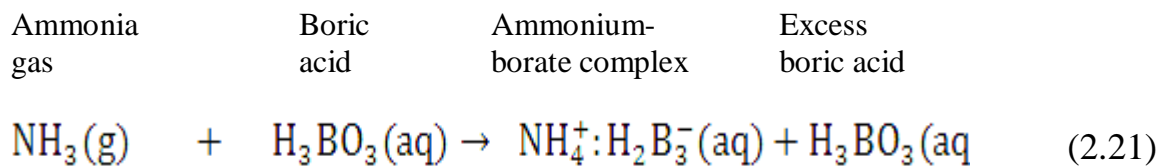
It is assumed that a mixture of pure proteins contains 16% nitrogen. Therefore, calculation of protein content in a sample is by the determined nitrogen content by multiplying nitrogen-to-protein conversion factor, 6.25 (that is, 100/16). Classical Kjeldahl method has been recognized and accepted universally as the authoritative method of analysis for determining the protein content in a wide variety of ingredients and finished products. The sample is digested in sulphuric acid, using copper sulphate/titanium oxide ($\text{CuSO}_4/\text{TiO}_2$) as catalysts, converting nitrogen to ammonia gas (NH_3), which is distilled and titrated directly by use of boric acid as the receiving solution, to determine the amount of nitrogen. In distillation, the acid digestion mixture is diluted and made a strong alkaline with sodium hydroxide (NaOH), liberating NH_3 as follows:



Source: AOAC, (1999).

The Kjeldahl flask is attached to a water condenser and heated to boil off NH_3 gas from the digest. The tip of the condenser is submerged in a flask of acidic receiving solution of

boric acid solution to again trap the distilled NH_3 in receiving solution. The titration used is a direct method. The chemical reaction obtained is shown below;



The boric acid captures the ammonia gas, forming an ammonium-borate complex. This method is applicable to a wide range of organic matters including raw materials, ingredients and finished products from animals, cereals and oil seeds.

2.8.9 Biogas composition

Biogas produced during anaerobic digestion is primarily composed of methane (CH_4) and carbon dioxide (CO_2), with smaller amounts of hydrogen sulphide (H_2S) and ammonia (NH_3). Trace amounts of hydrogen (H_2), nitrogen (N_2), carbon monoxide (CO), saturated or halogenated carbohydrates and oxygen (O_2) are occasionally present in the biogas (biogas & natural gas fuel mixture for the future). Biogas has a Heating value of 21.48MJ/m^3 .

2.8.10 Biogas utilization



Plate 2.1. Biomass for biogas production (Source: Greenfinch Ltd., 2006)

By definition, biogas is the gaseous emissions from anaerobic degradation of organic matter by a consortium of bacteria. Biogas is energy rich and is well suited as a source of energy within many areas. In summary, biogas is applicable to all appliances designed for natural gas subject to some relevant upgrading. The following are the most common uses of biogas; used for heating in boilers; used in combined heat and power (CHP) units; used as a fuel for vehicles and methane contained in biogas, acts as a fuel in fuel cells. It is also applied in building heating and district heating. It is used in power generation. By the help of a gas powered generator, electricity and heat are generated.

In a well advanced processing of biogas, the gas is used to fuel vehicles. The processing involves removal of water, carbon dioxide and compressing it to use as fuel. In Stockholm for example, biogas is injected into existing gas networks where it is used for gas cookers, heaters, baking ovens, and water heaters. In industries like sugar milling, distillers, dairies and paper mills generate waste water that is digested into biogas.

Thereafter, this gas is used for heating premises, district heating, power production and oven heating. When biogas is used as a fuel in power generators and boilers, the gas should contain less than 200 parts per million (ppm) of hydrogen sulphide. This ensures long life of the generators. In pipes, the hydrogen sulphide shall not exceed 4.6ppm at 0°C, the carbon dioxide level shall too be lower than 2 per cent (Wilkie, 2004).

2.9 Mathematical Model Analysis

Korir (2004) indicates that modeling has the following purposes; predict and analyze the influence of various parameters of the system; optimize the design and processing of the installation and develop control strategies of the plant; to develop linear plots in order to make comparison easier between different sets of data.

2.9.1 Classification of mathematical models

Mathematical models are built using numbers and symbols that can be transformed into functions, equations and formulas. They can be used to build much more complex models such as matrices or linear programming models. Mathematical models can be classified according to use (description or optimization), degree of randomness (deterministic and stochastic), and according to degree of specificity (specific or general).

2.9.2 Densification-compression models

Compression models predict the behavior of biomass particles during pelleting and help optimize the pressures required to obtain a quality pellet. Pellets are formed through pressure agglomeration or compaction and bound with or without binders (Tumuluru *et*

al., 2010a). Compression models according to Tumuluru *et al.*, (2010a) which have been used in biomass densification are discussed here after;

i. Spencer and Heckel Model

Heckel model is widely used for understanding the compression behavior of pharmaceutical and cellulosic materials. It is further applicable to obtaining compression data of alfalfa pellets. The Spencer and Heckel model equation used to express density in terms of packing fractions as a function of applied pressure;

$$\ln \frac{1}{1-\rho_f} = m\rho + b \quad (2.22)$$

Where

$$\rho_f = \frac{\rho}{\rho_1 x_1 + \rho_2 x_2} \quad (2.23)$$

The two Equations (2.22) and (2.23) are used to describe the compression behavior of the powder material where constants (m) and (b) describes two stages of compression;

- 1) Pre- occupation and
- 2) The particle rearrangement due to densification.

The constant b is related to relative density at particle rearrangement (ρ_f) proposed by the following equation.

$$b = \ln \frac{1}{1-\rho_f} \quad (2.24)$$

A high ρ_f result in greater volume reduction due to more particle rearrangement and m is the reciprocal of the mean yield pressure required to induce elastic deformation. Higher

m values indicate the onset of plastic defamination due to low yield pressure, meaning the material is more compressible.

ii. Walker model

Walker (1923) developed a model based on the experimental data on compressibility of powder and expressed the volume ratio (V_R) as a function of applied pressure (P).

$$V_R = m \ln P + b \quad (2.25)$$

$$V_R = \frac{V}{V_s} \quad (2.26)$$

Where;

P = applied pressure (MPa)

V_R = volume ratio

V = volume of compact at pressure P (m^3)

V_s = void free solid material (m^3)

The walker empirical model on its use with wheat straw and poplar indicated that increasing the cylinder temperature increases the compressibility of the untreated feed stocks. Compressibility decreased with an increase in moisture content.

iii. Jones model

The model was developed by Jones (1960) for application in the density and pressure data of compacted metal powder.

$$\ln \rho = m \ln P + b \quad (2.27)$$

Where ρ is the bulk density of compact powder mixture in kg/m^3 and P is the applied compressive pressure in kPa. The constants b and m are intercepting and slope change respectively for plot of $\ln(\rho)$ versus $\ln(P)$.

$$b = \ln(1/1 - \rho_0) \quad (2.28)$$

And

$$\rho_f = \rho / (\rho_1 x_1 + \rho_2 x_2) \quad (2.29)$$

Where;

ρ_f = packing fraction or the relative density of the material after the particle rearrangement

ρ_o = relative density of the powder mixture (Kg/m^3).

ρ_1 and ρ_2 = are the particle density component of the mixture (Kg/ m^3).

x_1 and x_2 = is the mass fraction of the component of the mixture.

Constants b and m are determined from the intercept and slope of extrapolated linear region of the plot $\ln\left(\frac{1}{1-\rho_f}\right)$ vs. P. Higher values of P_f will indicate increased volume reduction of the sample due to particle rearrangement. A large m value will indicate that yield pressure is low and plastic deformation onsets at relatively low pressures showing that the material is more compressible.

Jones (1960) model applied in the study of compression of wheat straw and poplar feed stocks showed that temperature had an effect on untreated feed stocks as opposed to the pretreated feed stocks to increase the compressibility. *Tablet et al.*, (2011) used the model for ground agricultural biomass material; they found out that the constant m value of the model gave valuable information about the onset of plastic deformation. It was observed

that ground particles obtained from large hammer mill screen size have higher compressibility. Also, application of pre-treatment improved the compressibility of ground agricultural biomass.

iv. Cooper-Eaton model (1962)

This model assumes compression to being two independent probabilistic particles according to Cooper and Eaton (1962) study of the compaction of four ceramic powders;

- 1) Filling voids of the same size as the particles and
- 2) Filling of voids small than particles

$$(v_0 - v)/(v_0 - v_s) = a_1 \exp.(-k_1/\rho) + a_2 \exp.(-k_2/\rho) \quad (2.30)$$

Where: V_0 = volume of compact at zero pressure (m^3) a_1 , a_2 and k_1 , k_2 are Cooper –Eaton model constants. This model was applied in ground agricultural biomass (Tabilet *al.*, 2011). The dimensionless values a_1 and a_2 values were obtained for agricultural biomass. The value of a_1 were high than a_2 value and thus the material was concluded to be densified through the process of particle rearrangement. When the sum of coefficients ($a_1 + a_2$) is more than unity, it implies that the densification could not be fully attributed to the two mechanism of compression as assumed by Cooper and Eaton (1962) model.

v. Kawakita and Ludde Model

This model includes the pressure and volume factors;

$$\frac{P}{C} = \frac{1}{ab} + \frac{P}{a} \quad (2.31)$$

$$C = \frac{V_o - V}{V_o} \quad (2.32)$$

Where;

C = degree of volume reduction or engineering strain; a and b are Kawakita- Ludde model constants related to characteristic of the powder. This compression equation holds true for soft and fluffy powders (Kawakita and Ludde, 1971).

In Kawakita and Ludde, (1971) model, the constant a represents initial porosity of the sample. Reports indicate that porosity and hammer mill screen sizes (corresponding to geometric mean diameter) are positively correlated (Tabilet *al.*, 2011). Also, Tabil and other writers further notes that porosity increases with application of pre-treatment, that is, grinding, drying to required moisture content; application of a binding agent; steaming and torrefaction, since organized lignocelluloses structure of biomass disintegrates during this process. The parameter $1/b$ in this model indicates the yield strength or failure stress of the compact. Yield strength has a negative correlation with hammer mill screen sizes. Application of pre-treatment to ground agricultural biomass lowers its yield strength. It has been proved that, this model provides an accurate representation of compression and deformation characteristics of agricultural biomass (Tabilet *al.*, 2011).

vi. Sonnergaard Model (Log-Exp-Equation)

The Sonnergaard Model is suitable for medium-pressure applications of approximately 50MPa. It is a log-exp-equation that considers two processes simultaneously; A logarithmic decrease in volume by fragmentation and an exponential decay representing plastic deformation of powders

$$V = V_1 - w \log P + V_0 e^{(-P/P_m)} \quad (2.33)$$

Where V_1 = volume at pressure 1MPa

P_m = mean pressure

W = constant

vii. Panelli-Fillo model

The Panelli-Fillo model is given by the following expression

$$\ln \frac{1}{1-\rho_r} = A\sqrt{P} + B \quad (2.34)$$

Where ρ_r = relative density of the compact

A = parameter related to densification of the compact by particle deformation.

B = parameter related to powder density at the start of compression

CHAPTER THREE

3.0 RESEARCH METHODOLOGY

3.1 Materials and Method

This chapter discusses the method and procedures used in conducting research. It states the research materials used, preparation of these materials, sets of experiments done to establish the quantity of bio-fuel the plant species can produce. The chapter is organized under the following five sections;

- a) Research material and equipment
- b) Material collection and preparation
- c) Determination of heating value/energy value
- d) Material pelleting and durability testing
- e) Determination of Combustion characteristics

3.2 Research Material and Equipment

3.2.1 Research material

- i. *Tradescantiazebrina* is the main research material in this study. It appears as shown in plate 3.1. Found in any agricultural farm, sprouts well along with other crops. It is evergreen with succulent stems and leaves. In warm climates, wandering jew is grown outdoors as a ground cover or a bedding plant or to effect a tropical atmosphere. It may also be grown indoors or in the greenhouse as a hanging basket plant or container plant.



Plate 3.1: A Photograph of fresh TRZE

- ii. Molasses binder. The binder was purchased from Chemelil sugar factory. It was used during pellet production. The cane molasses enabled the TRZE particles bind together during pelletizing process. Cane molasses was sprinkled on the material before placing it in the die. Molasses has a density ranging from 1.3 to 1.5g/cm³ with approximately 15% by weight water.
- iii. Water as a binder. Running treated tap water obtained from Moi University water supply network systems was used. A measured volume of water was sprinkled over the material using a spray gun.

The binders used were 15% of the total weight of the material mass. This was arrived at by conducting preliminary tests for mass of the binder beginning from 1% to 20% at a

range of 2%. Binding of the material was realized at 15% and thus the researcher adopted the value for the experiment.

3.2.2 Research equipment

The following equipment and tools were frequently relied upon for successful completion of the research work.

i. Oven furnace.

Manufactured by ELSKLO from Czech Republic, the oven is of LNT 20 type with a serial number of 33. It draws a voltage of 415V, an electric current of 15A, an alternating frequency of 50 cycles per second (Hz) and a total power of 6kVA. Its maximum furnace temperature is 1300⁰C. It weighs 135kilograms with air as its atmosphere. The equipment provides heat in an enclosed surface that is conducive for determining the moisture content of a combustible material, for drying, devolatilization and char combustion. The researcher used the equipment located at the automotive laboratory, school of engineering, Moi University.

ii. Electronic precision balance.

The electronic precision balance used is registered under Citizen Scale Inc., USA, and of model: CTG1202, S/NO.: 025 with an accuracy of 0.01grams. The balance scale was borrowed from the department of Civil and Structural engineering within the School of engineering.

iii. Pressure gauge.

The pressure gauge found in the automotive laboratory, has two scales. The first scale used by the researcher range from 0.0-700psi with every division representing 1.00psi. These scale units were translated to pre-determined loads in bars. The second scale range

from 0.0-10000psi in which every division represents 200psi. The first scale found convenient in relation to its high accuracy.

iv. Laboratory test sieve.

Manufactured in England by ELE International, Glenammer Engineering, ISO 3310-1. Aperture sizes of 2.36mm, 2.0mm, 1.18mm, 600microns and 425microns were used. The sieve gave sizes of particles that passed through each of the apertures. These sizes enabled the researcher to test pellet durability, relaxation time, effects of various types of binder with these sizes and penetration as well as the particle size distribution.

v. Vernier caliper.

Found at the workshop, the tool measures in range of 0-300mm with an accuracy of 0.02mm. It measured the diameter of the pellet produced and the height variation after compression.

vi. Pair of tongs.

The equipment carries hot objects. In this study, the tongs carried crucibles with the specimens from the furnace to the weighing machine and into the furnace during weight measurements.

vii. Milling machine.

The mill produces small particles of dried TRZE material. The dried TRZE material, were put at the hopper as they passed through meshing teeth for milling. A mesh screen of 4.0mm was used.

viii. Two-column load frame instron testing/compression machine.

Found at the automotive laboratory in the School of Engineering. The press was instrumental with a system for recording displacement, force and time. The machine

measures plastic deformation of metal rods. This part was removed and replaced with a hydraulic press and die. The press fitted unto the chuck of the machine so that it moves up and down when pressure forces are applied. The die system rested on the base of the machine provided the channel unto which the material was placed for compression. The instron machine is fitted with a pressure gauge which records compression pressure loads that is applied on the material under test.

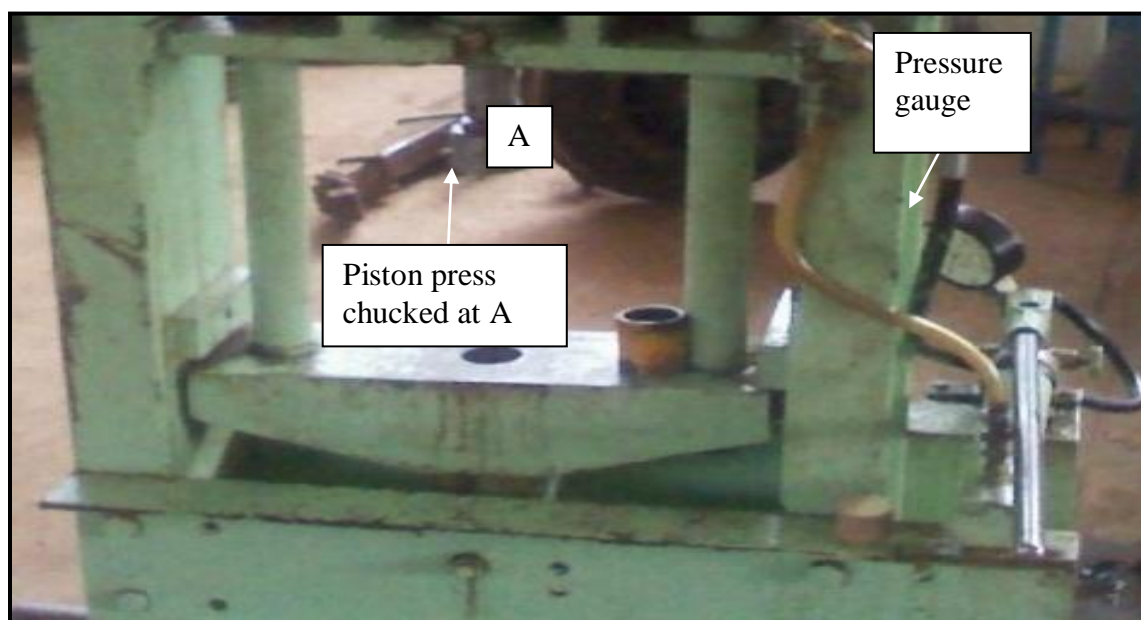


Plate 3.2. A Photograph of instron compression machine

Table 3.1. Physical properties of pelleter used

Manufacturing company	-
Type of die used	A cylinder and piston press
Channel diameter	41.5mm
Channel length	30.0mm
Length of pellet produced	21.0mm
Type of press	Hydraulic Press.

ix. Plunger and a die (single-pelleter)

It consists of a cylindrical die and a plunger. The single-pelleter was fabricated by the researcher in the workshop of school of engineering, Moi University. The die was cut

from a 41.5mm diameter G.I. metal pipe. By use of a hack saw and a measuring tape, the pipe was cut approximately into 30.0mm in length. The pipe was smoothed in its internal circumferential surface by use of a lathe machine to obtain a smooth surface for easy compression of material, and thus avoiding abrasion and friction. The plunger was well cut from a metal rod of less close fitting diameters than the die for easy slipping. The rod cut was weld at one end of the rod with a close fitting but easy slipping metal cylinder on it. The full system is as shown in figure 3.1.

x. Rolling mill.

Rolling machine, found at Chemelil Sugar Company, agronomy section, was used to roll the material to extract juice from the lignocelluloses fibers. By structure, the mill is comprised of finely ground solid chilled cast iron cylindrical drum rollers mounted on cast iron stands. Milling is achieved on the rollers by re-segmenting the drum with 18-2inch circular ring segment each chased with an 8 tooth per inch V-shaped high speed steel chaser to 16 v-grooves and into 80 helical grooves by use of tapered milling cutter. The rollers with extended collar shaft are connected to the gearbox via a universal cross bearing joint. Motion in the helical gear train box is provided by a 30hp and a 415V squirrel caged star-delta electric induction motor that transfers its motion through pulleys interconnected by 3 v-belt. The rollers rotate in opposite direction at different speeds and are provided with independent water cooling arrangements. A discharge hopper with doctor blades is provided for scraping material from a take-off roller. The gap between rolls is adjustable by means of mechanically hand operated spiral dial gauge wheel provided by side of feed and discharge roller. A sturdy cast iron and steel fabricated

frame is provided for mounting the mill on the foundation floor and minimize vibrations on the rollers.

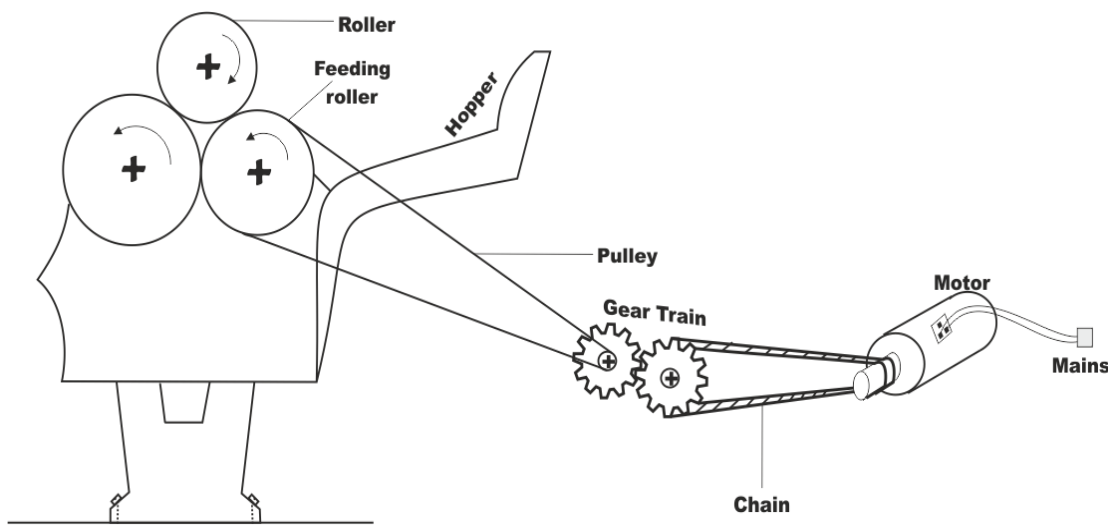


Figure 3.1. Schematic diagram of a 3-roller milling machine (Source: Researcher's drawing, 2014)

3.3 Material Collection and Preparation.

3.3.1 Material collection

Before collection, the plant material was identified by Mr. Nyamosi, a research laboratory technician at the testing laboratory of Agronomy section of Chemelil Sugar Company. These samples were comparatively used at the study site to obtain the specimen from farms through uprooting.

Tradescantiazebrina was collected at different sugarcane fields of Chemelil Sugar Company on Tuesday, 10 July 2012. The general weather condition during this day was wet and humid. Farm practices like tilling make the plant soiled with some dirt of fine sand particles intermingled and intertwined within it. Major foreign materials include

Napier grass, sugarcane stalk leaves, soil particles and star grasses. All these foreign materials were removed through handpicking before rolling. Most of TRZE material was found in areas that are wet and fertile. TRZE intertwines spirally along sugarcane stem length. Sparse distribution of the material was experienced in dry areas; the stalks were very weak and lost much of its water through evapo-transpiration. The material was collected by hand weeding from their habitat and put in a polybag for carriage to the rolling mill.

3.3.2 Material preparation

Rolling was the major preparation done for TRZE material. At Chemelil Sugar Factory, Agronomy laboratory, a roller machine with three rollers, two rotating counterclockwise while the third roller in anticlockwise direction. Rolling was done to break the succulent leaves and stems to remove the fluid extract in the plant material and expose the surface for evapo-transpiration. The major objective for rolling process was to obtain a water free cellulose fiber of TRZE. Rolling was done in a three roller, 2-inch clearance machine to increase the surface area exposed to natural air drying. 19.5kilograms of pure TRZE were fed onto the rolling machine. The roller machine contains a hopper where the massive TRZE is fed onto; the hopper regulates the flow of the material to the feed roller. The machine has three rollers operating at different speeds and directions. The material is fed between the rollers and is discharged from the final roller by a scrapper blade. The paste passing between the rolls is subjected to high stress and frictional forces resulting in the breaking up and separation of the particle to produce a finely dispersed film. The gap adjustments between the rollers can be done manually or hydraulically. After rolling, the material was aired for 2hours at a mean temperature of 24.0⁰C, weighed and packed

tightly in a polybag for transportation. Thereafter, the sample weighing 13.7kg by weight was packed in a tightly closed polythene bag and transported to Eldoret town for drying. The analysis of the transported material was carried out in July and August 2012 at Moi University, Eldoret. Rolled TRZE were dried to avoid any biochemical degradation process during storage and production of fuel pellets. Drying was realized through natural-sun and air by spreading 1 kilogram of TRZE on the floor of a workroom at a daily average temperature of 37⁰C. A thermometer was placed at the spread material for the entire period of drying. Initial weight and temperature of the material was taken after every 24hours. The dried TRZE's moisture content was determined by dividing mass loss by original mass and multiplying by 100. The procedure was repeated until a constant mass was achieved. The data obtained was recorded in the table shown in appendix II.

3.4 Measurement of Moisture Content

Moisture content is the ratio expressed as a percentage of the mass of the water to the mass of the solid material. The moisture content of the sample was determined in three phases; first phase involved drying 10.5kg of a freshly harvested sample by the natural air to constant mass at a daily average temperature of 24⁰C until a constant mass of sample was reached. The mass of the sample was determined by weighing total weight of sample with the container and then subtracting the mass of the container. After every 24hours moisture content was determined by;

$$\text{Moisture content(\%wt)} = \frac{\text{mass after 24 hours}}{\text{original mass}} \times 100 \quad (3.1)$$

The second phase involved measuring a known mass in grams of milled TRZE by an electronic precision balance. The weighed mass was placed inside a crucible and their

total weight recorded. The crucible and its contents were put inside an oven/ furnace set at 105⁰C and heat to a constant mass or zero mass change. The crucible and its contents were removed from the oven by use of a pair of tongs. They were weighed and its moisture content determined. Percentage moisture content was calibrated using, (Eqn. 2.2) proposed by Darra (1999). The data was recorded as shown in Appendix II.

The last phase was conducted when the material was in pellet form. After the material had been pelletized from a compressive hydraulic press, it was immediately dried in the oven furnace to constant weight at 105⁰C (Bureau of Energy Efficiency) which was approximately 23hours. Weight loss that occurred in every temperature value versus time was recorded as in appendix IV.

3.5 Determination of Repose Angle

TRZE milled material of different particle sizes were placed in the oven set at 105⁰C for 2hours. The material attained constant weight. The dried milled TRZE material were removed from the furnace and sorted into 0.6mm, 1.18mm and 2.0mm particle sizes by a laboratory test sieve. This was done to dry the material before determining the angle. Each dried particle sizes of the material were, placed in an open ended hollow tube measuring 41.5mm by 30.0mm. One side of the tube was inverted on a clear clean board and the material filled into the tube. The tube was then removed slowly taking care not to affect the formed pile. The angle formed by the diagonal side of the pile to the horizontal surface was measured using a protractor. This procedure was repeated five times for TRZE biomass material of particle sizes 0.60mm, 1.18mm and 2.00mm until a constant value of the angle was obtained. The protractor for measuring the angle was rotated

around the pile as readings were being taken. Plate 3.3 below shows how the angle was measured.



Plate 3.3. Measuring repose angle of 0.6mm particle size.

3.6 Procedure for Production of Pellets

3.6.1 Screening, conditioning and compressing

Dried TRZE material was milled, sieved/screened through aperture size of 1.18mm, weighed and stored in well-labeled sealed plastic bags. The average particle size distribution of the material was assessed to determine uniformity and randomness of particle size distribution by running different masses of the material through a Laboratory Test Sieve (Glenammer Engineering, ISO 3310-1) with aperture sizes 1.18mm, 0.600mm and 0.425mm was carried out. Data obtained were recorded in table 4.2. The particles in clear polybags were labeled in batches of sizes 1.18mm, 0.600mm, 0.425mm and stored

separately for making pellets. Pellets were prepared first without a binder, with water as a binder and with a starchy cane molasses for each of the three batches.

Method 1: Pelletizing the material without a binder involved placing 15.0grams of every 1.18mm, 0.60mm and 0.425mm particle sizes into a die separately. Observations in density, volume, moisture content and durability were made for pellets produced at pressures of 0bars, 6.89bars, 13.79bars and 20.68bars.

Method 2: The material was sprinkled with water and mixed uniformly. The procedure adopted in Method 1 was followed.

Method 3: The material was conditioned evenly with 15% cane molasses binder method 2 followed. This was determined by weighing specific amount and finding 15% of this mass to get the weight of the binder to be used. The plate below shows a uniformly distributed cane molasses binder in TRZE material.



Plate 3.4. Milled TRZE evenly mixed with 15% cane molasses binder



Plat 3.5. Weighing 15.0g of milled TRZE for pellet making

The compression of biomass feedstock was carried out in a single-pelleter (plunger-cylindrical die) assembly as shown in drawing 3.1 by the researcher.

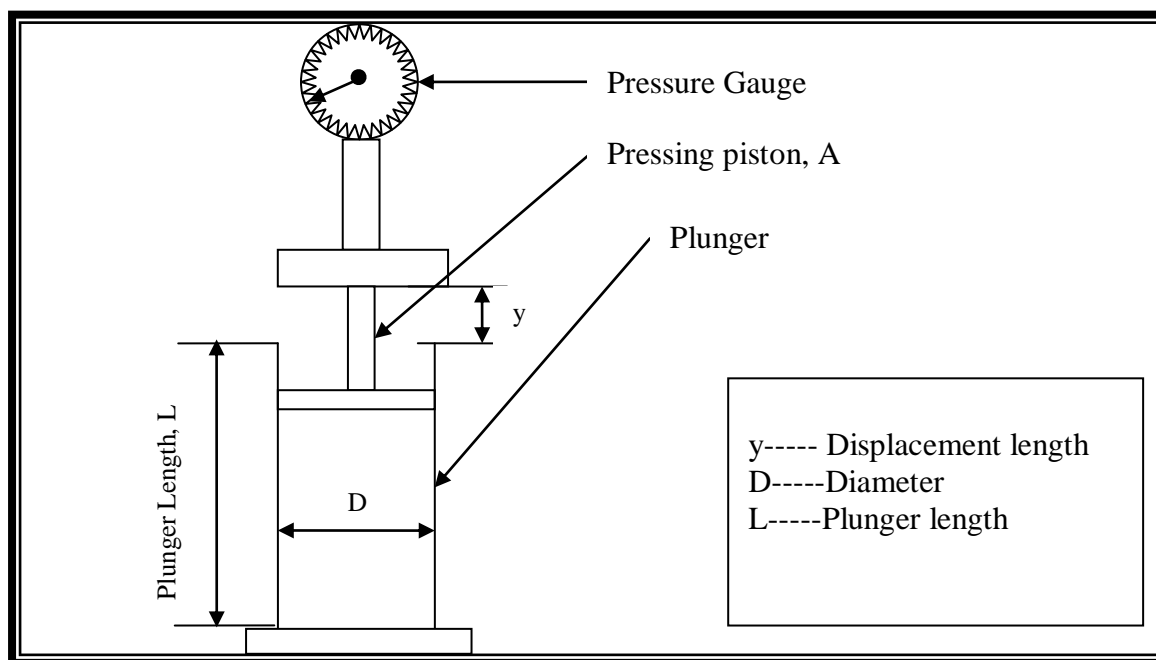


Fig 3.2: Schematic Diagram of a pelleter, 2013

The metal apparatus has 41.5mm internal diameter and 30.0mm internal chamber height. A 41.5mm plunger/piston cut from a drill iron rod was fitted via a chuck attachment to Instron model 1011 universal testing machine, which provided means to compress the biomass material. The cylinder die slip-fit into a steel base upon which the materials were compressed. The Instron was equipped with 20.68bar (300psi) pressure load through a handle-operated hydraulic press and the corresponding change in displacement was recorded in the pressure versus displacement data table shown in appendix VIII.

15.3 g of the selected milled TRZE feedstock was loaded into the die cylinder channel. Pre-set loads of pressures of 0, 6.86bars and 13.79 bars (0, 100psi and 200psi) were used to compress the charge material. The Instron was set to lower the plunger and compress the biomass. Pellets for no binder, water and cane molasses binders were formed at pressures of 6.86bars, 13.79bars and 20.68bars. The same procedure was repeated for milled TRZE of particle sizes 0.6mm, 1.18mm, 2.0mm and 2.36mm. For every pellet formed at each pressure level, the plunger was held for 10s then extruded and its size recorded as 0second relaxation time. Further, variation in size was recorded at 10s, 20s, 30s and 40s as the relaxation time for the pellet produced. A table indicating the pressure of pellet production, size variation versus relaxation time was recorded as shown in Appendix XII.

No lubricant was used in the die, and the plunger-cylinder fit was such that it was assumed that there was negligible friction between the two components. Once the pre-set load was achieved, the plunger was stopped, the steel base removed and a steel plate with a centrally located hole was inserted underneath for support. The formed pellet was

ejected out via load application through a plunger. The pressure versus displacement data was collected and recorded in Table 4.4.

3.7 Determination of Energy Content of TRZE

The gross Heating value (higher heating value, HHV) and the net Heating value (lower heating value, LCV) at constant pressure measures the enthalpy change of combustion with and without condensed water respectively. Heating value was tested in two scenarios; first, by fitting models proposed by Jain (2013) as shown in equations (2.3), (2.4) and (2.5) and secondly by use of ballistic bomb calorimeter to measure heating value.

In the latter case, the B002.BB1.B Gallenkamp Ballistic bomb calorimeter model was used to determine the gross Heating value of raw TRZE. Sectioned parts of the material from the plant were placed in a stainless steel crucible and a cotton fuse was used to ignite the material in the vessel (bomb).

The vessel was filled with oxygen to 25 atmospheres and surrounded by a water jacket. A sample of benzoic acid was measured, recorded and put into the vessel. A cotton fuse thread was connected to the sample – benzoic acid. The bomb galvanometer scale was zeroed. The bomb vessel was fired and the maximum deflection of the galvanometer reading was recorded. The bomb chambers were cooled and cleaned for the TRZE sample analysis. The same procedure was repeated for TRZE sample and the maximum deflection was recorded too. Tests on each sample of TRZE were repeated three times for reproducibility.

From the data obtained, TRZE's heating value was determined by the following procedure.

Mass of Benzoic acid	= W_1 grams	
Heating value of benzoic acid	= 6.32kcal/g	
Heat release from benzoic acid	= 6.32 W_1 kcal	
Galvanometer deflection without sample	= θ_1 divisions	
Galvanometer deflection with benzoic acid	= θ_2 divisions	
Galvanometer deflection due to benzoic acid	= $\theta_1 - \theta_2$ divisions	
Calibration constant,	$Y_1 = \frac{6.32 \times W_1 \text{ kCal/g}}{\theta_1 - \theta_2}$	(3.2)
Mass of the sample	= W_s grams	
Average meter deflection with the sample	= θ_3	
Thus, meter deflection due to the sample	= $(\theta_3 - \theta_1)$ divisions	
Heat released from sample	= $(\theta_3 - \theta_1) \times Y_1$ kJ	
Therefore, the Heating value of the sample	= $(\theta_3 - \theta_1) \times \frac{Y_1}{W_s}$ kJ/g	

(Instruction Manual for Ballistic Bomb Calorimeter, Model: B002.BB1.B)

3.8 Determination of Pellet Durability

The pellets produced from Section 3.6, were stored in airtight bag. After the pellets attained a constant shape and size, a laboratory test sieve gauge 3.35mm was loaded with a pellet of known mass, and vibrated for one minute at 50hertz frequency. The compacted mass of the pellet that remained on the sieve after shaking were measured as well as the original total mass of the pellet. Durability of the pellet was calculated using Equation (2.11).

3.9 Determination of Pellet Density

The true density of each pellet was calculated by measuring the length and diameter of the pellet cylinder using a vernier caliper and the mass of the pellet using an electronic beam balance with a precision of 0.01g. Pellet density was calculated by dividing the mass of individual pellets by their volume calculated from length and diameter. The value of pellet density was the average of ten measurements.

3.10 Compressibility Testing

The research adopted Jones (1960) model, (Eqns. 2.27 to 2.29), was applied in the study. The equation further gave a ground to determining compressibility of material with two different binding agents and with same binding agent but varied particle sizes. The binding agents applied were water with particle sizes of 2.0mm and cane molasses binder with 0.6mm, 1.18mm, 2.0mm and 2.36mm particle sizes. The mass of the material used in compression was constantly maintained at 15.0g while the volume varied with varying pressures, particle sizes and binding agent as well.

The volume of the pellet produced was calculated immediately it was removed from the die. Measurement of the diameter and height was evaluated by a vernier caliper scale of 0.02mm accuracy. The vernier caliper did not have a parallax error. This was done by testing coincidence of zero graduation mark in the fixed (upper) scale with zero mark on sliding, lower scale. The density was calculated in g/cm^3 and converted to kg/m^3 by multiplying the result by a factor of 1000. The natural logarithm of the density and pressure was calculated according to Equation (2.27). Pressure was too converted from

per square inch (psi) to kilopascal (kPa) through multiplying the psi by a factor of 0.689. A graph of $\ln(P)$ versus $\ln(\rho)$ was plotted in MS Excel and the constants m , b and R^2 evaluated. The plotted graph was imported as shown in Figure 4.8. The values of $\ln(P)$ and $\ln(\rho)$ were recorded in Table 4.8.

3.11 Determination of Physical Combustion Characteristics

The following is the methodology for determining volatile matter, fixed carbon, ash, air-fuel ratio and the nitrogen content for TRZE material.

3.11.1 Measurement of volatile matter (V.M.)

Volatiles are any substances that have a tendency to vaporize given the right conditions. Substance volatility is measured by its vapour pressure, the point at which a substance turns from a solid state to a gas or vice versa. Fresh samples of TRZE were weighed, placed in a covered crucible and heated in a furnace at a temperature of 350°C (Supunneeet.al., 2009) for 10 minutes. The process was repeated for four samples and the mean value obtained was recorded. The sample was weighed immediately after removal from the furnace conditions unchanged. The weight loss recorded represented moisture and volatiles. The remainder weight represented fixed carbon and ash.

$$\text{VM} = \frac{\text{moisture mass} - \text{volatile mass}}{\text{initial mass}} \times 100 \quad (3.3)$$

Where VM = volatile matter in percentage.

$$\text{Volatile dry} = \text{VM} \times \frac{100}{100 - \text{M.C}} \quad (3.4)$$

3.11.2 Measurement of fixed carbon and ash

The oven furnace was set at 500⁰C. Then the contents in the uncovered crucible after volatiles have been determined were placed in a closed furnace. The weight of crucible was determined after every one hour until the mass in the crucible became constant. That is, till all the carbon content had been combusted. The residue in the crucible represented incombustible ash only was weighed. The difference in weight represented fixed carbon (FC). In practice, fixed carbon (FC) is derived by subtracting from 100 the value of moisture, volatile matter, and ash.

$$\text{Ash Dry} = \text{Ash} \times \left[\frac{100}{100 - \text{MC}} \right] \quad (3.5)$$

$$\text{FC Dry} = 100 - [\text{volatile dry} + \text{Ash dry}] \quad (3.6)$$

MC= the moisture content

$$FC = 100 - [MC + VM + Ash] \quad (3.7)$$

3.11.3Determination of Air/ Fuel ratio

The stoichiometric air fuel ratio of TRZE was determined by applying Equations (2.7) and (2.8) to obtain the stoichiometric formula that is necessary during combustion of any biomass material. From Equation (2.9), an oxygen balance on the reactants versus the products for the number of moles was equated.

$$y + 0.21(2n) = 2 + x/2$$

3.11.4 Determination of N, C and C/N ratio

Kjeldahl assembly method at the Kenya Bureau of Standards (KEBS) science laboratory was used. 0.25 gram sample of TRZE were measured and put into a digestion tube. Kjeltabs of copper sulphate with titanium oxide ($\text{CuSO}_4/\text{Ti}_2\text{O}$) catalyst and 10ml of concentrated sulphuric acid (H_2SO_4) were added. The contents in digestion tube were placed in a pre-heated digestion block for 30minutes until a green solution was formed. The reagents were then removed, cooled and transferred to the Kjeltac analyzer.

The solution was then steamed and distilled with sodium hydroxide (NaOH). The nitrogen evolved was collected over boric acid and finally titrated with 0.5M hydrochloric acid (HCl). The percentage content of nitrogen was determined by the protein titre volume by nitrogen-to-protein conversion factor 6.25 (100/16). It is assumed that nitrogen content in proteins is 16% by volume.

Nitrogen content in TRZE was determined by multiplying nitrogen-to-protein conversion factor of 6.25 (100/16) since it is assumed that the nitrogen content in proteins is 16%.

3.11.5 Single particle combustion characteristics

The oven was put on and by use of a temperature adjusting knob; temperature was set at 850°C . The oven was left on as it rose from 10°C to a surface temperature of 850°C . A single cylindrical pellet measuring 21mm length by 41.8mm diameter was cut into 1.5mm by 1.5mm by 1.5mm cube in order to investigate the drying, devolatilization and char combustion behavior of TRZE biomass material. The procedure involved suspending the particle cube by type K thermocouple connected to a data logger shown in

figure 3.2 that displayed temperature reading after every 5seconds. Porcelain bricks were used to seal the door cover of the oven furnace leaving a small aperture of approximately 1.8mm to deliver the suspended particle into the furnace. The thermocouple measured the temperature changes as the particle got burn out. The schematic diagram is set up for conducting single particle combustion of a TRZE material.

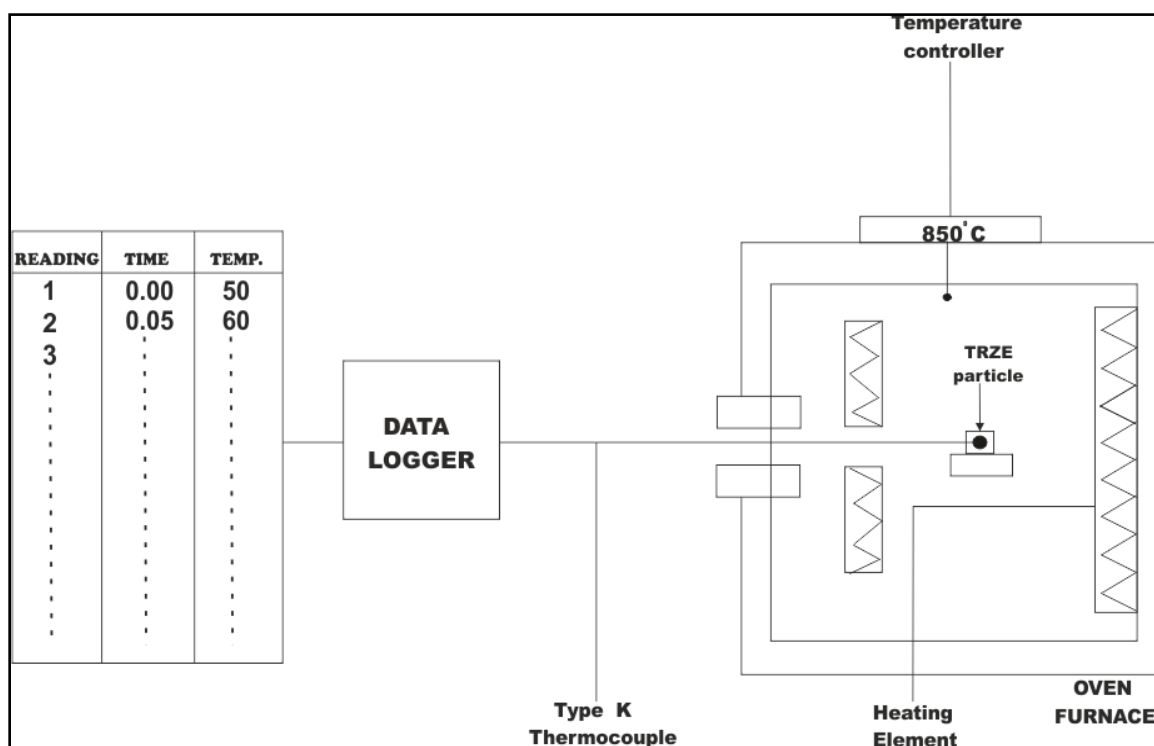


Figure 3.3: Schematic view of single particle combustion system (Source: Researcher's drawing, 2014)

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

This chapter presents the results of the study carried out to achieve the objectives stated in chapter one as well as those of equipment used. Section one presents results of experimental test runs carried out to determine the particle size distribution, repose angles of the material, material conditioning, energy valuation, durability tests, density, compressibility study, proximate and ultimate and nitrogen contents. Section 2 presents the general discussion of the chapter.

4.1 Material and Pellet Moisture Content

4.1.1 Material moisture content

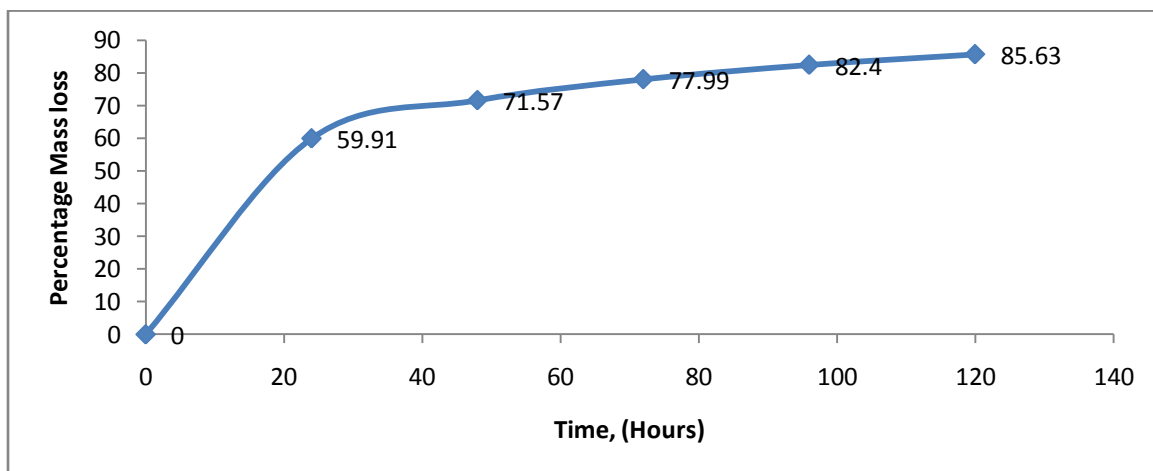


Figure 4.1: Percentage Mass loss versus time during air drying of TRZE at 22.7°C

Figure 4.1 above shows water loss versus time of the material immediately after rolling and drying in open air at a daily average temperature of 22.7°C for 5 days. There is about 60% water loss from the plant during the first 24 hours; this was accelerated by

evaporated water that was on the surface of the material. The percentage loss decreased for subsequent hours because much of the water had escaped and the few that was left existed within the inter fibers. In this part, heat was conducted from each ion or molecule of water to the next before much of heat is accumulated for evaporation to take place. Above 80 hours, the material exhibits a constant percentage mass loss of 80%. Mass loss would continue, but because the temperature was constant for the first five days, otherwise it varies depending on the weather conditions. A constant temperature was achieved by monitoring the thermometer reading after every one hour. At any slight drop or rise in reading the value was recorded. When the temperature varied into $>-5^{\circ}\text{C}$, the material was removed from airing. Averagely, the temperature remained constant in the course of five days of the experiment.

The moisture content analysis of rolled TRZE was necessary for milling and storage feasibility. High moisture content cause decomposition of the material during storage and increase transportation costs due to its added weight. Hence reducing the water content of the material at the harvesting stage was a necessary step for storage purposes before milling. Milling requires nearly dry materials for easy processing through the screens. Processing biomass with high moisture content could be a time, energy and money consuming activity. Otherwise, the material can cause rusting of mill equipment, reduction in mass of the material put at the hopper of the mill since the material get attached at the walls of the mill, it demands labour work in removing the material stuck on the walls and the energy consumed by the mill during milling process increases.

It can be concluded that drying of this research material is achieved at no cost due to availability of space and natural sunlight. The material achieved 15% moisture content in a short time as seen from figure 4.1. Thus, TRZE has a potential drying at the source of harvest before being transported to the milling and pelleting industry hence saving transport costs of transferring bulky materials. Material storage will be efficient regarding the use of sunlight to dry the material therefore no decomposition that will take place.

4.1.2 Pellet moisture content

The pellet moisture content calculated is 14.2%. The figure indicates that pellets can easily burn like any other woody biomass material. There is a 35.88 percent increase of moisture content from the original unbound material of 10.45%. From this work of study, variation in moisture content was majorly influenced by the following reasons:

- i. The increase of moisture content during conditioning by binding agents.
- ii. The increase of moisture content due to accumulation of water vapourhygroscopically.

These findings are true to the research findings of Verena (2011) that low moisture bound pellets when conditioned achieve a good quality and high stable form.

4.2 Particle Size Distribution

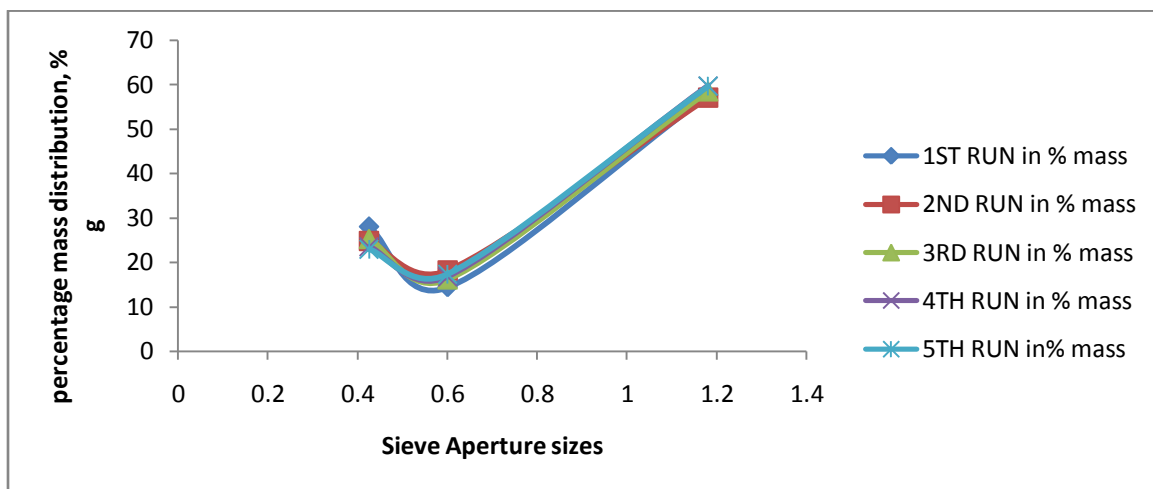


Figure 4.2. Particle size distribution of milled TRZE

Figure 4.2.above shows the percentage of particle size distribution at various aperture sizes respectively. It is observed that at a higher percentage of particle spread out of sieve of aperture size 1.18mm and the least quantity in the 0.600mm aperture size. The percentage mass distribution from the aperture size of 0.425mm is higher than percentage mass distribution of 0.600mm aperture size. The high presence of small particles embeds other particles into large particles leading to production of best pellet. The distribution of masses is random. Presence of different size particles improves the packing dynamics and contributes to high static strength (Grover & Mishra, 1996). Depending on the intended packing of particles within the pellet, such widening of the distribution is desirable because it leads to higher packing density of all pellets formed. Previous studies show that most of the mass distribution obtained from the experiment confirm to a similarity mass distribution.

4.2.1 Repose angle results

From Plate 3.3 the repose angle for TRZE pile was found to vary with sizes. Lower particle sizes of 0.6mm and 1.18mm had a repose angle of 30⁰ ranging to 40⁰ for higher particle sizes of 2.0mm hence TRZE has a low flow ability. The following table shows the results obtained for each particle sizes.

Table 4.1. Angle of repose for 0.6mm, 1.18mm and 2.00mm particle sizes

Particle sizes	Repose angle range
0.60mm	30 ⁰ -38 ⁰
1.18mm	35 ⁰ -43 ⁰
2.00mm	40 ⁰ -45 ⁰

4.3 Material Conditioning and Pellet Production

Table 4.2. Conditioning of TRZE

Mass of the container (g)	245.2
Mass of TRZE placed in the Jar (g)	97.1
Mass of binder (cane molasses) sprayed (g) 15% of total weight.	14.5
Ease of mix with binder	Not easy to mix through sprinkling. However, mixes well through continuous churning.
Stickiness	Yes
Presence of cohesion	Yes

Cane Molasses binder forms solid body bridges with the material. Due to the presence of starch and protein in molasses, provide further bonding of the material. A uniform distribution of the binder was not easily achievable therefore; continuous churning of the material until a uniform spread of the binder observed was necessary. Weighing an exact amount of this churned mass for pellet production showed tricky when trying to achieve a certain amount of grams. This was due to the bonding together of the masses and thus separating a balancing mass particle required hand picking.

15.00 grams of the pure TRZE sample placed in a pelletizing chamber measured 41.5mm in diameter. The mass poured on a clear clean surface, recorded an average area of 75 ± 2.5 mm by 75 ± 2.5 mm while at rest. After pressing the sample at 0.0, 6.89bars, 13.79bars and finally 20.68bars, the pellet formed a varying height between 20.00mm to 33.00mm with diameter varying of between 41.5–45.5mm after a relaxation time of 1minute. Conditioners of 15% by weight cane molasses, 15%wt water and at no binder, showed a varied densified form of the pellet at 6.87bars, 13.79bars and at 20.68bars. The results showed a densified form of the pellet with similar measurements as shown in table 4.5.

Table 4.3. Mean Values of Pellet Production process

	Pellet No.	Mas s,A (g) before pelleting	Area (mm ²)	Elongation(mm) at pressures (bars)				Lengt h (mm)	Diam eter (mm)	Mas s B after pelleting (g)
				0	6.89	13.79	20.68			
Ave. data	1	15.3	5625.0	23.0	22.0	21.5	21.3	21.3	42.4	15.1
compression ratio, $x/2r$ (Tabil, <i>et al.</i> , 2011)				0.542	0.520	0.508	0.502			

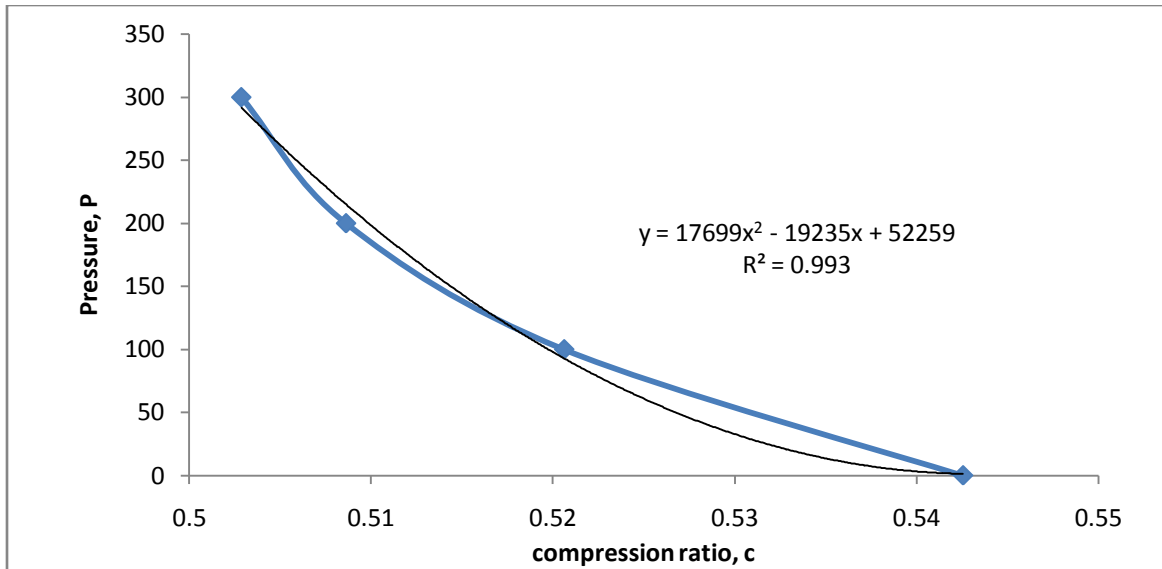


Figure 4.3. Pressure, (P) vs. Compression ratio, (c).

Generally, from Figure 4.3 above, there is uniform decrement of length to pressure applied in the range of 0 to 20.68bars. The particles percolate within the interstitial spaces of the compacted mass progressively.



Plate 4.1. TRZE Pellets produced at 20.68bars pressure load.

In analyzing the process quality of the experiment, it was found the overall performance of the pelletizing process was consistent throughout the experimental period. Considering

Plate 4.1 above, pellets formed achieved a uniform spread of particles. The pellets are of the same appearance and colour. The binding agent is evenly distributed. The pelleting process does not influence any property on the pellets apart from compressing particles into a fine shape. The minimum variation of mass for making pellets before and after pelleting is a true reflection of a compress-channeling chamber. The variation in mass is due to particles stuck to the piston and the platform.

In order to determine the fine fraction of pelleting process, the measured mass of the pellet produced was measured. A beam balance was used to measure the mass of immediately produced pellet in order to determine the compression/relaxation parameters. The mass recorded showed little variation from that measured when the material was not compacted. The assumptions made for any little variation were; addition/ loss of mass that stuck along the pelletizing chamber; loss of material during extrusion of the pellet from the chamber; loss of material during transfer of loose material from the measuring plate to the pelletizing chamber; loss of material stuck on the pressing piston; loss of loose material stuck on the measuring plate; and loss of material binder through flow due to pressing at high pressure. Mass recording and measurement helped the researcher to determine the mass per unit time the material losses during combustion. This further enables calculation of durability of the pellet. The experiment was repeated more than five times until a mass of unpelletized milled biomass material equaled that of pelletized material and the results were tabulated.

The relaxed density of TRZE varied with diametral expansion and longitudinal expansion of the pellets. Lower initial pellet densities than packing densities indicate that the pellets

expanded once the load was removed. At higher loads the packing density of the feed stocks exceeded the particle density. This was likely possible due to voids present within the particles that were not exposed during conditioning and milling.

The lengths and diameter of pellets produced had 2-4% increase from immediate formed pellet, indicating that pellet relaxed immediately following pelletizing. This was due to; first, it may be due to unpacking of the particles from the forced positions within the mass; secondly, smaller particles compact well when compressed than larger particles.

Secondly, moisture absorption from the atmosphere contributed greatly to varying dimensions. Sizes of the pellet produced were measured to determine the allowable space required for storage during mass production. The sizes further give the baseline for determining size increase due to exposure of the pellets to the air. It also notes the time taken in transferring pellets for storage before there are changes in sizes, if delay is long, the material will occupy large spaces. The particles that are bound will not relax to change size.

Table 4.4. Preliminary results for material conditioning

Expt.	Binder	Moisture content after pelletizing (%)	Pellet production
1	Molasses + 1.18mm p.s. TRZE	14.2	Existent
2	Starchy wheat flour + 0.600mm particle sizes. TRZE	-	Little existent
3	Water, wheat flour + 0.600mm particle sizes. TRZE	-	Quite existent
4	No binder, TRZE alone	-	Not existent

Table 4.4 above shows the conditions that were tested in order to produce the pellets. The first condition involved mixing 15% cane molasses binder by mass of 67.0grams of the

material obtained through a sieve of aperture size 1.18mm. Pellets were produced with 14.2% moisture content. The next condition involved using starchy wheat flour and particle sizes of 0.6mm and compressed by an Instron compression machine at 20.68bars. This condition produced a pellet that ruptured immediately it was removed from the pelletizing chamber. Hence, this pellet was never analyzed for the moisture content in it. The third condition involved spraying water 15% by mass of pelletizing material with starchy wheat flour and 0.6mm particle sizes of the material. This condition quietly existed produced a pellet that did not withstand any analysis. TRZE material with a uniform distribution of three different aperture sizes, no binder was added nor water into the material. The material did not pelletize completely. Thus, the researcher decided to use cane molasses binder for pellet formation. Cane molasses binder was cheaply obtained, from nearby sugar industry as a by-product of sugar milling process.

4.4 Energy Content of TRZE

The energy content of TRZE was evaluated by two models; various models as proposed by researchers were fitted with the analyzed components and the values obtained were assumed true for the material. Secondly, the material was assessed by a calorific ballistic bomb calorimeter through a practical laboratory experiment, the values obtained were used in the heating value calculation formulae.

4.4.1 Energy valuation by fitting energy models

The ash content, fixed carbon, elemental carbon, hydrogen, oxygen and volatiles obtained from proximate experiments were fitted into the heating energy value models as proposed in equations 2.3 to 2.6.

Table 4.5. Heating values of TRZE by three models

Energy models	Model 1	Model 2	Model 3	Adetogun, et al., 2014
Energy content in TRZE (MJ/Kg)	14.52	15.71	17.41	24.78

4.4.2 Energy valuation by bomb calorimeter method

The average values obtained for benzoic acid during the experiments was 6.8 divisions while repeated experiment produced 5.5 divisions for TRZE. For a sample mass, W_s of 0.6 grams and mass of benzoic acid of 0.5 grams, the benzoic galvanometer reading was at 6.8 divisions. For a known value of gross calorific value of benzoic acid of 6.32 kcal/kg, thus calorific value for 0.5g of benzoic acid is given by $6.32 \times 0.5/1 = 3.16$ kcal.

Table 4.6. Results of calorimetric experiment on sample and benzoic acid

Sample	Test A	Test B	Test C	Average Results
Benzoic acid	6.5	6.5	7.0	6.8
TRZE	5.6	5.5	5.4	5.5

The calibration constant obtained, after applying, (Eqn. 2.10), from the benzoic acid is given by;

$$Y_1 = \frac{6.32 \times 0.5}{6.8} = 0.465$$

For a mass of $W_s = 0.6g$

The meter deflection due to the sample is given by $\theta_3 - \theta_1 = 5.8$

Thus, the heat released from the sample is determined from the formula $[\theta_3 - \theta_1]Y_1 kJ = 2.697kJ$

And the heating value of the sample $\frac{[\theta_3 - \theta_1]Y_1}{W_s} = \frac{4.495kJ}{g} = \frac{4.495MJ}{Kg}$

The values obtained from the above evaluations indicate that the unbound material of TRZE has a heating value of 4.495MJ/Kg while after pelleting; the energy value obtained according to applied models is averagely 15.00MJ/Kg. This research proves true with the findings of Tumurulu and other writers (2010), which shows that the HV of pellets is affected by in-feed pre-treatment and also by those with high density have a high heating value too.

4.5 Pellet Durability

The following graphs show the data and trend in percentage of pellet durability versus particle size, pressure and binder used in pellet production and comparison of pressure with density of formed pellet.

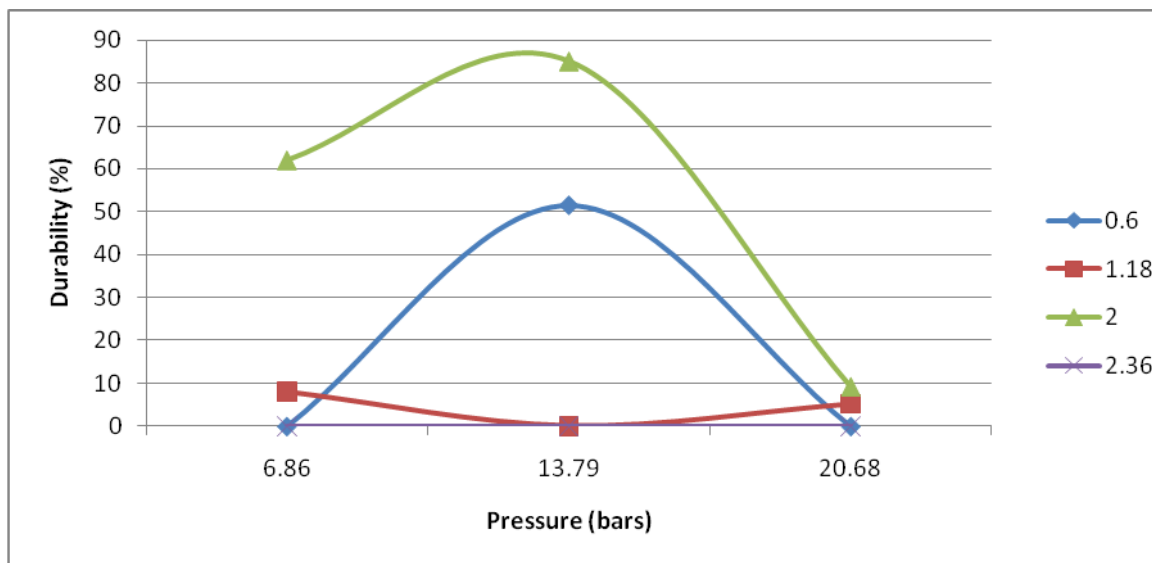


Figure 4.4. Trend of durability versus pressure for a pellet produced at no binder condition

From figures 4.4, higher durability of pellets existed for a pellet produced with 2.0mm particle size followed by pellet from 0.6mm particle size. 2.36mm particle sizes recorded lowest durability. Durability increased steadily as pressure increased but reached saturation point at 20.68bars. Lignin in the plant material saturated at 13.79bars. At 6.86bars, 13.79bars and 20.68bars pellet formed from particle size of 2.36mm did not form well. They often broke down into dust once extruded from the die. Large particle sizes are devoid of small particles that embeds larger ones. Therefore, durability of a pellet made from TRZE without a binder, increases from 6.86bars to 13.79bars for a material of particle size 2.0mm.

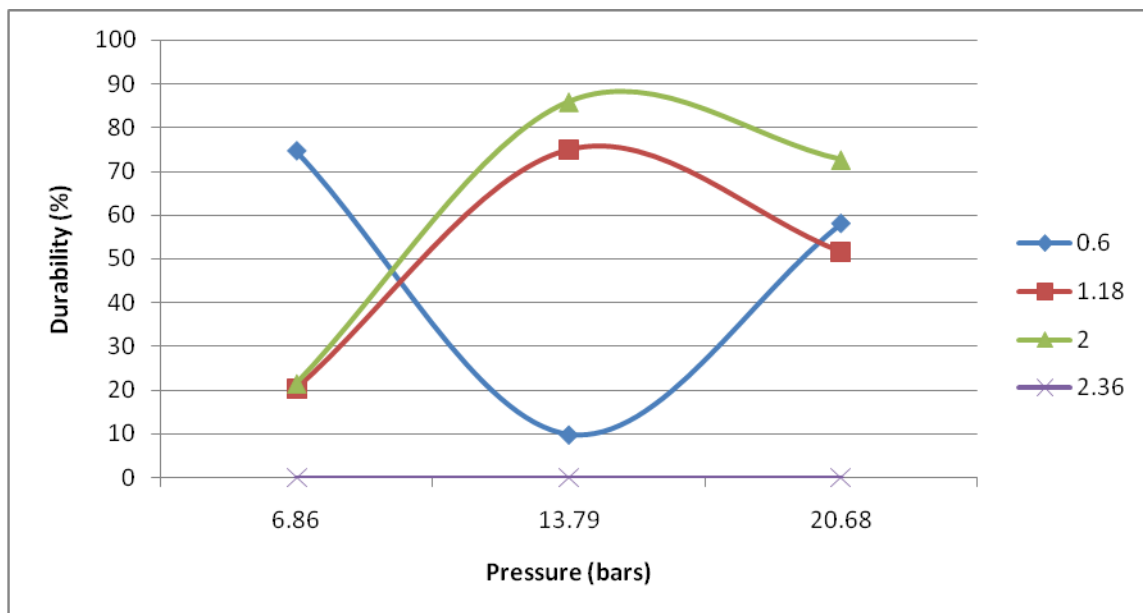


Figure 4.5: Trend of Pressure versus pellet durability for water bound pellets

When water was used as a binder, particle sizes of 0.6mm, 1.18mm and 2.0mm formed a densified form except that of 2.36mm particle size. The large particles absorbed the binding agent into the cellular tissues of the plant material, thus water molecule could not bound it. By conclusion, water as a binder provides a high moisture content that further produces the binding effect on the milled TRZE. Water binder produces pellet of a high durability at small particle sizes at lower pressures and at larger particle sizes at a higher pressure. For 1.18mm particle size, a good quality pellet is obtained at 13.79bars when the material is conditioned with water. For a particle size of 2.0mm, good quality pellet is obtained at 13.79bars and 20.68bars. Particle size of 0.6mm for water conditioned milled TRZE, a good pellet is produced at 6.86bars followed by a pressure of 20.68bars as the trend in figure 4.5 shows.

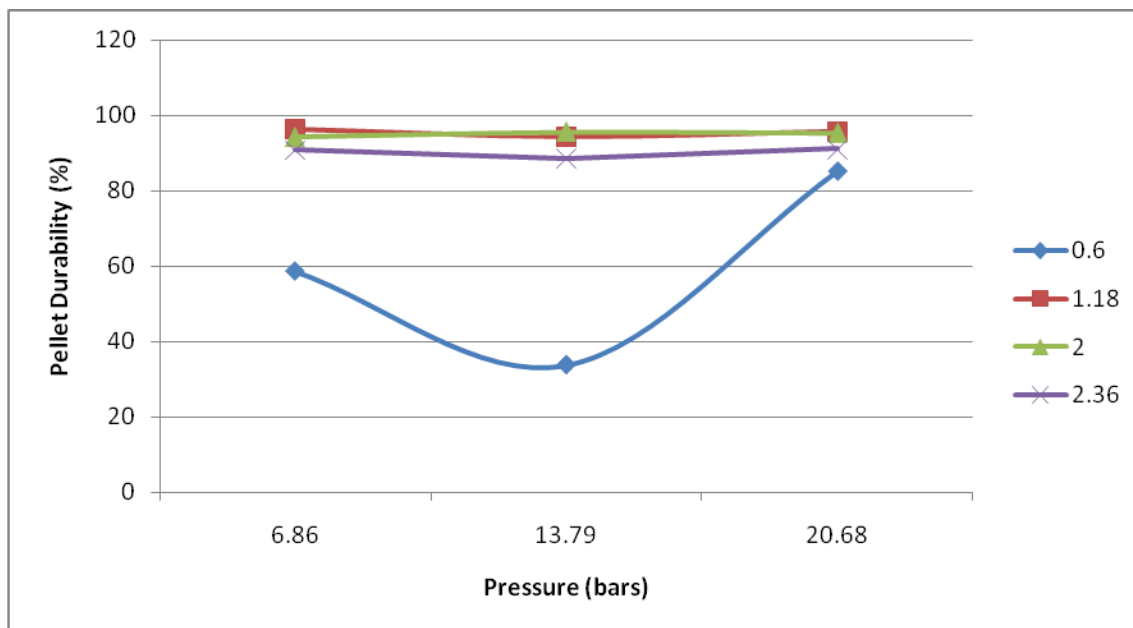


Figure 4.6: Trend in pressure versus pellet durability for molasses bound pellets

On average cane molasses binder performed well at pellet forming at all pressure values. Cane molasses contains about 5.7% by weight of proteins that improves the binding capacity of the pellet thus achieving high durability. The protein in itself contains over 15% by weight moisture content that triggers binding effect in biomass material. After shaking the pellet in checking abrasion resistance, the pellet showed little tendency of breakage. This was due to the stickiness of molasses binder providing high viscosity that allows particle granules to stick together and produce pellets that are less likely to break down during transportation. It can be noted that when molasses binder is applied, a high durable pellets are formed for particle sizes of between 1.18mm and 2.0mm for pressures ranging 6.86bars to 20.68bars. 0.6mm particle sizes produce pellets of high durability at 6.86bars and 20.68bars.

In general, pellet durability increases with an increase in applied pressure and sieve screen size. It is observed that durability is affected by pressure, particle size and type of

binder used under similar conditions of moisture content. Further, the mean durability index of pellets made of TRZE increased from 59.15% to 90.18% when the particle size increased from 0.6mm to 2.35mm when cane molasses binder was used. This could be due to the effect of mechanical interlocking of long cellulose fibers at high particle sizes.

4.6 Density Results from Fitted Models

The following figure shows the trend of density versus pressure loads applied.

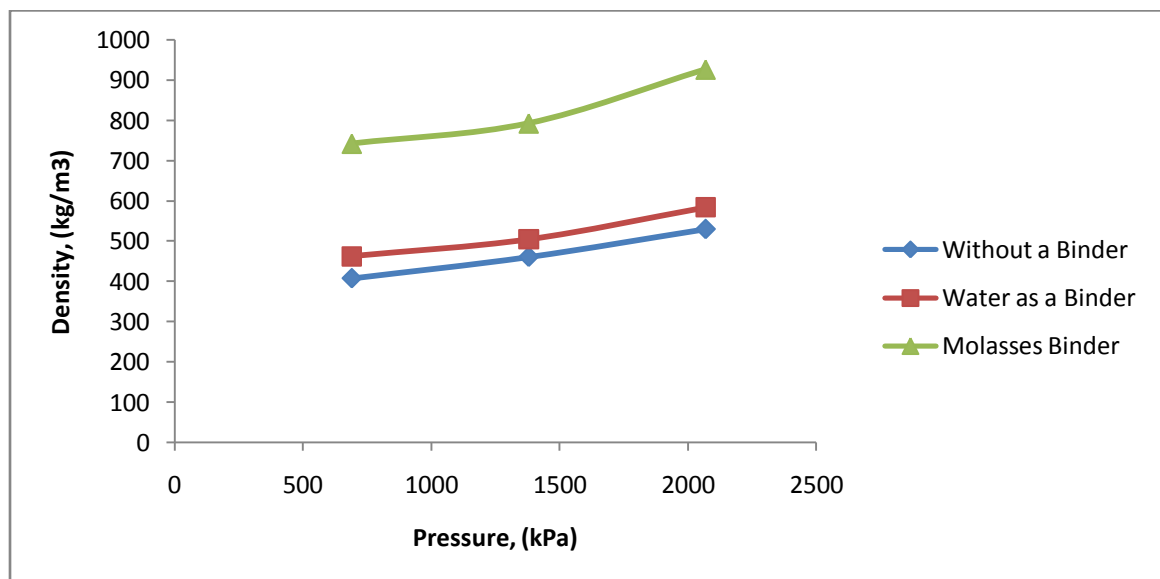


Figure 4.7 Variation of pressure versus density for a 2.0mm particle size

The relationship of density and pressure is in figure 4.7. This study used a 2.0mm particle size for three conditioning parameters; without a binder, water as a binder and use of cane molasses as a binder. The results show a density increase as pressure increases for pellets during formation. Pellets with conditioning agents have higher density compared to those without a binder. Among the three curves, molasses bound pellets obtained a higher density followed by water as a binder and least are pellets without conditioning agents. It

can be concluded that a binder fills the spaces within the particles and forms a pull of particles together thus reducing the size of the pellet during compaction and thus leading to a higher density packing.

4.7 Compressibility Study Graphs

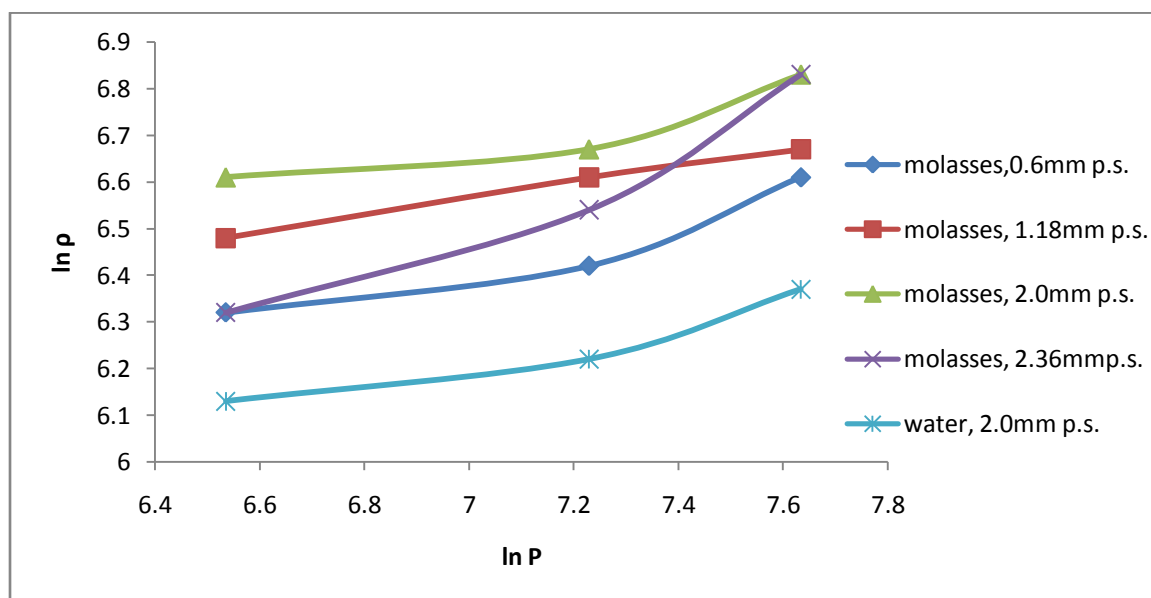


Figure 4.8. Compression behavior of TRZE particles using Jones (1960) models

The model equation 2.27 proposed by Jones (1960) was fitted with pressure loads and density data points where ρ is the bulk density in kg/m^3 and P is the applied compressive pressure in kPa. The constants \mathbf{m} and \mathbf{b} are intercepting and slope change respectively for plot of $\ln(\rho)$ versus $\ln P$. The molasses bound TRZE material with particle sizes of 2.36mm has a large value of \mathbf{m} as compared to rest of particle sizes. This is an indication that milled TRZE material of this particle size began to deform at a lower pressure. The application of molasses binder improves the compressibility of the TRZE during pellet forming. This finding confirms to *Tabilet al.*, (2011), who studied grounded agricultural

biomass and found out that ground particles obtained from larger hammer mill screen sizes had higher compressibility.

4.8 Combustion Behavior of TRZE

The following are results of experiments that were conducted on determining the proximate analysis, ultimate analysis, stoichiometric formulae, mass loss at varying temperatures, time for complete combustion of TRZE particle, nitrogen content in TRZE and its C/N ratio.

4.8.1 Proximate and ultimate percentage composition of TRZE

Table 4.7. Proximate and Ultimate composition of TRZE

Parameter	% composition	
Proximate analysis (% wt)	Moisture content	10.45
	Volatile matter	54.30
	Ash content	16.03
	Fixed carbon	19.22
Ultimate analysis (% wt)	Nitrogen	1.42 ± 0.1
	Carbon	50.37
	Hydrogen	4.92
	Oxygen (by difference)	43.29
	C/O Ratio	1.16

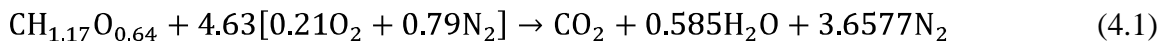
The stoichiometric formula according to equations (2.7) and (2.8) were calculated. Atomic ratio for x and y values were obtained as 1.17 and 0.64, thus the general formula can be written as $C H_{1.17} O_{0.64}$. Atomic ratios and their air fuel ratios for other biomass material are as shown in table 4.8. below.

4.8.2 Stoichiometric formula for certain biomass

Table 4.8. The x and y values of certain biomass materials (Source: Jain, 2013).

Biomass	X	Y	Air fuel ratio
<i>Acacia nilotica</i>	1.532	0.713	4.29
<i>Arhar stalk</i>	1.055	0.560	4.68
<i>Eucalyptus</i>	1.491	0.646	4.66
<i>Leucaenaleucocaphala</i>	1.142	0.564	4.78
Bagasse	1.519	0.635	4.55
Paddy husk	1.587	0.807	3.34
Maize cobs	1.273	0.765	3.06
Paddy straw	1.630	0.795	3.30
Cotton sticks	1.153	0.600	4.48

Equation (2.9) can be written as;



Calculating n value, TRZE is found to have an air fuel ratio of 4.63. For other biomass material, the stoichiometric air fuel ratio varies from 3.34 for paddy husk to 5.1 for acacia *auriculiforms* (Jain, 2013).

4.8.3 Percentage mass loss at varying temperature

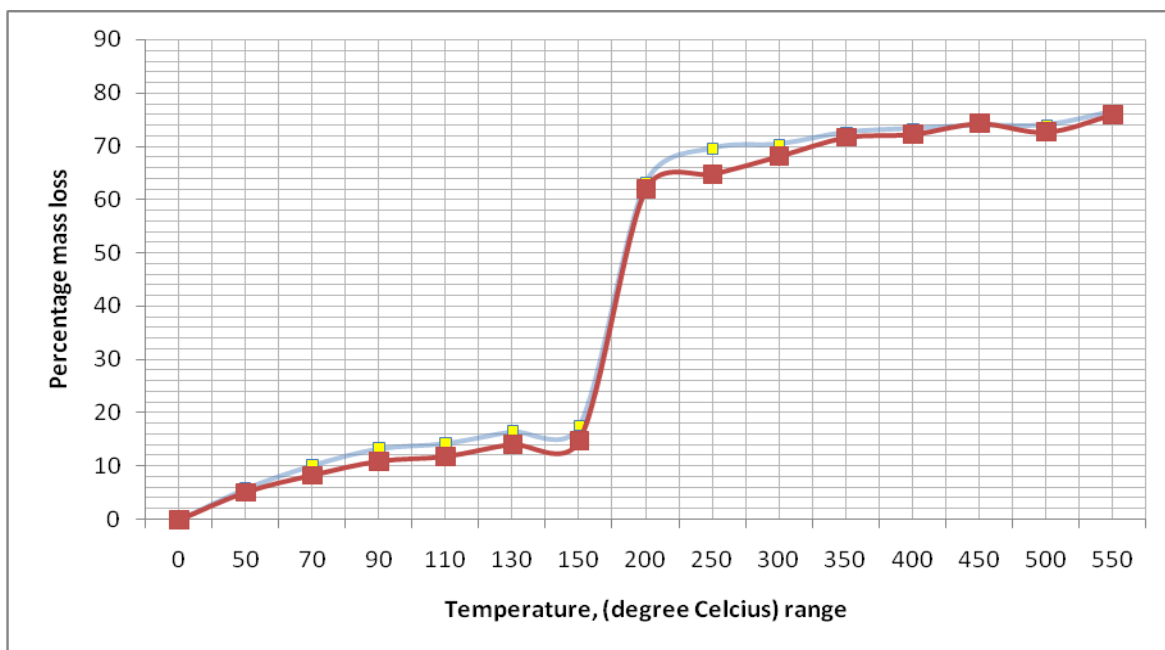


Figure 4.9 Mass loss of TRZE at a temperature range of 0 to 550°C.

Most agricultural residues have high moisture content. They range from 11% to as high as 60%. TRZE is a different case in point; its moisture content is 10.47% on as-it-is basis. Since this value is below 15%, the value required for any combustible material, TRZE could be used for heat generation. Other agricultural residues that include rice straws, coffee husks, maize stalks, cotton stalks and bagasse have the following percentage content in moisture; 17, 11.45, 26, 40 and 50 respectively (Omwando, 2006). High moisture content in a combustible material is a problem in conveying and storing more so in bunker choking and bed temperature maintenance (Arbon, 2002). It further leads to poor ignition, reduction in combustion temperature of the fuel. Presence of moisture too leads to formation of flue gases during combustion.

Agricultural residues like rice husks contain ash ranging from 18-25% and with less than 1% for coffee parchment husks. TRZE has 16.03% ash content by weight which when

compared to agricultural residues, the content of minerals in it are small. This amount of ash in TRZE would be important in design of the furnace grate and combustion volume for ash disposal.

TRZE has 19.22% of fixed carbon by weight. This amount takes a high percentage in mass of the material investigated. The amount of fixed carbon in a material contributes to the heating value of TRZE and acts as the main heat generator during combustion (Stahl *et al.*, 2002-2006). The amount of volatile matter in a material is a key factor to ease of ignition. The plant material, TRZE, has a 54.30% by weight volatiles thus indicating that when well dried, TRZE ignites easily, a factor that is necessary in heat generation.

4.8.4 Single particle combustion mechanisms of TRZE

The single-particle combustion experiment compares temperature variation versus time in an oven furnace. The furnace temperature also referred to surface temperature is the heat recorded from heating elements placed at the walls of the furnace. This is what is recorded at the controller.

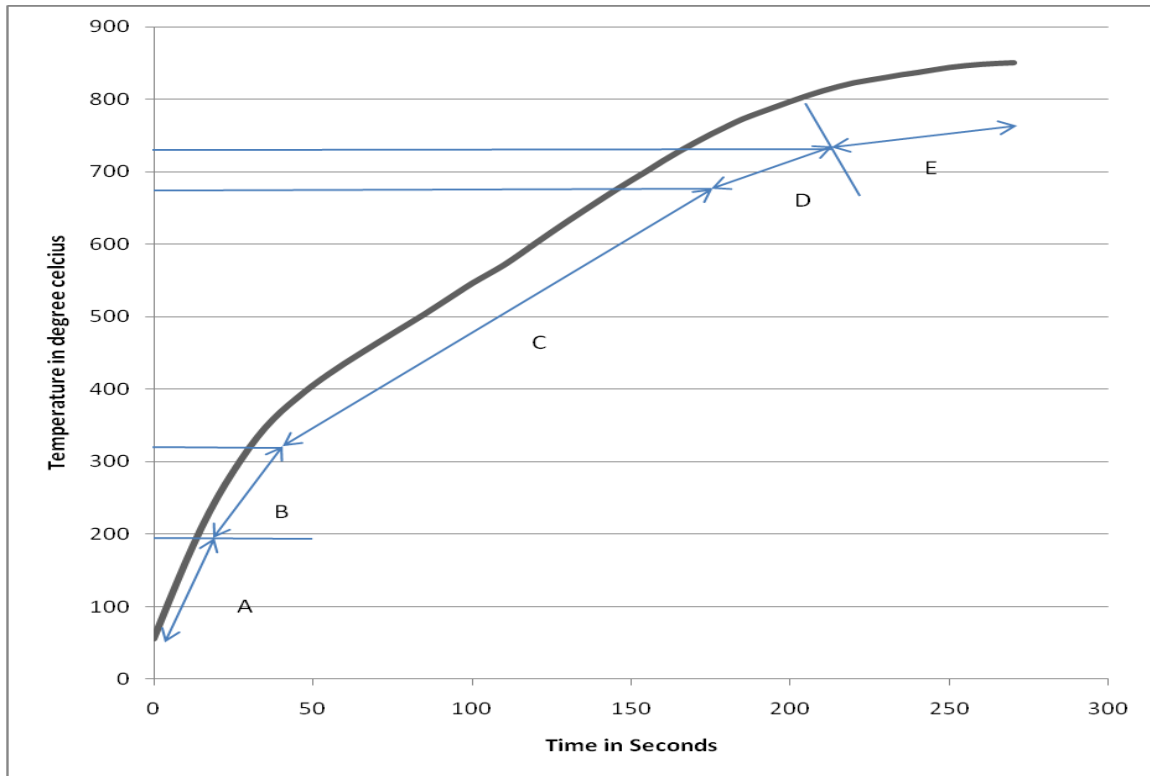


Figure 4.10: TRZE singular particle behavior in a combustion chamber.

From the graph, temperature is rising up from 5seconds to the 270th second (4.5minutes). When the particle is suspended in the oven, the particle first heats up at the surface where the boundary layer is thinnest and this heat is recorded by the thermocouple as the lowest temperature. Thin free moisture evaporates from the internal surface, leading to inward propagation and recondensation. Moisture evaporation completes in less than 1 second from the start of the process.

Once all the moisture has escaped, the particle temperature increases rapidly until devolatilization slows the particle heating rate due to endothermic decomposition of biomass material and the effect of rapid mass loss. Volatile gases released ignite and form a flame envelope surrounding the particle. Ignition of the released volatile gases occurs at $t=25s$. As combustion proceeds, the particle volume shrinks and the

devolatilization is also initiated at the inner part of the particle as the solid temperature exceeds 210⁰C.

The devolatilization zone is much thicker than evaporation, because of the high volatile content and low moisture content. Char starts to burn as devolatilization approaches the final stage, and a circular char burnout front is formed, which travels inward and leaves as ash shell behind. Char burn out takes more than 5s; this is due to the combustion of light gas, char and tar that has been formed.

In addition, the residual char undergoes a rapid center temperature rise to nearly surface temperature due to its lower mass and lower heat capacity. After drying and devolatilization of TRZE, the char that remains continues to react with oxygen until all burns out. The concentration of char carbon in the fuel depends heavily on the composition of fixed carbon in the material. Fixed carbon includes other components which have not been evolved during the process of devolatilization.

Drying of TRZE pellet takes place at temperatures from 95⁰C to close 200⁰C. The range could be attributed to the presence of inherent, surface and decomposition moisture. Decomposition moisture is only formed when the material is fully decomposed through thermal conversion reaction. The devolatilization of TRZE begins at low temperatures of 210⁰C–350⁰C (upon completion of drying). At around 350⁰C devolatilization is high with significant weight loss whereas at above 500⁰C the weight loss remains more or less constant as in the graph section C.

Volatiles forms the highest matter in TRZE, therefore its combustion dominates during the combustion mechanism process. At high temperatures of the furnace, TRZE ignite instantaneously and heat release occurs at the point where particles devolatilize.

This characteristic is important in the design and operation of combustion systems, especially fuel feeding systems, furnace design and the distribution of combustion air (Siagiet *al.*, 2000).

4.8.5 TRZE nitrogen and its suitability to AD process

The amount of nitrogen found in TRZE is 1.42% by volume (Kjeldahl method). In combustion, nitrogen is considered a temperature reducing dilutant that must be present to obtain the oxygen required. However, a high amount of nitrogen reduces combustion efficiency by absorbing heat from the combustion of fuels and diluting the flue gases. This reduces the heat available for transfer through the heat exchange surfaces. High nitrogen amount increases the volume of combustion by-products, which travels through heat exchanger and up the stack faster to allow the introduction of additional fuel air mixture. Nitrogen can also combine with oxygen at high flame temperatures to produce oxides of nitrogen, which are toxic pollutants (Bureau of Energy Efficiency).

4.8.6 Carbon to nitrogen ratio results

Kjeldahl method provides nitrogen content with low of 1.06% by volume and a high of 1.78% by volume. Thus by average TRZE has 1.42% of Nitrogen and the protein quantity of 8.87 by volume% [Dumas method, nitrogen combustion method] is obtained. To analyze Carbon content of the material, the following formulae proposed by Bureau of Energy Efficiency, was applied;

$\%C = 0.97C + 0.7(VM - 0.1A) - M(0.6 - 0.01M)$ Where; C is the percent fixed carbon; VM the percentage of volatile matter; A represents the percentage of ash content and M the percentage of moisture content within the biomass material.

The method found out that the material has carbon content with a high of 51.81% and a low of 48.92% and 50.37% by weight on average. The relationship between the amount of carbon and nitrogen present in organic materials is represented by C/N ratio. Optimum C/N ratios in anaerobic digesters are between 20 and 30. The data obtained shows that C/N ratio is 35.47, which is not within the required optimum range. TRZE alone cannot be used for anaerobic digestion (AD). At a ratio of 35.47, nitrogen is rampantly consumed by methanogens leading to lower gas production. However, variables like total solid content, temperature, retention time, pH value, mixing and organic loading rate (OLR)/volatile solids are physical.

4.9 Discussion

The study on distribution and combustion characteristics of TRZE shows that the biomass material has a potential for energy generation, however its utilization is minimal. This may be contributed by;

- a) Much of existing data has given attention to petroleum and hydroelectric power sources of energy for heating purposes. Information on biomass energy materials available is limited to research institutions unlike implementers.
- b) TRZE has physical and chemical characteristics, which may affect its utilization. Such properties includes; moisture content, fixed carbon, nitrogen, ash content

and volatiles. If this material is to be continuously used as a heat source, further improvements can be achievable.

- c) Implementation costs are too high. The required adjustments from current suited machines, operating under petroleum fuels is difficult.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

During densification, Tumuluru *et al.*, (2010b) found that the heating value of pellets depended upon process conditions like temperature, particle size and in-feed pretreatment. Pellets with higher density have higher heating value. For example table 5.1 shows the change in heating value due to impact of processing condition.

Table 5.1. Change of HV due to pelletizing process

Process	Type of pellets	HV	References
Torrefaction and steam explosion	Wood pellets	17-18MJ/Kg	Tumuluru <i>et al.</i> ,2010b
	Straw based pellets	17-18MJ/Kg	Satyanavayana <i>et al.</i> , 2010
Torrefaction at 200-300 ⁰ C	Corn stover&miscanthus	Increased by 20%	Tumuluru <i>et al.</i> ,2010b

Likewise, TRZE has exhibited a similar scenario. While raw, TRZE energy value was evaluated by the bomb calorimeter and obtained a value of 4.49MJ/Kg but after fitting models with determined combustion characteristics of pelletized TRZE, the energy value was 18.10MJ/Kg on average. Also, in the analysis of density versus pressure loads applied with pellets made out of cane molasses binder, water as a binder and no binder state as shown in Fig.4.7, it can be concluded that pellets produced by use of cane molasses binder has higher density and has higher heating value than those with low

density values. This is in agreement with the findings of Tumuluru and other writers (2010b) in table 2.2 and 2.3.

In comparison with TRZE it is realized that the percentage moisture content (10.45) and ash content (16.03) obtained lies between de-oiled bran (7.11, 18.46) and paddy husks (10.79, 16.73) as found by Oladeji (2010), while volatile matter content for TRZE is lower by 2% than paddy husks, the fixed carbon content for TRZE (19.22) is between coconut shell (20.62) and saw dust (17.15) an indication that TRZE has high heating value than sawdust. The range of moisture content and ash content obtained indicates that TRZE as well is a combustible material.

Ash content results are necessary as they are used in the calculation of ash load and material balance purposes in industrial boiler systems and in ultimate analysis of oxygen by difference. The comparison on ultimate composition of TRZE with other materials indicates; the carbon content of TRZE (50.37%) is higher by 1.82% over sawdust which affects TRZE from being used as a raw material for biogas energy production in anaerobic digestion (AD); the hydrogen (4.92%) content lies between coconut shell (4.99%) and deoiled bran (4.15%) while the oxygen obtained by difference is within sawdust and rice husks.

5.2 Recommendations

Pelletization or briquetting alleviates the problem faced by combustion equipment in heat energy production and sustainability. Also characterization of physical and chemical

features of a pelleted fuel in terms of durability, calorific value, compressibility and ultimate composition is basic towards selection of raw materials for energy production.

Regarding TRZE collection

From the experiment conducted on drying, it's recommendable that the resource material is dried at the point of harvesting for 5days and its moisture content analyzed, for clarification, before transporting. This will have a cost effective returns on investment in TRZE pellet making industry. Conclusively, precise assessment of TRZE material by use of remote sensing and GIS software ArcGIS 9.2 should be adopted for mapping the material distribution in both local and continental distribution.

Regarding storage and transportation

The durability found shows that TRZE can endure over-handling incurred during production, transportation, storage and during consumption, the stages other woody biomass undergoes. The use of molasses binder combines with ease with TRZE and brings about increase in CV and durability. Pellet made from cane molasses binder are cost effective in transportation, since their bulk density is high thus occupy little space during storage. Compressibility analysis experiments leads to a recommendation stating compression loads at which the resource material is compressed to for achieving better combustion characteristics. It is thus recommendable that TRZE pellet is manufactured at a load of 13.79bar and bound by cane molasses binder.

Regarding use

The calorific value obtained shows that TRZE has valuable amount of energy if harnessed. The results of 35 C/N ratio, indicates a high carbon content in the material and thus the material could not be suitable for biogas energy production alone unless blended

with a material of lower C/N ratio that can averagely bring about 25-28 that is optimum for AD process. Likewise, carbon content in a combustible material forms a recipe for heat production, but care should be taken in ensuring recommended air of combustion is supplied to avoid the formation of CO and thus loss of kilocalorie of heat per kilogram of carbon.

For safety, the person handling the fresh material during harvesting should be in full attire of PPE to avoid development of skin rushes caused by the material and other effects from plantations.

Regarding further studies on TRZE

The findings of this study are a revelation of characteristics of a material that was initially scattered, succulent and leafy but now with a potential for energy harnessing.

Since this work tried to find out the characteristics of TRZE by considering different particles sizes obtained after milling and available binders, the study recommends further studies to be conducted purely on 2.0mm particle size, use of cane molasses binder and at pre-set loads corresponding to 13.7bars.

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APPENDICES

APPENDIX I: DEFINITION OF TERMS

Tradescantiazebrina (TRZE) formerly known as *Zebrinapendula*, is a species of spiderwort more commonly known as an inch plant or *Wandering Jew*, native to the Gulf Coast region of eastern Mexico.

Weed plant, used to refer any unwanted planting in agricultural farms that is ever removed to allow healthy growing of planted crops.

Pelletization is the process of forming nearly spherical pellets by tumbling moist particulate fines with or without addition of binders and other necessary additives.

Combustion refers to the rapid oxidation of fuel accompanied by the production of heat, or heat and light. Complete combustion of fuel is possible only in the presence of an adequate supply of oxygen.

Anaerobic Digestion (AD) is a biological process that happens naturally when bacteria breaks down organic matter in environments with little or no oxygen. It is effectively a controlled and enclosed version of the anaerobic breakdown of organic waste in landfill which releases methane.

Biogas is the gaseous emissions from anaerobic degradation of organic matter (from plants or animals) by a consortium of bacteria.

APPENDIX II: MASS LOSS OF TRZE IN AIR DRYING

No. of Times	1 st	2 nd	3 rd	4 th	5 th
Moisture Content (%)	59.91	28.86	22.34	19.75	18.02
Mass Loss (g)	599.1	715.7	779.91	823.99	856.26
Time (Days)	1(1600hrs)	2(1600hrs)	3(1600hrs)	4(1600hrs)	5(1600hrs)
Initial Mass (g)	1000	404	287.4	223.19	179.11
Final Mass (g)	404	287.4	223.19	179.11	146.84
Mass of Container(g)	3.1	3.1	3.1	3.1	3.1

APPENDIX III: PARTICLE SIZE DISTRIBUTION VERSUS DIAMETER OF THE SIEVING EQUIPMENT

Sieve Aperture size	RUNS IN CUM. PERCENT MASSES (g)				
	1 ST RUN in % mass	2 ND RUN in % mass	3 RD RUN in % mass	4 TH RUN in % mass	5 TH RUN in % mass
1.180 mm	57.6	57.0	58.5	59.7	59.6
0.600 mm	14.4	18.2	16.2	16.8	17.4
0.425 mm	28.0	24.8	25.3	23.5	23.0

APPENDIX IV: PELLET MOISTURE CONTENT DETERMINATION

Time interval, (hrs)	0	2	4	6	8	10	12	14	16
Weight, (g)	313.9	311.9	311.7	311.7	311.7	311.7	311.7	311.7	311.7
Weight of crucible, (g)	298.4								
Moisture content, (% W_{TRZE})	14.2								

APPENDIX V: MASS LOSS VERSUS TEMPERATURE OF THE PELLET PRODUCED

Temp. (°C) range	Mass (g) P ₁	Cum. Mass loss (15.49)(174.82)	Percentage of Cum. Mass loss (g)	Mass (g) P ₂	Cum. Mass loss (14.80)(296.92)	Percentage of Cum. Mass loss (g)
0	190.91	0.00	0	312.60	0.00	0
50	190.01	0.90	5.8	311.83	0.77	5.2
70	189.32	1.59	10.2	311.35	1.25	8.4
90	188.84	2.07	13.3	310.97	1.63	11.0
110	188.68	2.23	14.3	310.83	1.77	11.9
130	188.35	2.56	16.5	310.50	2.10	14.2
150	188.17	2.74	17.6	310.39	2.21	14.9
200	181.12	9.79	63.2	303.40	9.20	62.1
250	180.12	10.79	69.6	303.00	9.60	64.8
300	180.00	10.91	70.4	302.50	10.10	68.2
350	179.66	11.25	72.6	301.99	10.61	71.7
400	179.56	11.35	73.3	301.90	10.70	72.3
450	179.45	11.46	73.9	301.60	11.00	74.3
500	179.44	11.47	74.0	301.84	10.76	72.7
550	179.16	11.85	76.5	301.34	11.26	76.0
TOTAL		11.85(ASH 3.64)			11.26(ASH 3.54)	

APPENDIX VI: RESULTS FOR SINGLE PARTICLE COMBUSTION

READING	DATE	TIME	TIME INTERVAL	CUM. TIME	TEMPERATURE
1	7/19/2012	6:36:41 PM	0	0	55.50
2	7/19/2012	6:36:46 PM	5	5	109.28
3	7/19/2012	6:36:51 PM	5	10	161.37
4	7/19/2012	6:36:56 PM	5	15	208.88
5	7/19/2012	6:37:01 PM	5	20	250.58
6	7/19/2012	6:37:06 PM	5	25	286.63
7	7/19/2012	6:37:11 PM	5	30	318.94
8	7/19/2012	6:37:16 PM	5	35	346.66
9	7/19/2012	6:37:21 PM	5	40	369.00
10	7/19/2012	6:37:26 PM	5	45	387.65
11	7/19/2012	6:37:31 PM	5	50	405.14
12	7/19/2012	6:37:36 PM	5	55	420.75
13	7/19/2012	6:37:41 PM	5	60	435.48
14	7/19/2012	6:37:46 PM	5	65	449.38
15	7/19/2012	6:37:51 PM	5	70	462.98
16	7/19/2012	6:37:56 PM	5	75	476.44
17	7/19/2012	6:38:01 PM	5	80	489.83
18	7/19/2012	6:38:06 PM	5	85	503.17
19	7/19/2012	6:38:11 PM	5	90	517.38
20	7/19/2012	6:38:16 PM	5	95	531.63
21	7/19/2012	6:38:21 PM	5	100	545.74
22	7/19/2012	6:38:26 PM	5	105	558.35
23	7/19/2012	6:38:31 PM	5	110	571.00
24	7/19/2012	6:38:36 PM	5	115	585.89
25	7/19/2012	6:38:41 PM	5	120	601.38
26	7/19/2012	6:38:46 PM	5	125	616.55
27	7/19/2012	6:38:51 PM	5	130	631.45
28	7/19/2012	6:38:56 PM	5	135	645.84
29	7/19/2012	6:39:01 PM	5	140	660.20
30	7/19/2012	6:39:06 PM	5	145	674.35
31	7/19/2012	6:39:11 PM	5	150	687.76
32	7/19/2012	6:39:16 PM	5	155	700.96
33	7/19/2012	6:39:21 PM	5	160	714.88
34	7/19/2012	6:39:26 PM	5	165	727.70
35	7/19/2012	6:39:31 PM	5	170	739.86
36	7/19/2012	6:39:36 PM	5	175	751.44
37	7/19/2012	6:39:41 PM	5	180	762.21
38	7/19/2012	6:39:46 PM	5	185	772.47
39	7/19/2012	6:39:51 PM	5	190	780.82
40	7/19/2012	6:39:56 PM	5	195	788.69
41	7/19/2012	6:40:01 PM	5	200	796.64
42	7/19/2012	6:40:06 PM	5	205	804.21
43	7/19/2012	6:40:11 PM	5	210	811.17
44	7/19/2012	6:40:16 PM	5	215	817.17
45	7/19/2012	6:40:21 PM	5	220	822.45

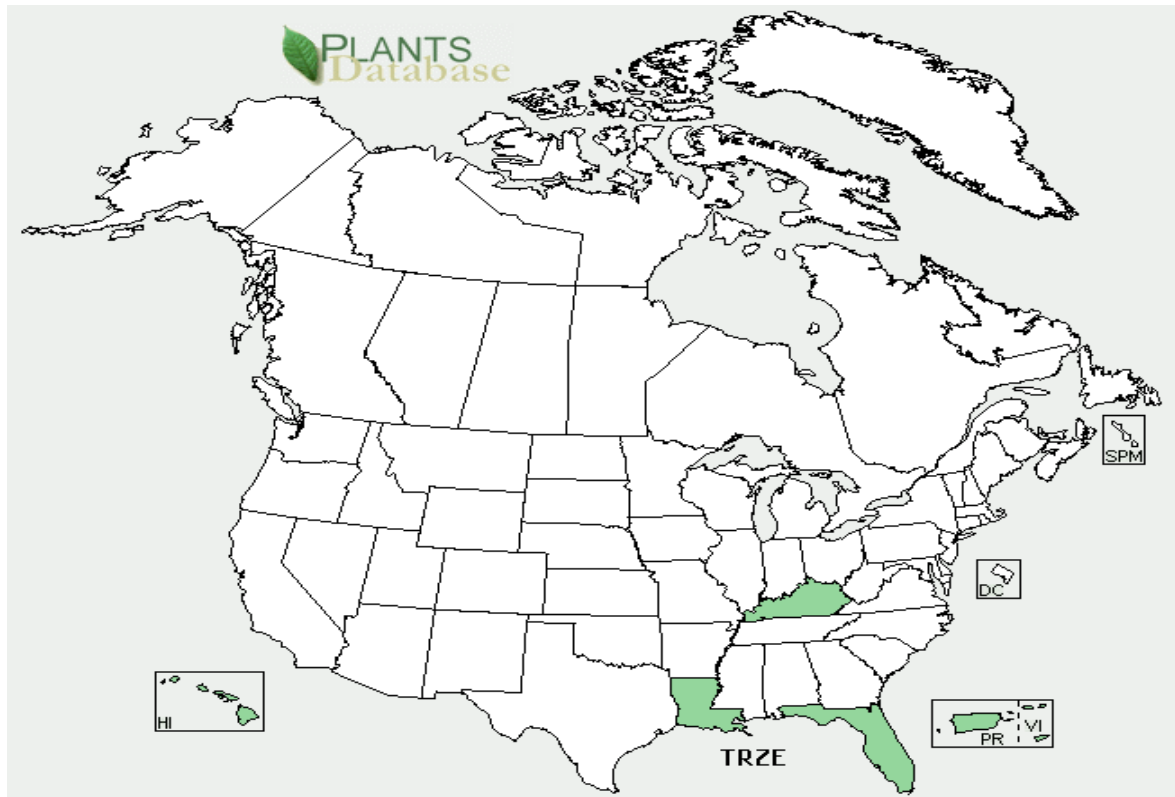
46	7/19/2012	6:40:26 PM	5	225	826.29
47	7/19/2012	6:40:31 PM	5	230	829.81
48	7/19/2012	6:40:36 PM	5	235	833.61
49	7/19/2012	6:40:41 PM	5	240	836.63
50	7/19/2012	6:40:46 PM	5	245	840.27
51	7/19/2012	6:40:51 PM	5	250	843.54
52	7/19/2012	6:40:56 PM	5	255	846.08
53	7/19/2012	6:41:01 PM	5	260	847.94
54	7/19/2012	6:41:06 PM	5	265	849.16
55	7/19/2012	6:41:11 PM	5	270	850.05

**APPENDIX VII: RECORD OF PROXIMATE COMPONENT DETERMINATION
RUNNING TWO EXPERIMENTS E₁ & E₂ AT THE SAME TIME**

		Temperature: 105.0 °C (15hrs)								350°C	500°C
		Mass reduction after time interval of recording- after every two hours								10min	2hrs
		0	2hrs	4hrs	8hrs	10hrs	12hrs	14hrs	16hrs		
E ₁	M ₁ (g)	402.10	400.93	400.84	400.79	400.78	400.80	400.79	400.79	393.90	390.65
	Cruc.	388.30 TRUE	Moisture content (w ₁ %) = 9.49								55.16
E ₂	M ₂ (g)	306.90	306.05	306.02	305.90	305.90	305.92	305.90	305.89	300.70	299.38
	Cruc.	298.05 TRUE	Moisture content (w ₂ %) = 11.41								66.19

APPENDIX VIII: PHYSICAL PROPERTIES OF PELLET PRODUCTION

Pellet No.	Mass A (g)	Change in pellet length (mm) at pressures 0, 100, 200 & 300 (psi)				Diameter (mm)	Height (mm)	Mass B after pelleting (g)
		0	100	200	300			
1	15.02	28.36	26.8	26.32	26.28	43.5	26.28	14.98
2	15.60	23	22.09	21.33	21.02	42.42	21.02	15.50
3	15.20	23.6	23.12	22.72	22.2	42.26	22.20	15.20
4	15.42	22.04	21.5	20.22	19.92	43.44	19.92	15.30
5	14.85	25.6	23.16	22.22	21.74	43.38	21.74	14.72
6	15.84	22.62	22.34	22.28	21.98	43.06	21.98	15.50
7	16.50	24.46	22.86	22.42	22.2	43.14	22.20	15.04
8	15.10	22.74	22.52	22.02	21.9	41.80	21.90	15.10
9	15.10	22.34	21.7	21.34	21.3	41.58	21.30	15.09
10	15.10	22.78	21.12	20.38	20	41.88	20.00	15.05
11	15.10	21.24	20.42	20.04	20	41.78	20.00	15.10
12	15.12	20.64	20.32	20.22	20	42.00	20.00	15.09
13	15.40	21.2	20.8	20.3	20	42.20	20.00	15.12
14	15.12	21.9	20.7	20.2	20	42.00	20.00	14.95
15	15.10	22.9	22	21.8	21.6	42.20	21.60	15.00

APPENDIX IX: MAPPED TRZE PLANT DISTRIBUTION IN MEXICO

Source: Tropicos.org.,(2009)

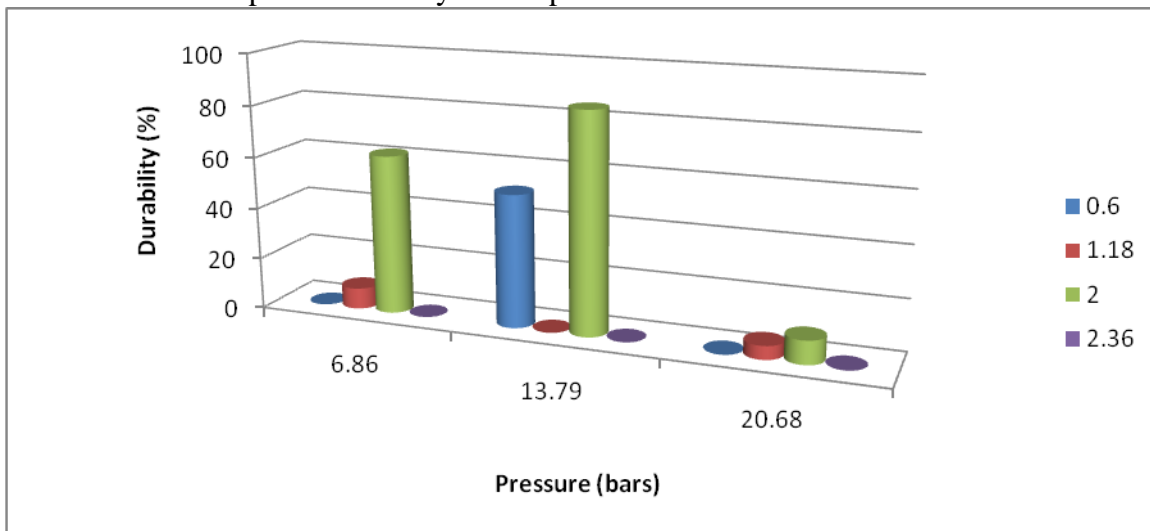
APPENDIX X: MOISTURE AND ASH CONTENT AND CV OF CERTAIN BIOMASS FUELS

Biomass	Moisture %	Ash %	CV (MJ/Kg)
Bagasse	50	1-2	9.2
Bagasse pith	40	2	7.5-8.4
Spent Bagasse	40	10	12.5
Sawdust	35	2	11.3
Rice husk	10-15	15-20	12.6-13.8
Rice straw	6	16	14.7
De-oiled rice bran	16	16	11.3
Coffee husks	11-14	2-5	15-17.5
Peanut shells	10	2-3	16.75
Coconut shell	10	1	18.8
Coir pith	8	15	16.75
Bamboo dust	9-12	7	7.5-15.9
Tobacco dust	8	30	11.7
Cotton stalk	7	3	18.4
Soya straw	8-9	5-6	15.5-15.9

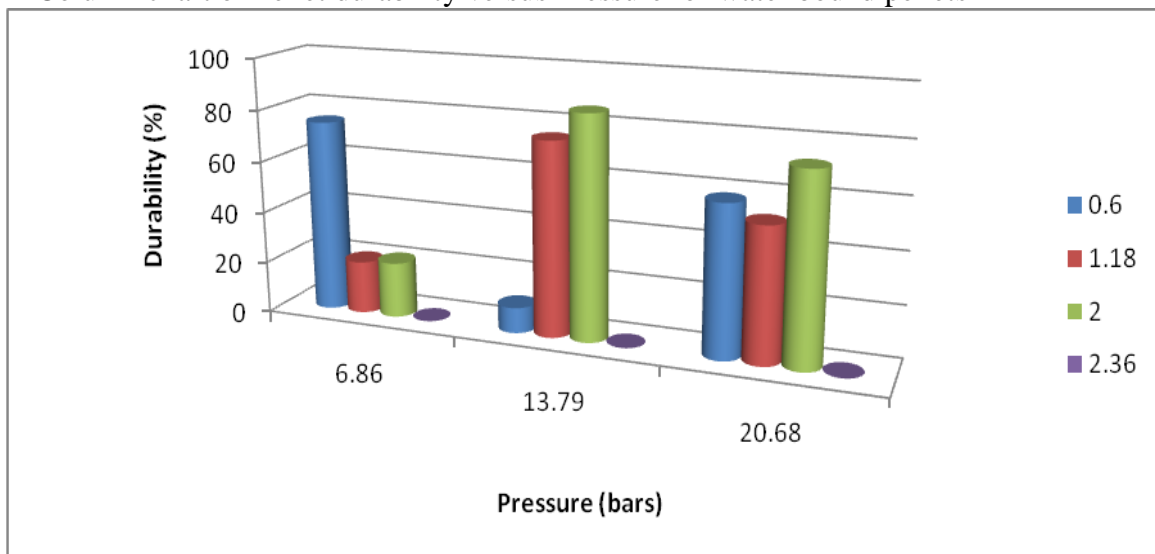
Source: Arbon, (2002)

APPENDIX XI: COLUMN CHARTS FOR DURABILITY TESTS

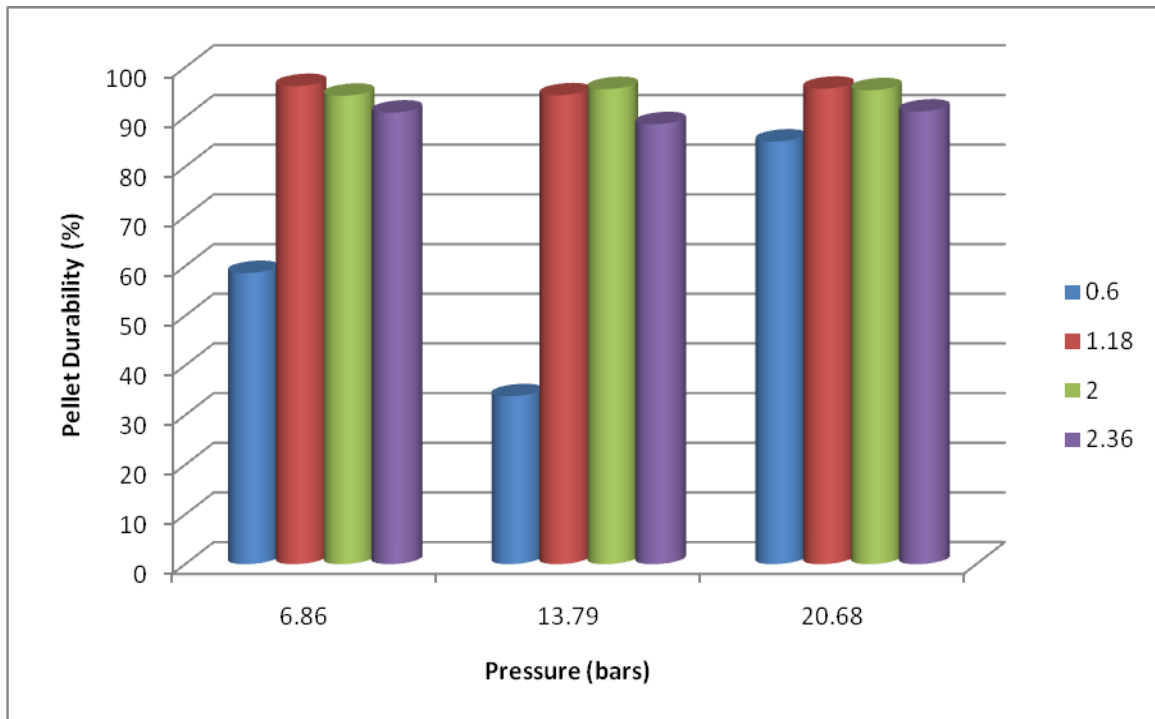
A Column chart of pellet durability versus pressure for without binder condition



A Column chart of Pellet durability versus Pressure for water bound pellets



A Column chart of Pellet durability versus Pressure for molasses bound pellets



APPENDIX XII; SIZE VARIATION AT DIFFERENT PRESSURES, PARTICLE SIZES, BINDERS AND RELAXATION TIME

PRESSURE (bars)	PARTICLE SIZE (mm)	CANE MOLASSES							
		RELAXATION TIME(s)							
		0		10		30		60	
		Ø	H	Ø	H	Ø	H	Ø	H
6.86	0.6	41.5	20	42.7	21	43	21	43	21
	1.18	41.5	17	42	20	42.5	21	43.5	24
	2.0	41.5	15	42.7	17	43	23	43.6	26
	2.36	41.5	20	43	24	44	23	44	25
13.79	0.6	41.5	18	43	21	43.4	21.5	43.5	22
	1.18	41.5	15	42	19	43	21	43.5	22
	2.0	41.5	14	42	18	43.1	21	43.2	21
	2.36	41.5	16	42.4	20	43	21	43	21.8
20.68	0.6	41.5	15	42	20.5	43	21.8	43	22
	1.18	41.5	14	41.8	19	42.4	22	43	23.5
	2.0	41.5	12	43	19	43	21	43.5	21
	2.36	41.5	12	42.5	15	42	20	44	21
		WATER AS A BINDER							
		0		10		30		60	
		Ø	H	Ø	H	Ø	H	Ø	H
6.86	0.6	-	-	-	-	-	-	-	-
	2.0	41.5	24	-	-	-	-	-	-
13.79	1.18			-	-	-	-	-	-
	2.0	41.5	22	-	-	-	-	-	-
20.68	0.6	-	-	-	-	-	-	-	-
	1.18	41.5	24	43.5	26	44.7	29	-	-
	2.0	41.5	19	-	-	-	-	-	-

APPENDIX XIII. BULK AND TRUE DENSITIES OF CERTAIN FUEL MATERIALS

FUEL	DENSITY (kg/m ³)
Coal anthracite	830-900
Coal bituminous	770-930
Hard Wood (20-40mm ³)	330
Soft Wood (20-40mm ³)	250
Charcoal	130-150
Saw dust	175
Paddy husk	105
Straws	50-80
Baggasse	70
	True density
<i>Acacia nilotica</i>	820
<i>Dalbergiasisoo</i>	710
Eucalyptus	770

APPENDIX XIV: C/N RATIOS OF OTHER BIOMASS MATERIALS

RAW MATERIAL	C/N RATIO	RAW MATERIAL	C/N RATIO	RAW MATERIAL	C/N RATIO
Urine	0.8	Peanut vine	18.6		
Turnip (root)	44	Fish scrap	3.6	Duck dung	8
Potato	18	Turkey dung	16	Human excreta	3.3
Seaweed	18.9	Elephant dung	43	Goat dung	12
Tomato	12	Sheep dung	29.1	Cow dung/buffalo dung	25.2
Pepper	15	Pig dung	12.6	Poultry carcass	5
Paper pulp	90	Chicken dung	11.1	Horse manure	26.7
Mustard	26	Carrot-whole	19.1	Fallen leaves	41
Garbage (raw)	40	Turnip tops	25	Straw (maize)	53.3
Ferns	43.5	Potato plant	6.6	Straw (wheat)	86.8
Cotton seed	7	Algae	26	Soya beans stalks	31.5
Cabbage	11.9	Clover	55	Grass	21.3
Saw dust	277.8	Paper mill sludge	480	Blood	3
Straw (rice)	66.7	Cardboard	485.7	Coffee grounds	20
Straw (oat)	60	Bark (hardwood)	40	Bark (softwood)	223.2

APPENDIX XV: Correlation of pellet density (ρ , Kg/m³) with applied pressure (P, kPa) and particle sizes (mm) for water and cane molasses bound TRZE milled material.

	Particle sizes in mm					
		Molasses bound				Water as a binder
	Ln(ρ)	0.6	1.18	2.0	2.36	2.0
Ln(P)	6.535	6.32	6.48	6.61	6.32	6.13
	7.229	6.42	6.61	6.67	6.54	6.22
	7.634	6.61	6.67	6.83	6.83	6.37
Constants	M	0.250	0.174	0.187	0.448	0.208
	B	4.660	5.342	5.363	3.366	4.750
	R²	0.896	0.996	0.843	0.948	0.916