CHARACTERIZATION OF WATER HYACINTH *(EICHHORNIA CRASSIPES*) COMPOSITE BRIQUETTE AS AN ALTERNATIVE DOMESTIC ENERGY SOURCE

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DECLARATION

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DEDICATION

I dedicate this work to my wife Naomi, children; Printer, Doreen, Donald, David, Diana and my Mother Alice who encouraged and supported me despite financial constraints.

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ABSTRACT

Biomass is one of the most promising energy sources to mitigate greenhouse gas emission during production and utilization. However, majority of biomass are not suitable to be utilized as fuel without an appropriate process since they are bulky, uneven and have low energy density. These characteristics make them difficult in handling, storage, transport and utilization. One of the promising solutions to overcome these problems is the briquetting technology. The study was conducted to characterize water hyacinth composite briquette as an alternative domestic energy source. Water hyacinth was chopped using a shredder and left for two weeks in a heap to partially decompose. The material was thoroughly mixed manually with dried and crushed charcoal dust and cow dung in the ratios of water hyacinth: charcoal dust: cow dung of 100:0:0 (control), 80:10:10, 70:20:10, 70:10:20, 60:30:10, 60:20:20 and 60:10:30 (by weight). The resulting material was then mixed into soupy slurry in water. Simple prototype briquetting mold was fabricated to facilitate densification of these residues into hollow cylindrical briquette at a pressure of 1MPa. The experimental results revealed that the mixture that gave optimal combustion characteristics was 60:30:10 and the calorific values ranged from 16.215 to 21.585 MJ/kg. Water hyacinth alone (100:0:0) gave the best emission characteristics having 28.51 ppm carbon monoxide and 452.80 ppm carbon dioxide though ranking third with 13,623 µg/m^3 in particulate matter. For quality control, water hyacinth composite briquette gave good indications on physical parameters that were measured. The results showed that resistance to water penetration range from 79.5% to 88%, durability index range from 57.9% to 99.6% with 60:30:10 and 60:20:20 ratios exhibiting poor index of 57.88% and 59.23 respectively probably due to high charcoal dust content which is known to have low bonding. The rest of mixtures gave 80% and above, with water hyacinth (100:0:0 ratio) showing the highest durability index of 99.63% probably because of partial decomposition which increases the binding effect of biomass. Equilibrium moisture content range from 8.5% to 15.2% at 29 ^{o}C and 58% relative humidity; water hyacinth alone was having the highest. This study therefore demonstrates that water hyacinth composite briquette have good physical and combustion characteristics and can therefore be utilized as alternative domestic energy source.

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LIST OF ACRONYMS, SYMBOLS AND ABBREVIATIONS

ALRI	Acute lower respiratory infection
ASTM	American Society for Testing and Materials
BR	Burn Rate
CDM	Clean Development Mechanism
CO	Carbon monoxide
CO_2	Carbon dioxide
DEEP-EA	Developing Energy Enterprises Project East Africa
EMC	Equilibrium Moisture Content
EPA	Environmental Protection Act
EU	European Union
FAO	Food and Agricultural Organization
g/cm^3	Grams per cubic centimeter
GCV	Gross Calorific Value
GHG	Greenhouse gases
H_2	Hydrogen
HC	Hydrocarbon
HCl	Hydrochloric acid
HCN	Hydrogen Cyanide
Hg	Mercury
IEA	International Energy Agency
ISO	International Organization of Standardization
K_2SO_4	Potassium Sulphate
KCl	Potassium chloride
Kg	Kilogram
Kg/hr	Kilogram per hour
Kg/m^3	Kilograms per cubic metre
KJ	Kilojoules
KNBS	Kenya National Bureau of standards
Kw	Kilowatts
kWh	Kilowatt hour

LPG	Liquid Petroleum Gas
LVEMP	Lake Victoria Environmental Programme
M	Mass
M^2	Square metre
M^3	Cubic metre
Masl	Metres above sea level
MJ	Mega Joules
MPa	Mega Pascal
MW	Mega Watts
N_2O	Nitrogen oxide
NAAQS	National Ambient Air Quality Standards
NEMA	National Environmental Management Authority
NGO	Non-Governmental Organization
NH_3	Ammonia
NH_4Cl	Ammonium chloride
NIC	Newly Industrialized Country
NO_2	Nitrogen dioxide
NOx	Nitrogen dioxides
O_2	Oxygen gas
^oC	Degrees centigrade
PAC	Percentage Ash content
PAH	Poly Aromatic Hydrocarbon
Pb	Lead
PCDD	Polychlorinated Dibenzodioxins
PCDF	Polychlorinated Dibenzofurans
PFBC	Pressurized Fluidized Bed Combustor
PM_{10}	Particles (the fraction of particulates in air of very small size (<10 µm))
$PM_{2.5}$	Particles (the fraction of particulates in air of very small size (<2.5 µm))
PMC	Percentage Moisture content
ppb	Parts per billion
ppm	Parts per million

PVM	Percentage Volatile Matter
SO_2	Sulphur dioxide
SOx	Sulphur dioxides
SSA	South of Saharan Africa
UOE	University of Eldoret
V	Volume
VM	Volatile Matter
VOC	Volatile Organic compounds
$\mu g/m^3$	Micrograms per cubic meter
ρ	Density

CHAPTER ONE

INTRODUCTION

1.1 Background information

In the last four decades, researchers have been focusing on alternative fuel resources to meet the ever-increasing energy demand and to avoid dependence on crude oil (Karunanithy, Wang, Muthukumarappan & Pungalendhi, 2012*)*. United States Energy Information Administration (EIA) projects that world energy consumption is growing by 56% between 2010 and 2040, from 524 quadrillion British thermal units (Btu) to 820 quadrillion Btu of which fossil fuels continue to supply nearly 80% of world energy use (International Energy Outlook, 2013).

Biomass (regenerative or renewable organic material that can be used to produce energy) appears to be an attractive feedstock because of its renewability, abundance, and positive environmental impacts resulting in no net release of carbon dioxide and very low sulfur content (Karunanithy *et al.*, 2012 & Biomass.net, 2010). In many parts of the developing world, Wood-based biomass is facing a threat as a result of deforestation to obtain land for agricultural use. This loss of forest was estimated by FAO global forest resources assessment at 13 million hectares per year from the year 2000 to 2010 (Institute for Advanced sustainability Studies (IASS) Potsdam, April 2015). This has therefore resulted in shifting the focus from forest biomass to agricultural and animal residues (Energy situation in Kenya, 2013). In Kenya, the energy sector is largely dominated by petroleum and electricity which are costly and unreliable, with wood fuel providing the basic energy needs of the rural communities, urban poor, and the informal sector. An analysis of the national energy shows heavy dependency on wood fuel and other biomass that account for 68% of the total energy consumption (petroleum 22%, electricity 9%, others account for 1%) (Energy situation in Kenya, 2013 & Kenya Vision 2030, 2007). The Energy Act 2006 already recognizes the biomass sector and how biomass regulation should be done setting out a good basis for drafting the biomass plan. It also recognizes the importance of renewable energy and energy efficiency (Energy situation in Kenya, 2013).

Water hyacinth, an aquatic weed, spreads rapidly clogging drainage, water intakes, and ditches, shading out other aquatic vegetation and interfering with fishing, shipping and recreational activities. It is also an environmental or public health problem; may create a micro habitat suitable for the breeding of many vectors of human diseases and for hosting poisonous snakes (WMB-314.pdf, 2014 & Agripinoy.net, Pinoy Farmer, 2008). In view of this, the weed has attracted attention of scientists to use it as a potential biomass for production of biofuel because of its high growth yield estimated at 100-120 tons per hectare per year and availability in large amount throughout the year (Agripinoy.net, 2008 & Mart, Solms, 2014). It has however low calorific value of 13.4MJ/Kg (Frank & Akhihiero, 2013)

Lake Victoria, the legendary source of the Nile, second largest fresh water lake was finally losing its capacity to support human life by 1996 due to spread of water hyacinth and this lead to several attempts being made from 1998 to control the weed as part of a larger Lake Victoria Environmental Management Project (LVEMP) (Agripinoy.net, 2008 & Africascience.blogspot.com /2007/07/lake victorious). Use of weevils was thought to have brought sigh of relieve by reducing water hyacinth covering about 12 000 ha of shores (Figure 1.1) of Kenya and Uganda by 90% in 1999 (Africascience.blogspot.com /2007/07/lake victorious). However, the weed is still a big problem as can be noted in a number of documents (Lilian, Venessa, CNN, 2012 & KORCE to use hyacinth for power generation, 2013).

Figure 1.1: Hyacinth coverage in Lake Victoria and the Kagera River Basin, 1989 – 2001

Source: Nile.riverawarenesskit.org

Charcoal is known to have high calorific value of 25-30 MJ/Kg (Eriksson, Prior, 1990 & Njenga *et al*., 2013). Therefore, charcoal dust use is expected to enhance calorific value of the mixture and reduce the use of firewood and charcoal, and therefore pressure on forest resources (Njenga *et al*., 2013). Use of charcoal dust would contribute to saving trees, which is important as the country struggles to move from less than 2% of forest cover to the recommended 10% (Kenya vision 2030, 2007). Saving trees has multiple benefits such as better management of water catchments, mitigating climate change as trees serve as carbon dioxide sinks, and conservation of biodiversity. Cow dung is available in our zero grazing units and though it has several uses; it's suitable as a feedstock and a binder for briquetting (WWW.madehow.com/volume-4/charcoal-Briquette).

This study was therefore looking at physical, chemical, combustion and emission characteristics of water hyacinth, cow dung and charcoal dust as a composite briquette and was aimed at generating scientific information necessary to promote increased utilization water hyacinth based briquette as an alternative domestic energy source. It is an important way of managing the weed problem and will provide part of solution to problems on many parts of Lake Victoria and other water bodies in Kenya.

Briquetting, which is compression and densification of aquatic plants, forest products and by-products, agricultural residues, agro- industrial residues has been long recognized as a viable technology for alternative energy generation and was used in this study.

1.2 Statement of problem

Energy has been identified as one of the infrastructural enablers of economic, social and political pillars of Kenya's vision 2030. As incomes increase and urbanization intensifies, household demand for energy will also rise. However, the current energy supply in Kenya is limited in availability and reliability. Kenya relies heavily on hydro-electric power and fossil fuels which come with a myriad of problems though this is changing with geothermal production in Olkaria. The main problems of fossil fuels are air pollution, regional acid deposition and global climate change. Renewable energy technologies on the other hand, can provide clean, sustainable and ultimately affordable supply, while providing additional social and economic benefits.

Water hyacinth is a major economic, social and environmental problem in Kenyan waters and has therefore attracted attention for use. Its use in briquetting as renewable source of energy is an important way of improving energy availability, managing the weed problem and contribution to environment management in Kenya. Used alone, water hyacinth may not satisfy minimum calorific value. The study is building on what various authors (Frank *et al.,* 2013) have documented on briquettes made from water hyacinth and other agricultural waste materials. Many tests have been conducted on various briquette fuels and the raw materials but little has been done on composite briquettes. In order to efficiently utilize water hyacinth composite briquette as source of fuel, it is important to characterize it and also get the composition that gives optimal combustion and emission characteristics.

1.3 Justification

Briquette made from a mixture of water hyacinth, charcoal dust and cow dung binder is expected to serve as a supplementary or an alternative domestic source of energy. Compared to fossil fuels, briquettes produce low net total greenhouse gas emissions because the materials used are already a part of the carbon cycle (Jindaporn, Songchai, 2007 & Biomass briquette for Green electricity production, 2010). Water hyacinth has potential biomass for production of biofuel because of its high growth yield estimated at 100-120 tons per hectare per year and availability in large amount throughout the year (Mart *et al*., 2014). Use of water hyacinth will also provide part of solution to wider problems created in Lake Victoria and other water bodies in Kenya and enhance rural economic development, farm income, business diversification, reduced negative environmental impact, and creation of employment opportunities in the area of production, harvesting, and processing in the Lake Victoria region (Agripinoy.net, 2008, Lillian *et al*., 2012 & Keith, Hans, 2000).

1.4 Objectives

1.4.1 Main objective

The main objective of the project was to characterize water hyacinth composite briquette as an alternative domestic source of energy.

1.4.2 Specific Objectives

i) To determine chemical (proximate analysis) and physical characteristics of water hyacinth composite briquettes.
ii) To determine the composition of water hyacinth composite briquette that give optimal combustion and emission characteristics.

1.5 Hypothesis

The hypotheses of the study are;

i) Ho: The water hyacinth composite briquettes are not chemically and physically suitable as alternative domestic source of energy.

   H_A: At least one water hyacinth composite briquette has good chemical and physical characteristic and therefore suitable as alternative domestic source of energy.

ii) Ho: The water hyacinth composite briquettes do not have suitable combustion and emission characteristics.

   H_A: At least one water hyacinth composite briquette has good combustion and emission characteristic and therefore suitable as alternative domestic source of energy.

1.6 Scope of study

The study looked at the characteristics of water hyacinth, charcoal dust, and cow dung briquette mixtures (different combinations) and also related them to wood and other agricultural waste materials. These characteristics are grouped as:-

(i) Fuel or combustion, emission and chemical characteristics and
(ii) Briquette handling or physical characteristics

The first aspect is mainly related to the properties of the raw materials and the shape and density of the individual briquette. The second aspect, relate to fact that the product should not crumble and disintegrate when handled, stored and transported, and is mainly a function of the quality of the densification process for a given raw material. Manual press densification method was employed using a metallic mold at a pressure of 1MPa found to be suitable for wet briquetting.

1.7 Limitations

It was not possible to determine all the parameters within the required time and the available resources. For example, only pressure of 1MPa was used but there is a possibility of producing better quality wet briquettes with higher pressure especially for those with higher charcoal dust content. The findings are specific to wet briquetting which is cheaper and suitable for rural setting and may differ from carbonized water hyacinth briquette.

1.8 Conceptual framework

The need for renewable and sustainable alternative energy sources are growing due to the rapid depletion of the non-renewable fossil energy resources and the negative impacts, and fuel increasing price. Global warming and other environmental problems are also critical issues. Therefore, biomass energy has been attracting attention as an energy source since zero net carbon dioxide accumulation in the atmosphere from biomass production and utilization can be achieved. The carbon dioxide released during combustion process is compensated by the carbon dioxide consumption in photosynthesis (Jindaporn *et al.,* 2007 & Biomass briquette for Green electricity production, 2010). In Kenya, the energy sector is largely dominated by petroleum and electricity which are costly and unreliable, with wood fuel providing the basic energy needs of the rural communities, urban poor, and the informal sector. An analysis of the national energy shows heavy dependency on wood fuel and other biomass that account for 68% of the total energy consumption (Energy situation in Kenya, 2013). Densification of the weed and the other biomass materials into biomass briquettes can provide an alternative household solid fuel, especially in rural areas. They can be manufactured industrially and on a small rural scale using a simple hand-press, making them very viable for poorer communities. Compared to wood which is dwindling and leading to environmental problems, other biomass briquettes are unique in that they provide opportunity to control the fuel density, moisture content, size and geometry in the manufacturing process. Water hyacinth is providing this opportunity because it has high growth yield, fibrous tissues and available in large amounts in Lake Victoria and other water bodies in Kenya (Agripinoy.net, 2008). It is an economic, social and environmental management problem (Figure 1.2) and it is now considered a serious threat to biodiversity (Agripinoy.net, 2008

& Africascience.blogspot.com /2007/07/lake victorious). Studies have shown that it can be used to provide alternative source of energy when combined with other agricultural wastes. Used alone, it may not satisfy minimum calorific value (Davies, Abolude, 2013 & Davies, Davies, 2013).

Figure 1.2: Water hyacinth & Stranded boats at Seka beach (Homa Bay).

Source: Author (July, 2015)

Cow dung was obtained from local zero grazing unit is useful as both a feedstock and a binder (Frank *et al.*, 2013, Lagat, Cleophas, 2010 & Cheryl, Mvula, 2009). Charcoal dust is a waste obtained from the use of charcoal as fuel (Figure 1.3). It has high calorific value (25-30 MJ/kg) and is to improve combustion characteristics of composite briquette; however, amount used in the mixture was limited. Increased use of charcoal as fuel is a major concern due to depletion of forest resources and therefore environmental management concern. Use of charcoal dust in briquetting has been documented and is contribution to environment management (Biomass. net, 2010, Pennise *et al.,* 2012 & Njenga *et al*., 2013).

Figure 1.3: Bags of charcoal placed on charcoal dust near Dunga Beach-Kisumu

Source: Author (April, 2014)

The study will promote increased utilization of water hyacinth briquette as an alternative source of energy and is an important way of improving energy availability, managing the weed problem and contribution to environmental management(Figure1.4).

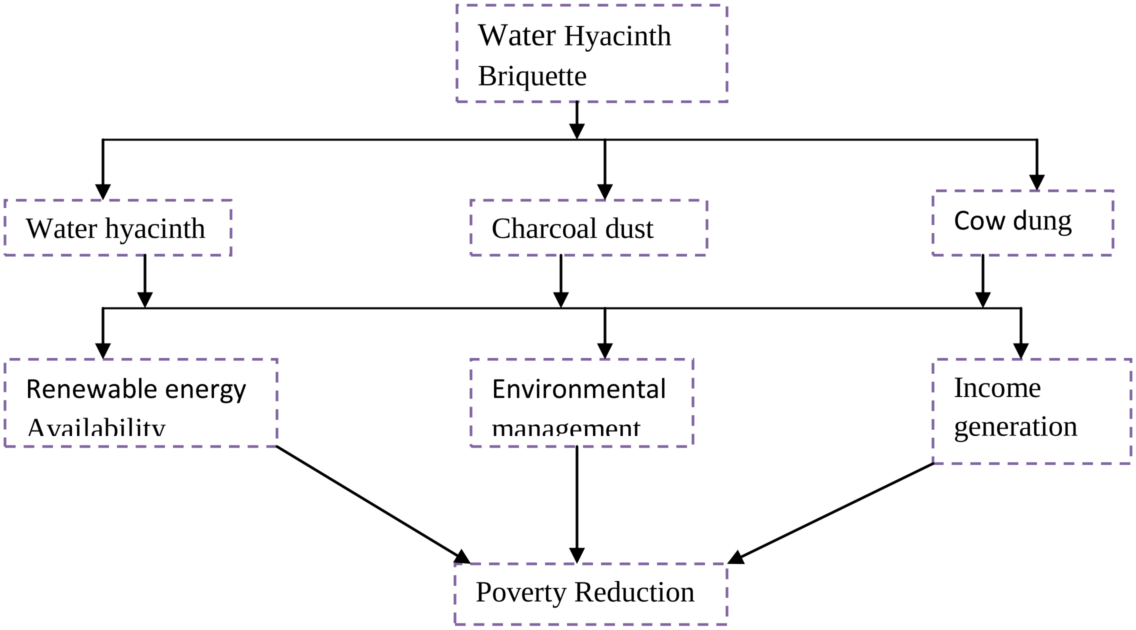

Figure 1.4: Conceptual framework

CHAPTER TWO
LITERATURE REVIEW

2.1 Overview

Briquette is a modern biomass fuel. It is biomass in condensed form with increased volumetric calorific value (Figure 2.1) .Biomass briquettes are commonly used for electricity generation, heat, and cooking fuel. These compressed compounds contain various organic materials including rice husk, bagasse, ground nut shells, municipal solid waste or agricultural wastes (Biomass briquettes, 2013).

Figure 2.1: Straw-hay briquettes

Source: http://en.wikipedia.org/wiki/file

The raw materials are gathered and compressed into briquette in order to burn longer, make storage and transportation of the goods easier. The briquetting technology has been used successfully to densify loose biomass into regular shapes such as pellets or cubes depending on densification equipment employed either with or without binder addition (Eriksson *et al.*, 1990). The equipments used are mechanical piston press, hydraulic piston press, conical screw extruders, screw extruders without die heating, screw extruders with die heating, twin screw extruders and manual presses (Eriksson *et al.*, 1990).

The use of biomass briquettes is predominant in the southern parts of India replacing use of coal and furnace oil. Its use is strongly encouraged by issuing carbon credits to those registered under CDM (Kyoto protocol 1995). One carbon credit is equal to one free ton of carbon dioxide to be emitted into the atmosphere (Biomass briquettes, 2013).

The whole process started with Charcoal. Charcoal is a desirable fuel because it produces a hot, long-lasting, virtually smokeless fire. Charcoal's transition from a heating and industrial fuel to a recreational cooking material took place around 1920 when Henry Ford invented the charcoal briquette (WWW.madehow.com/volume-4/charcoal-Briquette).

2.2 History of briquetting

2.2.1 Use in developed world

There has been a recent push to replace the burning of coal (fossil fuels) with biomass. In 1925, Japan independently started developing screw press technology to harness the energy from sawdust briquettes (Figure 2.2), known as ***"Ogalite"*** (Biomass briquettes, 2013).

Figure 2.2: Japanese charcoal briquettes made from sawdust briquettes *(Ogalite)*.

Source: http://en.wikipedia.org/wiki/file

Europe and the United States however at the same time pursued and perfected the reciprocating ram/piston press. Between 1964 and 1969, Japan increased production fourfold by incorporating screw press and piston press technology. The technique was later adopted in European countries due to its superiority in briquetting (Biomass briquettes, 2013).

2.2.2 Use in developing world

The briquette production technology only improves upon the ancient practice by increasing the efficiency of pyrolysis. Increased use are in China and India whose economies are rapidly increasing due to cheap ways of harnessing electricity and emitting large amounts of carbon dioxide (Biomass briquettes, 2013). In the African Great Lakes region, biomass briquette production was spearheaded by a number of non-governmental organizations (NGOs) with Global Village Energy Partnership (GVEP) taking a lead in promoting briquette products and briquette entrepreneurs in the three Great Lakes countries; namely, Kenya, Uganda and Tanzania (Global Village Energy Partnership International, February 2010 & Biomass briquettes, 2013). This was achieved by a five year European Union (EU) and Dutch government sponsored project called Developing Energy Enterprises Project East Africa (DEEP EA) which was running from March 2008 until 2013 (Biomass briquettes, 2013). The main feed stock for briquettes in the East African region has mainly been charcoal dust although alternative like sawdust, bagasse, coffee husks and rice husks have also been used. Briquettes have been produced on a small-scale in Kenya since the 1970's (Global Village Energy Partnership International, February 2010). However, they are not widely used because of the cultural preference for charcoal and lack of cooking equipment compatible with the type of briquettes being produced (Eriksson *et al.*, 1990). A wider program of awareness-raising and dissemination of energy-efficient cooking equipment will assist with uptake of briquettes as an alternative or supplementary fuel to charcoal and lead to a reduction in deforestation as indicated by other authors (Global Village Energy Partnership International, February 2010).

2.3 Water hyacinth

2.3.1 Plant description

Water hyacinth (*Eichhornia crassipes*) is an aquatic plant which can live and reproduce floating freely on the surface of fresh waters or can be anchored in mud (Figure 2.3). Plant size ranges from a few inches to a metre in height (Agripinoy.net, 2008). The plant belongs to the family *Pontedericeae*, closely related to the lily family (*Liliaceae).* The stems and leaves contain air-filled tissue which gives the plant its considerable buoyancy.

The vegetation reproduction is asexual and growth is greatly enhanced by high nitrogen, phosphorus and potassium level (Mart *et al*., 2014).

Standing crops have been estimated to produce 100-120 tons per hectare per year (Agripinoy.net, 2008 & Mart *et al*., 2014). Water hyacinth roots naturally absorb pollutants, including such toxic chemicals as lead, mercury, and strontium 90 in concentrations 10,000 times that in the surrounding water (Mart *et al*., 2014).

Figure 2.3: Water hyacinth (*Eichhornia Crassipes*) at Seka (Homa Bay County) beach.

Source: Author (July, 2015)

The plant originated in South America, particularly in the Amazonian basin and was introduced into many parts of the world as an ornamental garden pond plant due to its beauty. It is particularly suited to tropical and subtropical climates and has become a problem plant in areas of the Southern USA, South America, East, West and Southern Africa, South and South East Asia and Australia (Agripinoy.net, 2008 & Mart *et al*., 2014). Its spread throughout the world has taken place over the last 100 years or so. It is a major problem for marine transportation, fishing, hydro power and irrigation schemes. It is also an environmental or public health problem; may create a micro habitat suitable for the breeding of many vectors of human diseases and for hosting poisonous snakes. Efforts are underway all over Africa to remove water hyacinth from waterways by hand, machine, chemical and biological control and it is now considered a serious threat to biodiversity (Agripinoy.net, 2008 & Africascience.blogspot.com /2007/07/lake victorious).

2.3.2 Practical application of water hyacinth

Although water hyacinth is seen in many countries as a weed and is responsible for many of the problems in the lakes, many individuals, groups and institutions have been able to turn the problem around and find useful applications for the plant. Although the plant has 95% water, it has a fibrous tissue and can be used for a variety of useful applications. Some of possible uses for the plant which have been developed or which are still in their infancy or remain as ideas are making paper, fibre, yarn and rope, basket works, biofuel production, water purification, animal fodder, fertilizer, fish feed (Agripinoy.net, 2008, KORCE to use hyacinth for power generation, 2013 & Keith *et al.,* 2000).

Studies have shown that water hyacinth can be used with binders or combined with other biomass materials to produce briquettes (Ighodalo, Zoukumor, Egbon, Okoh, Odu, 2011, Davies *et al*, 2013, Frank *et al*., 2013). The calorific value for water hyacinth was found by Frank *et al*., (2013) to be 13.4MJ/Kg.

2.4 Charcoal dust

Studies have shown that there is a loss of about 10-15% along the charcoal supply chain in form of dust or fines as a result of breakages during handling and this dust is mainly found at the retailing and wholesale stalls (Figure 1.3). Charcoal dust poses disposal challenges. Most often, it is either dumped in open drainage systems or left as unattended heaps that risk environmental pollution (Global Village Energy Partnership International, February 2010 & Njenga *et al*., 2013). The annual per capita consumption of charcoal in Kenya is about 150 kg which translates to an annual national consumption of 2.4 million tons (Njenga *et al*., 2013). This implies that about 0.24-0.36 million tons of charcoal dust is produced annually. Briquette use could displace up to 5-10% of present charcoal consumption (Global Village Energy Partnership International, February 2010). Expansion would be limited by availability of charcoal dust. This scenario would see the briquette industry making a modest impact on national energy access and, by recycling a waste product, relieving some pressure on the nation’s forestry resources (Global Village Energy Partnership International, February 2010). Charcoal produce low emissions which is a positive indicator in addressing indoor air pollution which has been known to cause over 1.6 million annual deaths globally, 400,000 occurring in SSA (Pennise *et al*., 2012 & Njenga *et al*., 2013). Two years of health data collected by Pennise *et al.,* (2012) from Kenyan families using wood and charcoal shows that charcoal users experienced 44-65 percent fewer cases of acute lower respiratory infection (ALRI) compared to wood users due to emission of particulate matter (Njenga *et al*., 2013).

Use of charcoal dust in briquetting has been documented and is contribution to environment management, it has high calorific value (25 - 30 MJ/kg) (Biomass. net, 2010, Pennise *et al.,* 2012 & Njenga *et al*., 2013).

Its use would therefore improve calorific value of hyacinth composite briquette; but amount used in the mixture must be limited to avoid extensive use of charcoal and not water hyacinth.

2.5 Cow dung

Cow-dung is a potentially large biomass resource. Healthy animals produce dry dung that is equivalent to four or five times their body weight each year, but dung is readily available only for confined livestock or in settings where the labor costs associated with gathering it are modest (FAO**,** 1985). Kenya produces over 14.1 million tons (Appendix A1) of animal dung annually (Energy and Development in Kenya, 2000). This can be dried and used for energy. The main challenge is the impracticability in gathering the waste, for animals which are left to graze. However, for animals in confined spaces like zero grazing and those that are taken to abattoirs, the dung can be collected easily. Traditionally, cow dung collected from cow shed has been used for cooking purposes. U.N.E.P, (2001) (as cited in Lagat *et al*., 2010) indicates that Cow-dung now contributes 2% of global non-food energy consumption. Much of this is through traditional low efficiency and highly polluting combustion practices in poorly controlled heating and cooking fires, which support a substantial share of the world's population.

In order to enhance the contribution of biomass to commercial energy needs, focus is made on improving both the efficiency and environmental impacts of biomass conversion. This is done by understanding the properties of cow dung as discussed by Lagat *et al.,* (2010). He concluded that Cow-dung can be efficiently used as a fuel at a particle size of 2.0mm, air flow rate of $4m^3$ /hr and mass flow rate of fuel of 3.4 kg/hr, which gave the highest temperature of 960 ^{o}C under fluidized bed combustor test. The moisture content was found to be 14.07%, volatile matter 58.91% while the calorific value was 14.539MJ/kg. The ash content was found to be 16.88% based on the proximate analysis of fuel and its melting point was above 1100 ^{o}C.

Cow dung is therefore fuel but of low calorific value though it also serves in briquetting as a binder (WWW.madehow.com/volume-4/charcoal-Briquette).

2.6 Biomass briquetting

It is the densification of loose biomass material to produce compact solid composites of different sizes with the application of pressure. The technology may also be defined as densification process for improving the handling characteristics of raw material and enhancing the volumetric calorific value of the biomass (Akowuah, Kemausuor, Mitchual, 2012 & Khardiwar, Kumar, Mahalle, Kumar, 2013).

2.6.1 Densification process

Densification essentially involves two parts; the compaction under pressure of loose material to reduce its volume and to agglomerate the material so that the product remains in the compressed state. The resulting solid is called a briquette if, roughly, it has a diameter greater than 30 mm. Smaller sizes are normally termed pellets though the distinction is arbitrary (Eriksson *et al.,* 1990).

Densification is affected by process and material variables according to Chaney *et al.*, (2005) and Chin Chin *et al.*, (2010) as discussed below;

2.6.1.1 Pressure

Compacting material with low to moderate pressure (0.2-5 MPa) reduces space between particles. Increasing the pressure will, at a certain stage particular to each material, collapse the cell walls of the cellulose constituent; thus approaching the dry mass density of the material. The pressures required to achieve such high densities are typically 100 MPa plus. Thus, process of compaction is entirely related to the pressure exerted on the material and its physical characteristics (Eriksson *et al.,* 1990). According to Eriksson *et* *al.*, (1990), depending on the material used, the following rough classification may be adopted whether or not an external binding agent must be added to agglomerate the compressed material:-

(i) Low pressure up to 5 MPa
(ii) Intermediate pressure 5-100 MPa
(iii) High pressure above 100MPa

Usually high pressure and temperatures processes will release sufficient lignin to agglomerate the briquette though this may not be true for all materials. Intermediate pressure machines may or may not require binders, depending upon the material whilst low-pressure machines invariably require binders. The softening of lignin and its subsequent cooling while the material is still under pressure is the key factor in high pressure briquetting. Chin Chin *et al.*, (2010) proposed the following relationship between the relaxed densities and applied die pressure (as cited in Faizal, Latiff, Mazlan, Darus, Pdf (24/01/2014) & Madhurjya, Deben, 2013).

$$\rho = a ln P + b \qquad (1)$$

Where;

ρ is the relaxed density,

P is the compaction pressure

a, b are empirical constants.

Effect of briquetting pressure on relaxed density is shown on Figure 2.4 and 2.5 below. In Figure 2.4, the materials are mixed with starch (20% of dried material) as a binder whereas in figure 2.5, the materials are partially decomposed before compressing.

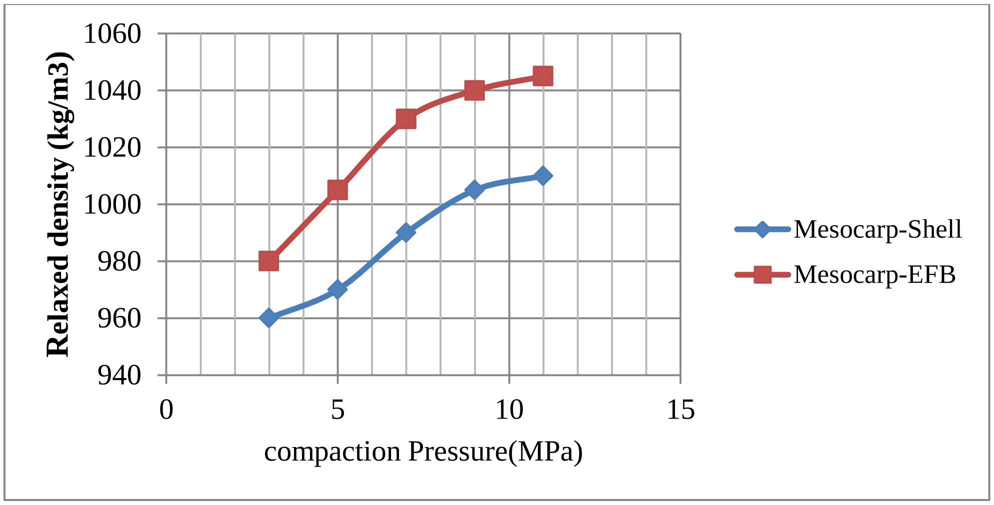

Figure 2.4: Relaxed density Vs Compaction pressure

Source: Faizal et al., 2014(dry briquetting)

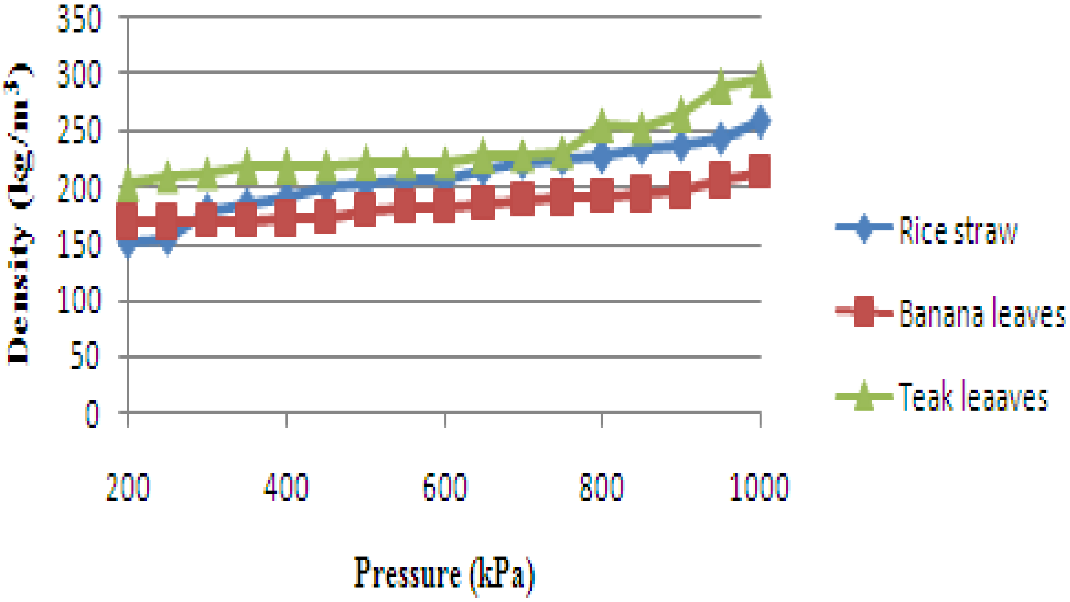

Figure 2.5: Relation between relaxed density and die pressure for different briquettes

Source: Madhurjya et al., 2013 (wet briquetting)

The above behavior of biomass briquettes is confirmed by Davis *et al.*, (2013) and Mitchual *et al.*, (2013) for different biomass materials. For wet briquetting it can be seen that the pressure work well before reaching 1000kPa.

2.6.1.2 Dwell time

This is the time the briquetting material is held in the mold (at constant pressure) before extrusion. The dwell time of the material in the mold influence the quality of the briquette. It is effective at low pressures and when pressures reach 138 MPa and above, the effect become negligible. Li and Liu, (2003) found that dwell time of more than 5 minutes have no significant effect on density, durability, and stability of briquette (as cited in Chirchir, Nyaaga & Githeko, 2012).

2.6.1.3 Die geometry

It refers to the shape of the die. Common types of briquette press feature a cylindrical piston and die with a diameter ranging from 40-125 mm. The die tapers somewhat towards the middle and then increases again before the end. The exact form of the taper varies between machines and biomass feedstock and is a key factor in determining the functioning of the process and the resulting briquette quality. It influences the amount of materials to be briquetted and energy required during compression process (Eriksson *et al.*, 1990). According to Saptoadi *et al.*, (2008), briquettes should not be more than 100 g for proper burning and handling and that a cylindrical shaped briquette with a central hole burns at ease (as cited in Bichitra *et al.*, 2013).

2.6.1.4 Particle size and shape

Particle size of biomass feedstock is crucial for dry briquetting. Kaliyan and Morey, (2006) indicated that generally, the finer the grind, the higher the quality of compact in case of dry briquetting. According to Stanley, (2003), particle size also plays important role in combustion as the voids between particles will be less and less space is available for mass diffusion e.g. water, volatile matter etc (Bichitra *et al.*, 2013). This is confirmed by Davis *et al.*, (2013) and Mitchual *et al.*, (2013). Davis also concluded that particle size had significant effect on the durability of briquette. This case may not be applicable to wet briquetting because the material undergoes decomposition and therefore fiber breakdown and also softening by adding water (Bichitra *et al.*, 2013).

2.6.1.5 Type and ratio of binder

Binding agent is necessary to prevent the compressed material from springing back and eventually returning to its original form therefore important in bonding of briquette (Erickson *et al.*, 1990). Some of the binders that have been used during briquetting include starch, molasses, gum Arabica, acacia gum, clay, cow dung, cement and mashed newsprint/wastepaper(www.madehow.com/volume-4/charcoal-Briquette).The proportion and the type of binder used influence the quality of briquette as discussed by Olorunnisola, (2007) (as cited in Chirchir *et al.,* 2012) and Davis *et al.,* (2013). For example, Olorunnisola found that briquettes made with starch burns faster and efficiently than those made with clay. This is because of the non-combustible character of the clay (mineral matter). Erickson *et al.,* (1990) noted that heat treatment (250-300 ^{o}C) could be used to soften the lignin of un-carbonized biomass to achieve self bonding. But densifications of charred biomass require binder because lignin component is destroyed during pyrolysis stage. Lignin can be defined as a thermo plastic polymer in biomass, which begins to soften at temperatures above 100 °C and is flowing at higher temperatures; it improves the binding characteristics (Erickson *et al.,* 1990 & Bichitra *et al.,* 2013). However, natural decomposition process can also be used to break fibers down and facilitate bonding (Bichitra *et al.*, 2013).

2.6.2 Densification technologies

The three different types of densification technologies that are currently in use are pyrolizing technology, direct extrusion type and wet briquetting technology.

2.6.2.1 Pyrolizing technology

Pyrolizing technology relies on partial pyrolysis (carbonization) of biomass, which is mixed with binder and then made into briquettes by casting and pressing**.** Particle size is important in this case (dry briquetting). It is capital intensive and unfriendly for small scale production (Bichitra *et al.,* 2013).

2.6.2.2 Direct extrusion type technology

In this technology, biomass is dried and directly compacted with high heat and pressure. Particle size of biomass feedstock is crucial for briquetting in this case (dry briquetting). It is capital intensive and unfriendly for small scale production (Bichitra *et al.,* 2013).

2.6.2.3 Wet briquetting technology

In this technology, biomass material is decomposed before compaction to briquettes (Bichitra *et al.*, 2013 & Madhurjya *et al.,* 2013). Natural decomposition is used to break fibers down and facilitate bonding. Studies by Bichitra *et al.*, (2013) found that decomposition of finely chopped biomass at anaerobic condition is faster while on the other hand Acharya *et al.*, (1935) found that aerobic decomposition of rice straw at about 30ºC is more than that of anaerobic decomposition. Bichitra concluded that keeping biomass materials in heap condition at sun will enhance decomposition. However, during compaction of briquettes, wet biomasses need to be kept on pressing at least for 40seconds and compaction pressure should not be less than 1 MPa for the purpose to yield good quality briquette (Bichitra *et al.*, 2013 & Madhurjya *et al.*, 2013). The decomposition period of lingo-cellulosic biomass depends largely on their lignin content and therefore desired level of decomposition varies with biomass types. Rice straw and teak leaves take 19 days while banana leaves take 28 days to reach the desired status (Bichitra *et al.*, 2013 & Madhurjya *et al.*, 2013). High lignin containing biomass takes longer time for decomposition. After pressing the material, it should be removed carefully from die and moved aside to dry with minimum handling (Bichitra *et al.*, 2013 & Chaney, Clifford, Wilson.Pdf, (24/1/2014 6.30am). Because low pressures are involved in wet briquetting, it requires less capital and very low technical machinery which can suit the rural environment for production of briquettes (Bichitra *et al.*, 2013). This technology was therefore adopted to prepare briquette for domestic consumption in rural areas.

2.7 Biomass briquette characteristics

There are three processes used to produce energy from biomass; pyrolysis, gasification and combustion. In combustion route, biomass (fuel) is burnt to produce steam among others. The steam is used for power generation through turbines. In gasification process, biomass is converted into producer gas and the producer gas is used for thermal or electrical application (Khardiwar *et al.*, 2013). Pyrolysis is thermal decomposition of organic matter either in the complete absence of or with such a limited supply of air that oxidation does not occur to an appreciable extent and relatively low temperatures are employed of 200 to 500 °C (Probstein & Hicks, 2006). Three products of pyrolysis are usually produced: gas, pyrolysis oil and charcoal. Majority of biomass are not suitable to be utilized as fuel without an appropriate process since they are bulky, uneven and have low energy density. These characteristics make them difficult in handling, storage, transport and utilization. One of the promising solutions to overcome these problems is the briquetting technology. In order to efficiently utilize briquette as fuel, it is important to characterize their physical, chemical and combustion properties.

2.7.1 Chemical properties of briquettes

Chemical properties are very important to determine the fuel quality**.** Study of proximate analysis of biomass is carried out to determine volatile matter, fixed carbon, ash content and Calorific value in the biomass. It is therefore important to know these parameters in order to understand combustion characteristics of fuels (Khardiwar *et al.*, 2013).

2.7.1.1 Volatile matter

During biomass combustion, a number of physical and chemical processes occur in time and space. The processes include: drying and preheating of the fuel, pyrolytic release of volatile matter, char, etc. In general the combustion of biomass produces, next to energy, ash, carbon dioxide and monoxide, un-burnt hydrocarbons, oxides of nitrogen and particulate matter. Those products, exclusive of moisture, given off by a material as gas or vapor during combustion are called Volatile matter (VM). Combustion process is exothermic, though it requires initial heating to 200-300 ^{o}C in order to start the phase of distillation of volatile substances and then fuel begins to oxidize and combustion of solid material starts. From then on, the heat is supplied from the combustion itself (McGill University, IATA, 2009 & Lagat *et al.*, 2010).

2.7.1.2 Ash content

Ash is the name given to the non-aqueous residual components or inorganic compounds of biomass that remain after it is burned or refers to the inorganic residue that remains after drying, devolatisation and combustion of fixed carbon. It consists mainly of metal oxides or salts, with 25-45% of the ash being composed of calcium carbonate (McGill University & IATA, 2009). Depending on the type of biomass, the ash content varies from less than 1% for wood to as high as 10-19% for cow-dung (Eriksson *et al.*, 1990). Ash is not combustible; therefore, a fuel with high ash content will have reduced energy density. Higher ash content in a fuel usually leads to higher dust emissions and affects the combustion volume and efficiency .The main consequences of presence of ash are: provision of an ash removal system, agglomeration, fouling and slagging and corrosion (McGill University, IATA, 2009 & Akowuah *et al.*, 2012).

2.7.1.3 Calorific Value

Calorific value or heating value is one of the most important characteristics of a fuel. It is the amount of energy per unit mass it gives off when burned. Heat value or calorific value determines the energy content of a fuel. It is the property of biomass fuel that depends on its chemical composition and moisture content (Akowuah *et al.,* 2012). The higher heating value at constant pressure measures the enthalpy change of combustion with water condensed. If the combustion is carried out at constant volume, the internal energy change due to combustion with water in the condensed state is the higher heating value at constant volume. This is the standard value measured with a bomb calorimeter. The lower heating value at constant volume measures the internal energy change with product water in the vapor phase. In addition, moisture in the fuel reduces the heating value compared to a dry weight (Akowuah *et al.,* 2012 & Lagat *et al.,* 2010). Estimation for Gross calorific value or higher heating value for water hyacinth, charcoal dust and cow dung are 13.4MJ/Kg (Frank *et al.*, 2013), 25.2 – 30MJ/Kg (Njenga *et al*., 2013) and 14.4-15.54MJ/Kg (Frank *et al.*,2013 & Lagat *et al.*,2010) respectively. However, in actual practice such as in a stove, any moisture in the fuel as well as that formed by the combustion of hydrogen is carried away through the stack as water vapor. The heat of condensation of water is not available as useful heat and has to be subtracted from the gross calorific or higher heating value resulting in the net heating or lower heating value (Abrahamson, 2002).

2.7.2 Combustion and Emission properties of briquettes

2.7.2.1 Combustion

Combustion process for different biomass fuels is basically the same, consisting of three main stages during firing: drying, pyrolysis and oxidation. The effect of each stage on the overall combustion process will depend on the following properties of biomass: moisture content, size of particles, calorific value, volatile matter, ash content and ash melting point (Lagat *et al.*, 2010). The schematic diagram (Figure 2.6) below shows the description of biomass combustion process (Abrahamson, 2002).

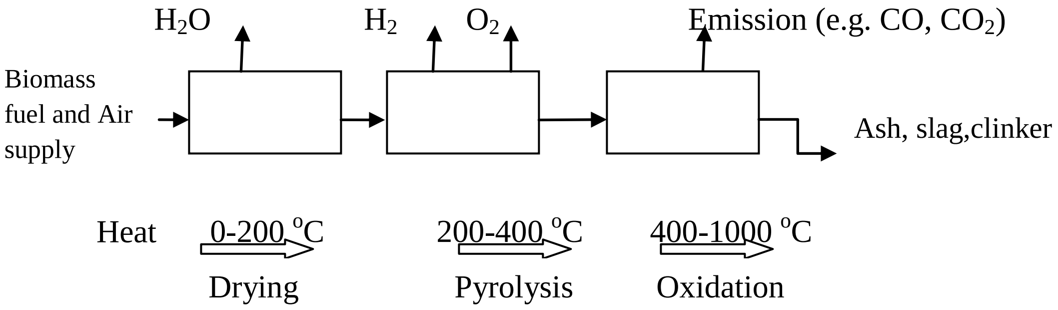

Figure 2.6: Process of biomass combustion [Abrahamson, 2002]

The first stage of the process is the evaporation of moisture from the fuel. The moisture Content and particle size of the biomass are important during this stage. High moisture content and large particle size requires a long drying time due to the relatively low surface to volume ratio of the fuel. The heat for drying is supplied by radiation from the flames and from the refractory materials used for the furnace walls. In addition, heat can be supplied from preheated primary air, of up to 400 ^{o}C, obtained via a heat exchanger located in the furnace flue (Abrahamson, 2002). As biomass gets close to being fully dry, the temperature increases until at around 200^{o}C. Pyrolysis then starts and the volatile matter in the form of mixed vapors or vaporized tars and oils start to be released. With further heating above 400^{o}C, the fuel begins to oxidize and combustion of solid material starts. From then on, the heat is supplied from the combustion itself. Combustion of the solid material will raise the temperature above the fuel bed igniting the volatiles, which are often seen as the yellow flame burning above the fuel (Ketlogestwe, Oladiran, Foster, 2004). The final stages of combustion involve particles of char arising from the disintegration of biomass. Char is composed mainly of carbon and burns to produce CO_2. The inert matter is made up of materials that are not combustible and becomes clinker, slag or ashes. Air must reach all of the char for its complete combustion and so the fuel should be in as small particles as possible as found by Tilma, 1991 (as cited in Ketlogestwe *et al.*, 2004). Airflow needs to be carefully controlled to ensure that there is sufficient oxygen for complete combustion of the fuel. Too little air will lead to incomplete combustion, resulting in low efficiency and high emissions of pollutants (i.e.

CO, smoke, particulates etc.). Too much air can have a cooling or quenching effect which reduces combustion temperatures, resulting in incomplete combustion and high emissions of pollutants (EU, 2000). Therefore, the amount of air for a given amount of fuel is critical for efficient combustion (EU, 2000). The relationship between the amount of air and the amount of fuel is known as the air fuel ratio and is expressed as the mass (kg) of air to mass (kg) of fuel. The air to fuel ratio will vary according to the type and grade of fuel being used.

However, Chaney *et al., (*2014) concluded that cooking is often done over open fires, which are highly inefficient transferring only 5-10% of the fuel's energy to the cooking pot. A part from addressing this problem by designing and optimizing improved stoves with the aim of increasing combustion efficiency and improving thermal heat transfer to the pot, it is important to improve the fuel combustion characteristics.

(i) Carbonization Process

Unless burnt in controlled conditions, biomass-based fuels tend to produce appreciable quantities of smoke, problematic if the fuel is to be used in indoor environments. A common way to overcome this in briquetting is to carbonize either feedstock or the finished briquette (Global Village Energy Partnership International, February 2010, Eriksson *et al.,* 1990 & Biomass briquettes, 2013). Carbonization drives off volatile compounds to leave more or less pure carbon; the biomass is heated to within a critical temperature band (around 300 ^{o}C or to 590 °C for coal) but with a restricted supply of air so that it does not ignite. Various processes options are available including simple earth kilns to more complex retorts that make use of the volatile compounds in heating the process. After being air-cooled, it is stored until needed (Global Village Energy Partnership International, February 2010, Eriksson *et al.,* 1990 & Biomass briquettes, (2013). However, the materials were not carbonized to avoid use of high pressures and therefore costly operations in the rural set up.

The Combustion characteristics in this paper are evaluated against burn rate, ignition time and water boiling time.

(ii) Burn rate of briquettes

This is the rate at which a certain mass of fuel is combusted in air. In terms of briquette combustion, effect of densities on burn rate have been studied by chin chin *et al.,* (2010), composition (Proximate analysis), fuel size done by various authors (Chaney *et al.*, 2014) and fuel geometry and burn rate efficiency by both kandpal *et al.*, (1995) and Chaney *et al.*, (2014). For example, Chaney found out that cylindrical briquette with central holes burn faster than slabs with an equivalent surface area to volume ratio. Figure 2.7 shows a sample curve of a mass/initial mass versus time which can be used to understand burning of biomass. There are three phases of the burn marked: Phase (1) is the ignition phase, phase (2) the steady state flaming combustion phase and (3) is when the flame dies and the briquette decomposes further by a char combustion mechanism. The gradient of phase (2) is the normalized steady-state combustion rate, referred to here as the normalized burn rate (NBR) and is expressed by equation 2 below:

$$NBR = \left[0.074\left({}^{A}\!/_{V}\right) - 0.0076\right] * \ e^{(-0.0023\rho)} \tag{2}$$

Where;

ρ = density of briquette, $\frac{kg}{m^3}$

A=area of briquette,m^2

V=volume of briquette,m^3 (slab geometry).This is confirmed by Chin Chin *et al.*, (2010). Equation (2) demonstrates the significance of briquette density and its A/V ratio in determining its burn rate and allows the power output and Heat values of a briquette to be written as equation (3) and (4) respectively (Chaney *et al.*, 2014)

$$Power = BR * M * calorific\ value(kw) \tag{3}$$

$$Heat\ release = calorific\ value * \ combustion\ rate \tag{4}$$

Where;

BR is Burn rate, Kg/minute

M is the initial mass of the briquette (Chaney *et al.*, 2014)

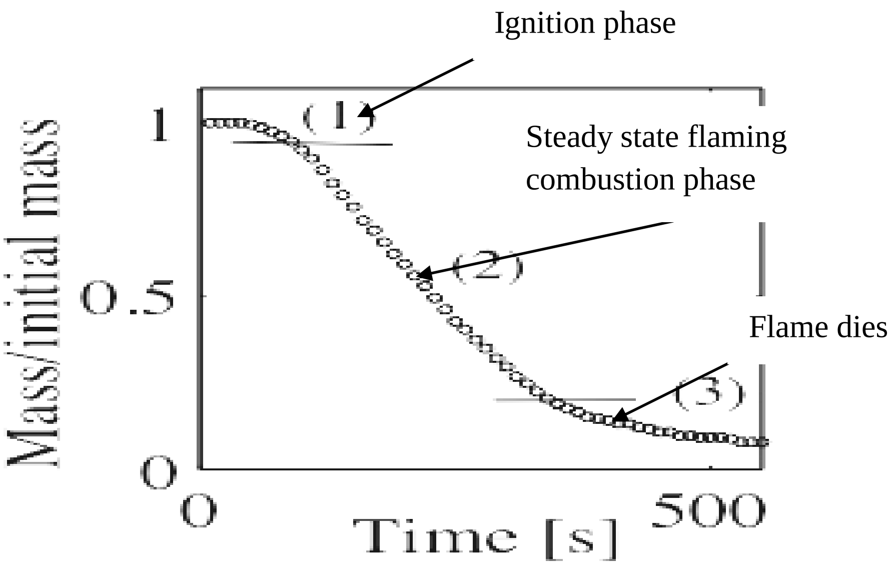

Figure 2.7: Typical curve showing the decrease of mass/initial mass of a briquette as a function of time throughout its burn

Source: Chaney et al., 2014

Figure 2.8 shows the variation of normalized burn rate/exp (-0.0023ρ), (to remove the effect of density) for cylinders with a central hole, where the A/V ratio is varied by changing the cylinder height. The dashed line is for briquettes of slab geometry and it is clear that these results deviate significantly from this line. Therefore, cylindrical briquettes with central holes will have a higher burn rate than slabs of the same A/V ratio. It is important to note that the curve describing this change in rate will never cross the y-axis. This is because as the briquette height increases, the rate of decrease of briquette A/V ratio decreases, until the point where increasing the height further has no effect on A/V ratio. In other words, for a given internal hole diameter and external diameter of a cylindrical briquette there is a maximum height beyond which further increases in the height will not change the effective A/V ratio of a dashed curve describing slab-geometry, giving the cylindrical briquette with a central hole an increasingly higher rate compared to what would have been achieved from the same A/V ratio with slab shaped geometry (Chaney *et al.*, 2014). This principle was adopted and therefore briquettes produced are cylindrical with central hole to improve on the burn rate and keeping the height as given by Chaney *et al.*, (2014) which is also suitable for use in KCJ stoves.

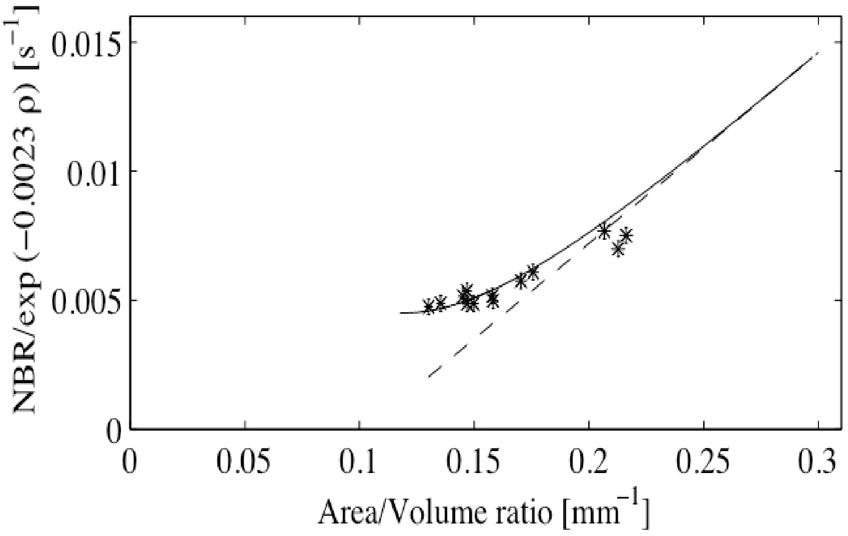

Figure 2.8: NBR/exp (-0.0023ρ) for different A/V ratios for cylindrical briquettes

Source: Chaney et al, 2014

(iii) Ignition time

Ignition time is the time taken to reach the ignition temperature or when the flame begins to flare from the fuel. Figure 2.7 shows the three phases of burn. Phase 1 indicates the ignition phase and ignition time is the time at the end of this phase.

2.7.2.2 Emission Characteristics & Environmental impact

Biomass burning is combustion processes that consume biomass fuels, either through natural processes (e.g. wildfires) or man-made processes (e.g. prescribed burning, agriculture field burning, land clearing, wood burning in fireplace, woodstove, and residential leaf burning). During combustion, large amounts of air pollutants, e.g. particulate matter (PM), volatile organic compounds (VOCs), nitrogen oxides (NO_x), ammonia (NH_3), carbon monoxide (CO), etc, can be emitted (Yongtao, Russell, n.d.) Burning biomass such as solid wood fuels, cow dung and agricultural residues is likely to be the largest source of indoor air pollution globally, and to the greatest extent in developing countries. (Pennise *et al.,* 2012). This fact is confirmed by Partnership for Policy Integrity report indicating that facilities burning biomass emit more air pollutants, including carbon dioxide, per megawatt-hour than those that burn coal. Additionally, the report said that even the cleanest-operating biomass facilities emit 150 percent more nitrogen oxides, 600 percent more volatile organic compounds, 190 percent more particulate matter and 125 percent more carbon monoxide than coal on a per megawatt-hour basis (Andrew & Bloomberg, 2014). However, biomass has been defended as a carbon-neutral fuel source scientifically by Jessica McFaul, a spokeswoman for American Forest & Paper association (Andrew & Bloomberg, 2014). A similar explanation is given by Jindaporn *et al.*, (2007) that during the plant life cycle, plant biomass materials derived from plant absorb carbon dioxide through photosynthesis at same rate as they released the gas in the combustion process, thus leading to no net increase in atmospheric CO_2 quantity. Due to the lower contents of sulfur and nitrogen in biomass, its application also creates less environmental pollution and health risk than fossil fuel combustion. This is the reason why utilization of biomass is eco-friendly (Biomass. net, 2010, Jindaporn *et al.*, 2007 & Biomass briquette for Green electricity production, 2010).

The pollutant emissions from biomass can be classified into two groups (Table 2.1). The first group consists of the un-burnt pollutants, which are mainly influenced by the combustion equipment and process. The other group consists of pollutants which are mainly influenced by the fuel properties.

Table 2.1: Pollutant emission during biomass combustion

	Origin of fuel	**Emissions**
1	Un-burnt pollutants (all biomasses)	CO, HC, PAH, tar
2	Oxidized pollutant (all biomasses)	NO_x , N_2 O
3	From biomasses containing Cl and S (urban waste woods, straw, grass, Mischantius etc	HCl, SO_2 , salts (KCl, K_2SO_4 , NH_4Cl)
4	Ash (all biomasses)	Particles
5	From biomass containing heavy metals (Urban wastes wood, sludge).	Pb, Zn, Cd, Cu, Cr, Hg etc
6	From fuel biomass containing high Cl	PCDD, PCDF

Source: Saxena, 1993

(i) Un-burnt pollutants

The un-burnt pollutants include CO, HC, tar, PAH, CxHy and char particles. These pollutants are usually produced due to poor combustion, which is either as a result of low combustion temperature, insufficient mixing of fuel with combustion air or too short residence times of the combustible gases in the combustion zone (EU, 2000 & Energy scenario, 2013). It can be expected from all agricultural residues depending on the furnace design and operation conditions of the firing systems. For biomass combustion in a stocker, grate or pulverized firing systems, up to 1000-5000mg/m^3 CO, 100-500mg/m^3 HCl, 0.1-1mg/m^3 PAH and 150-500mg/m^3 CxHy may be expected if less efficient combustion techniques are employed (Rosyida, Kang, Mohammad, 2007).

(ii) Pollutants based on fuel properties

The pollutants which are influenced by the fuel properties include HCl, SO_2, NOx and N_2O. The formation of HCl and SO_2 is almost nearly proportional to the contents of Cl_2 and S in the fuel. The nitrogen contents of the agricultural residues range from 0.6 to 3.5 weight % and are comparable to or higher than those of coals. Measurements in laboratory units and large-scale plants confirm that high NOx emissions can be generated during the combustion of agricultural residues. NOx emissions in the range of 300 to 800 mg/m^3 have been reported from straw, grass and miscanthus whereas from pine wood, beech wood and chip board some 173, 231 and 921 mg/m^3 NOx were reported from a laboratory furnace (Pennis *et al.,* 2012a & Pennise *et al.,* 2012b). The emission standards for a combustion process by the National Ambient Air Quality Standards (NAAQS) are as shown in Table 2.2.

Table 2.2: National Ambient Air Quality Standard

Pollutant [final rule cite]		Primary/ Secondary	Averaging Time	Level	Form
Carbon Monoxide [76 FR 54294, Aug 31, 2011]		primary	8-hour	9 ppm	Not to be exceeded more than once per year
			1-hour	35 ppm	
Lead [73 FR 66964, Nov 12, 2008]		primary and secondary	Rolling 3 month average	0.15 $\mu g/m^3$	Not to be exceeded
Nitrogen Dioxide [75 FR 6474, Feb 9, 2010] [61 FR 52852, Oct 8, 1996]		primary	1-hour	100 ppb	98th percentile, averaged over 3
		primary and secondary	Annual	53 ppb	Annual Mean
Ozone [73 FR 16436, Mar 27, 2008]		primary and secondary	8-hour	0.075 ppm	Annual fourth-highest daily maximum 8-hr concentration, averaged over 3 years
Particle Pollution Dec 14, 2012	PM$_{2.5}$	primary	Annual	12 $\mu g/m^3$	annual mean, averaged over 3 years
		secondary	Annual	15 $\mu g/m^3$	annual mean, averaged over 3 years
		primary and secondary	24-hour	35 $\mu g/m^3$	98th percentile, averaged over 3 years
	PM$_{10}$	primary and secondary	24-hour	150 $\mu g/m^3$	Not to be exceeded more than once per year on average over 3 years
Sulfur_Dioxide [75 FR 35520, Jun 22, 2010] [38 FR 25678, Sept 14, 1973]		primary	1-hour	75 ppb	99th percentile of 1-hour daily maximum concentrations, averaged over 3
		secondary	3-hour	0.5 ppm	Not to be exceeded more than once per year

Source: Environmental Management and co-ordination (Air Quality Standards) Regulations, 2008, Kenya

NB: standards set by EPA:-

1) **Primary standards-** provide public health protection, including protecting the health of "sensitive" populations such as asthmatics, children, and the elderly.
2) **Secondary standards** -provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings.

2.8 Summary of published literature

The following observations were noted on findings taken from published literature:-

(i) Water hyacinth used alone, may not satisfy minimum calorific value

(ii) The properties of briquette fuel that affects combustion include moisture content, volatile matter, density, energy density, and geometry and Area/ volume ratio. Moisture content of a fuel affects combustion process in that high moisture makes it difficult for the fuel to burn. For efficient combustion, fuels need to be dried to reduce moisture content so that they can burn well and produce less smoke. The amount of volatile matter affects fuel combustion as volatiles in fuels sufficiently lower the fusion temperatures of ash melting in a combustor or vaporizes and condenses on the boiler tubes. Energy density affects combustion of a fuel in that high energy density fuels sufficiently burns unlike lower energy fuels that do not offer smooth fuel combustion process.

(iii) Binder type and level is important in determining briquette quality.

(iv) Increase in compaction pressure causes decrease in the burning rate but elongates the ignition time of the briquettes.

(v) Composition of briquette mixture is important in determining properties of fuel. It is therefore important to characterize fuel. However; much has not been done on composite mixtures in particular for water hyacinth, Charcoal dust and cow dung binder.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Sources of the materials

The test was carried out using water hyacinth harvested(Appendix F1 & F2) from Rare beach of Lake Victoria, Kisumu west Sub-county of Kisumu County (Figure 3.1).The site is located at longitudes 35^{o} 4’ 5.03” E, latitude of 00^{o} 59’ 54.2”S and altitude of 1135 Masl.

Cow dung was obtained from the local zero grazing unit and charcoal dust purchased from a vendor operating in the local area.

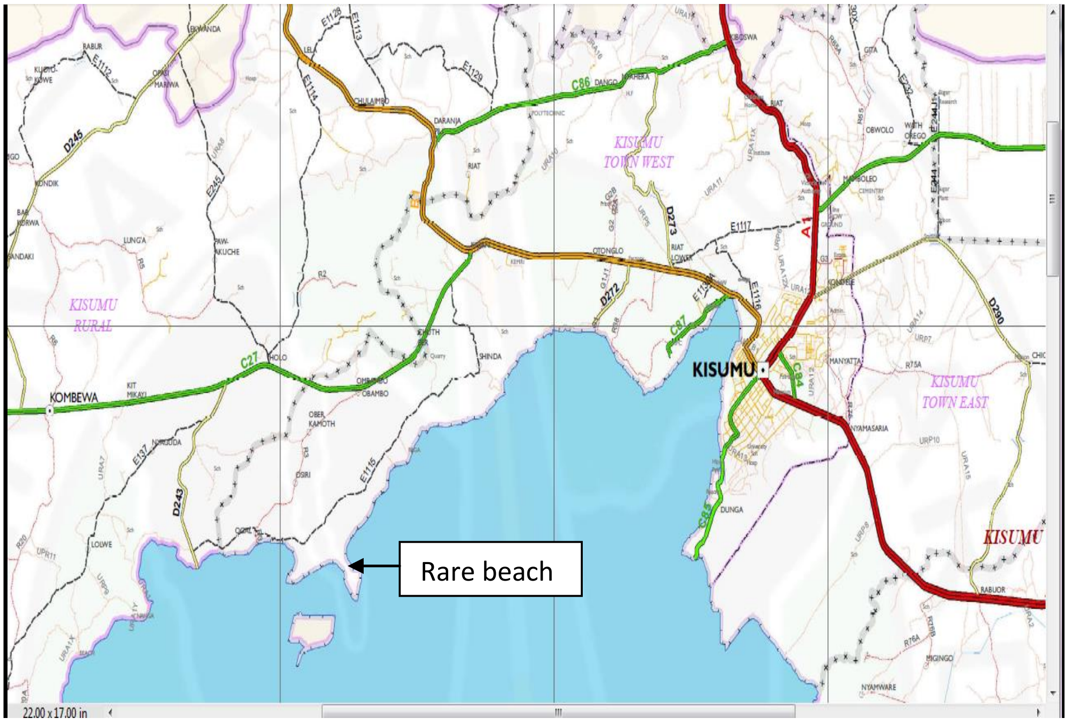

Figure 3.1: Kisumu maps-Roads map, satellite view and street view (Extract)

Source: Kenya Roads Board, 2009

3.2 Design and preparation of the briquette

Water hyacinth was chopped using a shredder and left for two weeks in a heap of 3.0m by 0.5m by1.0m to partially decompose (Figures 3.2 & 3.3). The material was thoroughly mixed manually with dried and crushed charcoal dust and cow dung (Appendix F3) in the ratios of water hyacinth: charcoal dust: cow dung (by weight) as shown in table 3.1 below; Water hyacinth was given preference as the main feedstock under consideration and therefore cow dung and charcoal ratios were each set at maximum 30% of the total mixtures.

Table 3.1: Blending ratios of water hyacinth, charcoal dust & cow dung

No.	**Blending ratios %**		
	Water hyacinth	**Charcoal dust**	**Cow dung**
1	**60**	**30**	**10**
2	60	20	20
3	60	10	30
4	70	20	10
5	70	10	20
6	80	10	10
7	**100**	**00**	**00**

The resulting material was then mixed into soupy slurry in water. The experimental design for this study is single factor (blending ratio) randomized block design with three replications. A total of 336 experiments were conducted as per the two specific objectives with 175 briquette samples per block.

Figure 3.2: Chopping water hyacinth using shredder (From ATDC Siaya)

Source: Author, 2015

Polythene sheet to cover hyacinth during rains

Figure 3.3: Decomposing water hyacinth (1mx0.5m3m)

Source: Author, 2015

3.3 Compaction of the briquette

Compaction is densification of biomass and affect combustion properties e.g. burning rate, ignition time etc. Compaction was done using metallic cylindrical mold (Appendix 6) of size 67mm diameter and 40mm tall having holes at the sides and base (for water escape during compaction) with 22.2mm central rod as demonstrated by Chaney *et a.*, (2014). A known quantity (250g) of the briquette mixture (Appendix F4) was added to the cylindrical mold and compressed manually using a press at a pressure of 1Mpa for wet briquetting to create cylindrical hollow briquette of the mold size which was then removed using ejector (Figure 3.4 & Appendix 5). Duration of load application of 40 seconds was observed for a briquette during formation .This was done for all samples.

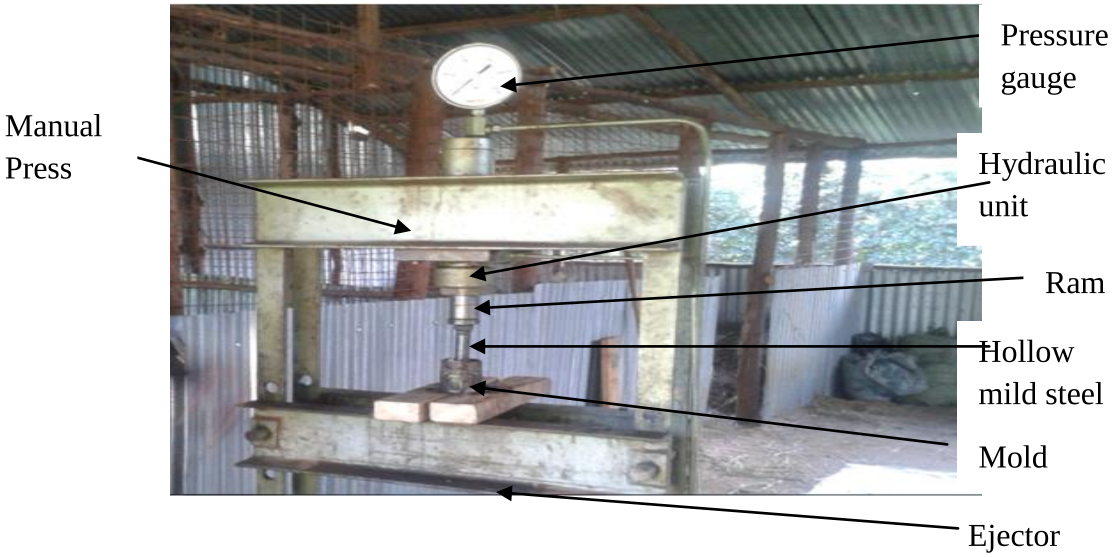

Figure 3.4: Briquetting process using manual Press

Source: Author, 2015

3.4 Physical and Chemical Characteristics of briquette

3.4.1 Chemical characteristics of briquettes

The dried briquette sample from each mixture was crushed using pestle and mortar to ensure homogeneity and sun dried for 7-10 days. Proximate analysis of dry sample weighing 5g was done to determine the percentage moisture content, percentage volatile matter, percentage fixed carbon, percentage ash content and 0.4g for gross calorific value.

3.4.1.1 Percentage Moisture content (PMC)

The moisture content of a solid is defined as the quantity of water per unit mass of the wet solid (wet basis). The moisture content plays an important role in the formation of briquette and subsequently its combustion. High moisture content means a lot of energy needed for water evaporation during combustion at the expense of calorific value of the fuel(<18% recommended), whereas very low moisture content (<10%) need high pressure to compress and therefore expensive and uneconomical. The initial weight of the sample was determined (w_1), and placed in an oven set at 103ºC for 24hours. The sample was removed, cooled in desiccators and reweighed (w_2). Moisture content is then calculated from equation 5 (Khardiwar *et al.,* 2013 & Mitchual *et al.,* 2013).

$$PMC = \frac{(W_1 - W_2)}{W_1} * 100 \tag{5}$$

Where;

w_1 = weight of sample before drying, (5g)

w_2= weight of dried sample, (g)

This was done for 3 replicates for the seven samples

3.4.1.2 Percentage Volatile Matter (PVM)

The resultant masses after the determination of moisture content (3.3.1.1) in a crucible was placed in a muffle furnace set at a temperature of 400°C .The masses of the samples were removed after 30 minutes, cooled weighed and returned. The experiments were run until no more change in weight of samples is observed. The percentage volatile matter (PVM) is then calculated using equation 6 (Lagat *et al.,* 2010, Khardiwar *et al.,* 2013 & Mitchual *et al.,* 2013).

$$PVM = \frac{(b - c)}{a} * 100 \tag{6}$$

Where,

a = initial weight of sample, 5g.

b = final weight of sample after cooling in desiccators (Heating temperature= 103ºC for 24hours).

c = final weight of sample after cooling (Heating temperature= 400°C).

3.4.1.3 Percentage Ash content (PAC)

The temperature in the furnace was then increased to 800^{o}C and the sample left to burn. The masses of the samples were removed after 30minutes, cooled weighed and returned. The procedure was repeated until no more change in weight was observed. The percentage ash content is then evaluated from the final weights and calculated using equation 7 (Khardiwar *et al.*, 2013 & Mitchual *et al.*, 2013).

$$Ash\ content, \% = \frac{weight\ \ of\ ash\ left}{weight\ of\ sample\ taken} *\ 100\% \qquad (7)$$

.

3.4.1.4 Percentage Fixed carbon (PFC)

The percentage fixed carbon (PFC) is computed by subtracting the sum of PVM, PAC and PMC from 100 as shown in equation 8 (Khardiwar *et al.*, 2013 & Mitchual *et al.*, 2013).

$$PFC = 100 - (Volatile\ matter\ \% \ +\ Ash\ content\ \% \ \ +\ Moisture\ \%) \qquad (8)$$

3.4.1.5 Calorific value

Analysis employs application of bomb calorimeter according to ASTM-D5468 (S.S., 1999 & Khardiwar *et al.*, 2013). A known quantity of raw material (0.40g) was added in a crucible and the lid for the bomb closed. Stirrer was started and initial water temperature noted. Current through the crucible was started and fuel sample burnt in the presence of oxygen. Steady state temperature of water (final temperature) was then noted. The Gross calorific value (GCV) of the briquette is calculated using equation 9 (S.S., 1999 & Khardiwar *et al.*, 2013).

$$Gross\ calorific\ value\ (KJ/Kg) = \frac{(M_1+M_2C_W)*\ (T_1-T_2)}{M_S} \qquad (9)$$

Where;

M_1 = Water equivalent of bomb calorimeter (heat capacity of calorimeter obtained from standard experiment), KJ/ ^{o}C

M_2 = Mass of water in copper calorimeter (kg),

T_1 =Initial temperature of water (^{o}C),

T_2 = Final temperature of water (^{o}C),

M_s = Mass of fuel sample taken (kg)

C_w=specific heat capacity of water (KJ/kg ^{o}C)

The tests were done in 3 replicates as above.

3.4.2 Physical characteristics of the Briquettes

3.4.2.1 Equilibrium Moisture Content

Equilibrium moisture content (EMC) is moisture content at which the sample is neither losing nor gaining moisture from the drying air. It depends on temperature and relative humidity of the air. The moisture content plays an important role as explained in (3.3.1.1). Equilibrium moisture content (EMC) of the briquette was determined after 20 days of room drying at 29 ^{o}C room temperature and 58% relative humidity using oven drying method . The initial weight of the sample after drying was measured (w_1), and placed in an oven set at 103ºC for 24hours. The samples were removed and cooled in desiccators then reweighed (w_2). Moisture content of the sample can then be calculated from equation 10 (Khardiwar *et al.*, 2013 & Mitchual *et al.*, 2013).

$$EMC = \frac{(\mathrm{w}_1 - \mathrm{w}_2)*100}{w_1} \tag{10}$$

Where,

w_1 = weight of sample before drying, (g)

w_2= weight of dried sample, (g)

This was done for 3 replicates for all the mixtures.

3.4.2.2 Determination of Bulk density

High density products are desirable in terms of transportation, storage and handling. Bulk density (ρ_{bulk}) is the density of a material when packed or stacked in bulk; it depends on the solid density, geometry, size, surface properties, and the method of measurement. It was determined 20 days after removal from the press and dried.

A stereo metric method was used to determine briquette bulk density. This was chosen over displacement methods in order to ensure the briquettes remain dry. The mass of briquette was determined using laboratory electronic balance (Bosch, PE 625) with accuracy of 0.01g. The diameter was measured at three points; top, centre, and bottom of the sample. Length was also measured at three points. These measurements were done using vernier calipers. The density for each briquette is calculated and the mean density for the 5 briquettes per batch determined and recorded.

$$Density = mass\ of\ sample, g/Volume\ of\ sample, cm^3 \quad (11)$$

3.4.2.3 Compressed density

Compressed density of briquette was determined immediately after removal from the press. High compressed density briquette give low burning rate and therefore good quality. The mass of briquette was determined using laboratory electronic balance (Bosch, PE 625) with accuracy of 0.01g (AppendixF7). The diameter was measured at three points; top, centre, and bottom of the sample. Length was also measured at three points. These measurements were done using vernier calipers. It was calculated as the ratio of measured weight over calculated volume using equation 12 (Mitchual *et al.*, 2013).

$$Compressed\ density = \frac{108000 * M}{(l_1+l_2+l_3) * \pi * \left(\left(d_1+d_2+d_3\right)^2 - (3d)^2\right)}\ \mathrm{g}/cm^3 \quad (12)$$

Where, d_1 , d_2 and d_3 are diameters of briquettes at the three points respectively and d is the internal diameter measured in millimeters. l_1 , l_2 and l_3 are lengths of briquettes at three points measured in millimeters and M is the mass of briquette in grammes. This was done for 3 replicates for all the mixtures.

3.4.2.4 Relaxed density

Relaxed density of briquette was determined 20 days after removal from the press and dried. The procedure is like that for determining compressed density (Mitchual *et al.*, 2013).

$$Relaxed\ density = \frac{108000 * M}{(l_1+l_2+l_3) * \pi * \left(\left(d_1+d_2+d_3\right)^2 - (3d)^2\right)}\ \mathrm{g}/cm^3 \quad (13)$$

Where, d_1 , d_2 and d_3 are diameters of briquettes at the three points respectively and d is the internal diameter measured in millimeters. l_1 , l_2 and l_3 are lengths of briquettes at three points measured in millimeters and M is the mass of briquette in grammes.

Relaxed density and compressed density are parameters used to characterize briquettes. High relaxed density implies that the briquette has good dimensional stability and therefore stable as a product giving low relaxation ratio (the product is good if the ratio is approaching one).It was calculated using equation 14.

$$Relaxation\ ratio = Compressed\ density/Relaxed\ density \tag{14}$$

3.4.2.5 Durability index

Durability is the measure of the ability of briquette to withstand mechanical handling. This test is done to minimize losses and preserve quality of the product during handling and storage. It is a function of moisture content and density. High moisture content reduces durability whereas high density enhances it. Briquettes durability index was measured according to ASTM D440-86(2002) of drop shatter developed for coal (WMB-. 314. Pdf & Davies *et al.,* 2013). The test was conducted after two weeks of briquettes samples formation. A test sample of five briquettes of known weight (W_1) was placed in a plastic polythene bag. The bag was dropped from a height of 2m onto concrete floor three times. After the dropping, the briquettes and fractions was placed on top of a 35mm square mesh screen and sieved. The experiment was replicated three times. The durability rating for each type of briquette is expressed as the ratio of weight of material retained on the screen (W_2) to weight of briquettes before the dropping. The handling durability of the briquettes was computed using equation 15 (WMB-314. Pdf & Davies *et al.,* 2013).

$$Durability\ index, \% = \frac{W_2}{W_1} \tag{15}$$

Durability of 80-90% is considered good and anything above 90% is very good (Frank *et al.,* 2013)

3.4.2.6 Water resistance

The resistance to humidity is traditionally tested in immersion tests, i.e. the briquettes are dunked in water and the elongation or swelling of the briquettes is recorded. Sometimes the time elapses until the briquette has completely disintegrated (Eriksson *et al,* 1990). Water resistance is the measure of water absorptive capacity of sample when immersed in water. High absorption of water may lead to significant disintegration.

Water resistance of dry briquettes was determined by immersing one sample per batch each in a glass container filled with water at room temperature for 2 minutes .Weight of briquette was measured before and after immersion in water using laboratory electronic weighing balance. This was replicated 3 times. The percent water gain is calculated and recorded by using equation 16 and then percentage resistance to water penetration is calculated using equation 17 (WMB-314. Pdf & Khardiwar *et al.*, 2013).

$$Weight\ gain\ by\ briquette\ ,\% = \frac{W_2-W_1}{W_1} * \ 100 \qquad (16)$$

Where;

W_1 = Initial weight of briquette, g

W_2 = Weight of wet briquette, g

$$Resistance\ to\ water\ penetration, \% = 100 - \%\ water\ gain \qquad (17)$$

3.5 Combustion and Emission characteristics of the briquette

This test was carried out at Chiromo campus, University of Nairobi. In order to test combustion and Emission characteristics, the apparatus were arranged as shown in the diagram below (Figure 3.5). Carbon Monoxide meter **(**EL-USB-CO), Carbon dioxide (Model 7545) meter and Particle sensor (UCB-PATS) were mounted on a string 1.5m above the ground and 1metre away from a thermocouple as shown in the diagram (Figure 3.5, Appendix E & F8).This was done to ensure there is no interference of heat from the stove. Briquette sample was placed in the cooking stove and fire lit using 30g of ethanol gel, noting the mass of stove both before and after putting the briquette sample. Initial temperature, carbon dioxide and carbon monoxide were noted from the instruments and then recorded before start of the experiments. These measuring instruments were later removed after the end of the experiments and connected to a laptop and data downloaded using software installed (Appendix C1).

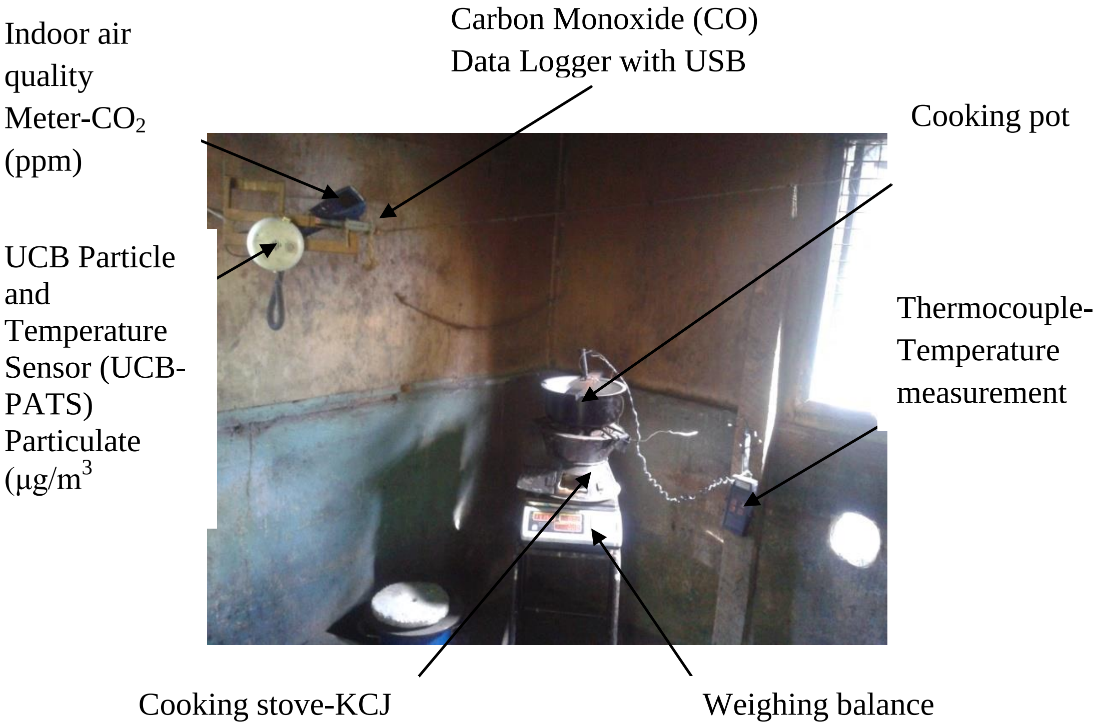

Figure 3.5: Gas analysis, cooking test, Ignition time and Burn rate data collection.

Source: Author, 2016

3.5.1 Ignition Time

Ignition time is the time taken to reach the ignition temperature or when the flame begins to flare from the fuel. In each test, briquette sample was placed in the cooking stove and fire lit using 30g of ethanol gel ensuring that the whole of the bottom surface of the briquette is ignited simultaneously. This was left until briquette just entered into steady state burning phase and the time taken noted. This was done for 3 replicates for all the mixtures (Figure 3.5).

3.5.2 Burn Rate

This is the rate at which a certain mass of fuel is combusted in air. If it is low, then it means the briquette has high energy density and therefore good quality. Fuel burn rate was determined using the above experiment set up (Figure 3.5). Initial weight of briquette sample and weight of stove before lighting was recorded. Fire was lit and time taken to boil water and weight of stove after boiling water was recorded. Weight loss at the end of boiling time was computed and burn rate calculated from equation 18 (Davies *et al.*, 2013).

$$BR = Total\ mass\ of\ burnt\ briquette/burning\ time = \frac{Q_1 - Q_2}{T} \qquad (18)$$

Where;

BR = Burning rate, g/min

Q1 = Initial weight of fuel prior to burning (g)

Q2 = Final weight of fuel after burning (g)

T = Total burning time (min).

This was done for 3 replicates for all the mixtures.

3.5.3 Water boiling test

To evaluate cooking potential of briquette mixture and combustion efficiency, 2.5 litres of water was boiled in a cooking pot on a cooking stove. Water temperature at the start of the experiment and at the start of boiling point was recorded using a thermocouple in arrangement as per the above diagram (Figure 3.5). Time taken for water to reach boiling temperature of 94 ^{o}C was also recorded; this is the water boiling point in Nairobi. This was done for 3 briquettes per batch for all the mixtures.

3.5.4 Emission characteristics

Flue gas emitted during burning was analyzed by using the arrangement described in paragraph 3.5 above (Figure 3.5). The instruments were read before and after boiling water and CO_2, CO and particulate matter recorded. This was done in 3 replicates for all the mixtures.

3.6 Data Analysis

Statistical analysis software (SAS) was used to analyze data and Analysis of Variance (ANOVA) at 95% confidence level done on treatment means for each parameter. To determine whether there was significant difference in the means, Duncan's Multiple Range Test (DMRT) was performed at 5% level. The parameters were also comparatively evaluated against documented values. Sample SAS results are discussed in chapter 4 (Gemes, Gemes, 1983 & Douglas, Montgomery, 2003).

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Physical and Chemical Characteristics of briquette

4.1.1 Chemical characteristics of briquettes

Chemical test results are shown below (Table 4.1).

4.1.1.1 Proximate analysis, calorific values of sun-dried briquette

Table 4.1: Proximate and calorific values of sun-dried briquette against blending ratio

Blending Ratio	calorific value ,MJ/Kg	Ash content %	Moisture content %	Volatile matter %	Fixed carbon %
60:30:10	20.835	19.43	6.39	32.6	41.58
60:20:20	19.16	21.27	7.25	35.5	35.98
60:10:30	17.585	17.62	6.95	40.00	35.43
70:20:10	21.585	21.25	6.41	38.84	33.50
70:10:20	18.42	22.47	9.30	38.00	30.23
80:10:10	18.99	23.2	7.58	35.12	34.10
100:00:00	16.215	17.17	10.34	41.7	30.79

Calorific values are ranging from 16.215 - 21.585 MJ/kg (Table 4.1) which is within the range for charcoal and other agricultural wastes (15 - 30MJ/kg) as shown in the appendix A1. Apart from water hyacinth (100:00:00), the other calorific values are fulfilling the minimum requirement of calorific value for making commercial briquette (>17.50 MJ/Kg) as given by Mitchual *et al.,* (2013). Water hyacinth alone (100:00:00) has given a very good calorific value compared to what was obtained by Frank *et al* , (2013) of 13.4MJ/Kg. This may have been possible due to increased density after partial decomposition.

It was expected that mixture of 60:30:10 having 30% charcoal would have high calorific value but instead 70:20:10 are giving higher calorific value probably due to its bonding i.e this observation could be adduced to porosity exhibited between inter and intra–particles which enable easy infiltration of oxygen and out flow of combustion briquettes .

4.1.2 Physical characteristics of the Briquettes

These properties relate to fact that the briquettes should not crumble and disintegrate when handled, stored and transported, and is mainly a function of the quality of the densification process for a given raw material. The results are discussed below;

4.1.2.1 Equilibrium Moisture Content (%)

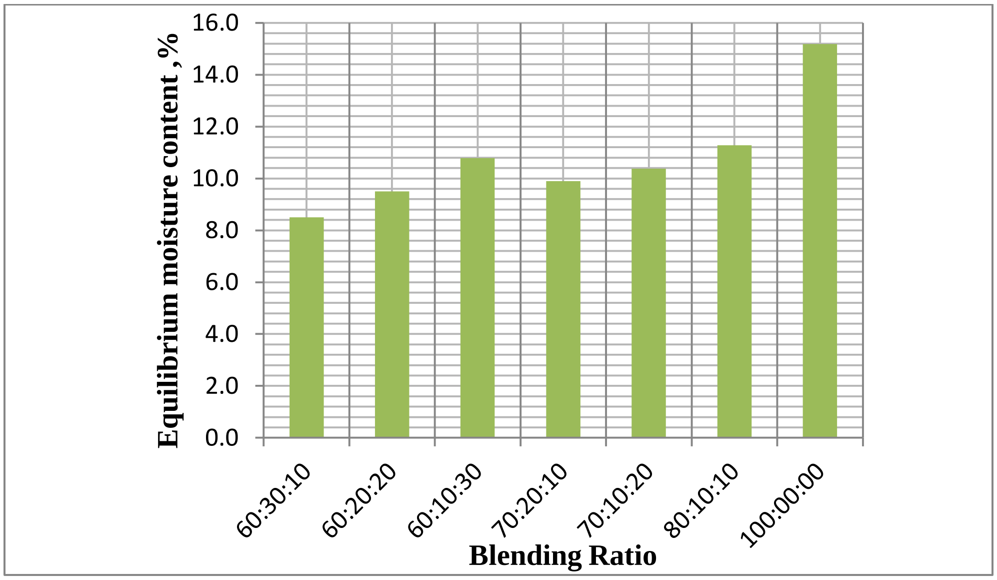

Figure 4.1: Equilibrium moisture content against blending ratios

Mean equilibrium moisture content at temperature of 29 ^{o}C and 58% Relative humidity range from 8.5% to15.2% (Figure 4.1). For good storability and combustibility of briquettes, equilibrium moisture content of <18% recommended by Khardiwar *at al.*, (2013) and therefore the briquettes produced fall within range .There is a general increase in equilibrium moisture content with increase in cow dung and water hyacinth, the latter (100:00:00) showing the highest equilibrium moisture content of 15.2%. It can also be concluded from the results that equilibrium moisture content decreases with increase in charcoal dust. The lowest equilibrium moisture content was given by the mixture of 60:30:10 having 30% charcoal dust. Antonio *et al.*, (2014) concluded that environmental conditions and particle size range strongly influence the moisture at equilibrium and the uptake rates. The smaller the feedstock particles, the higher the moisture content at equilibrium and the moisture uptake rate. This probably explains why materials with high water hyacinth and cow dung ratios have high equilibrium moisture contents. The two materials soften more reducing their particle sizes when water is added to them compared to charcoal dust.

4.1.2.2 Bulk density (g/cm^3)

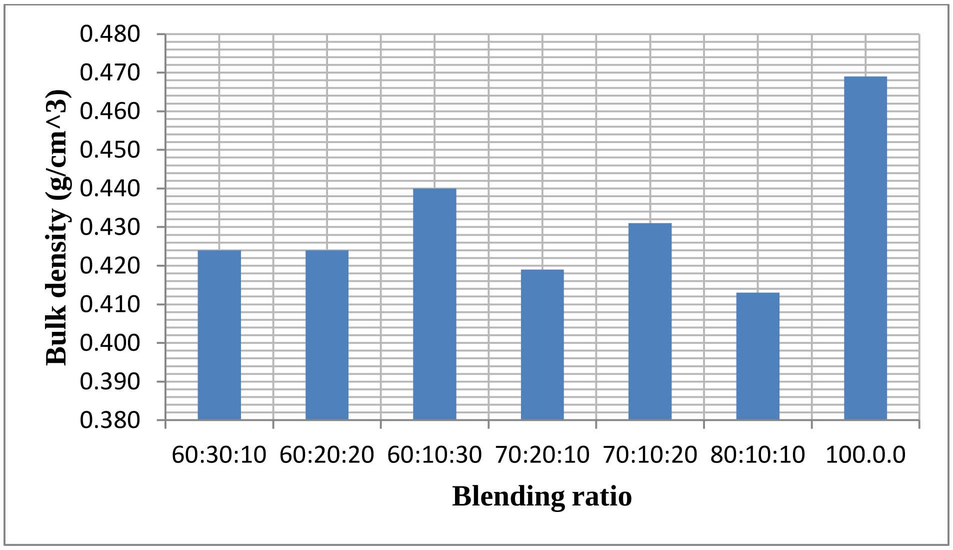

Figure 4.2: Bulk density against blending ratios

Mean bulk density range from 0.413 g/cm^3 to 0.469 g/cm$^{3.}$ The densities are low due low compression pressure of 1Mpa.It is seen that within the same water hyacinth ratio, bulk density reduces with increased charcoal dust. However, Water hyacinth alone has surprisingly the highest bulk density. This is due to high shrinkage (reduction in volume) with corresponding heavy loss in weight probably as a result of partial decomposition (Figure 4.2).

Anova table (Appendix D8) shows that at $\propto = 0.05$, blending ratio(P-value,0.0076 $<\propto = 0.05$) and blocking (P-value,0.2282 $>\propto = 0.05$) have significant effect on bulk density, otherwise means of blending ratios apart from that of water hyacinth alone are not significantly different using Duncan's Multiple Range Test (Appendix E1)

4.1.2.3 Compressed density (g/cm^3)

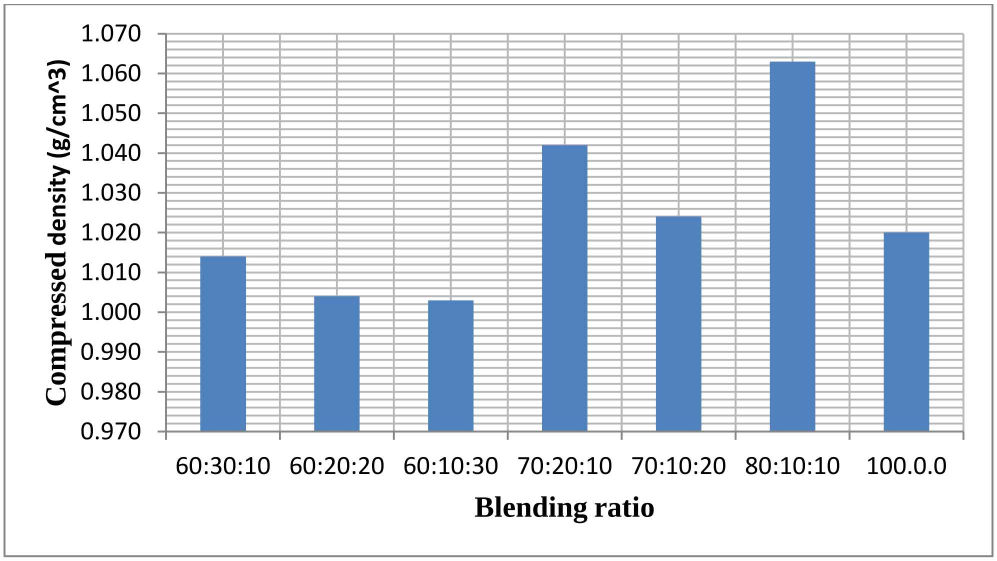

Figure 4.3: Compressed density against blending ratios

The experiment shows that, compressed density range from 1.003 g/cm^3 to 1.063 g/cm^3 (Figure 4.3). It is difficult to attach any sequence in relation to proportion of water hyacinth. However, it can be seen that at 60% and 70% water hyacinth, compressed density reduces with increase in cow dung.

4.1.2.4 Relaxed density (g/cm^3)

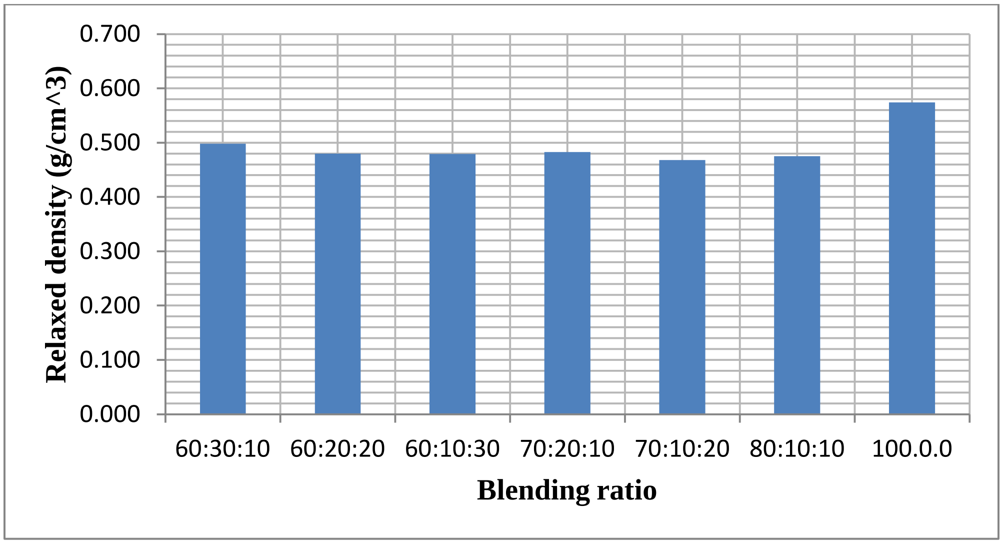

Figure 4.4: Relaxed density against blending ratios

Relaxed density and compressed density are parameters used to characterize briquettes. High relaxed density implies that the briquette has good dimensional stability and therefore stable. Mean relaxed densities are ranging from 0.468g/cm^3-0.574g/cm^3.The densities are low due low compression pressure of 1Mpa.

Anova table (Appendix D 9) shows that at ∝= 0.05, blending ratio (P-value,0.0013<∝= 0.05) and blocking (P-value,0.1933 >∝= 0.05) have significant effect on relaxed density otherwise means of blending ratios 60:30:10,60:20:20,60:10:30,70:20:10, 70:10:20 and 80:10:10 are not significantly different using Duncan's Multiple Range Test(Appendix E2))

4.1.2.5 Relaxation ratio

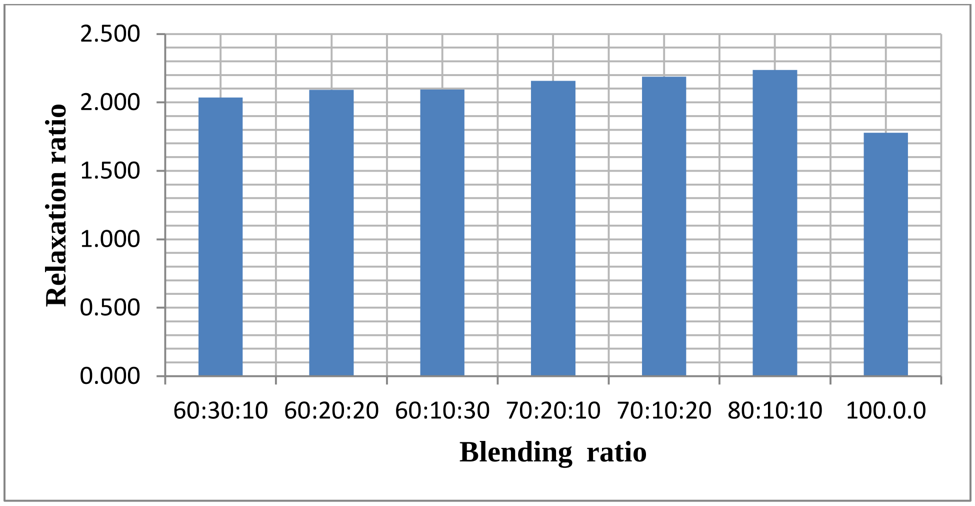

Figure 4.5: Relaxation ratio against blending ratios

There is a general trend in increments of relaxation ratio as we increase water hyacinth and cow dung (Figure 4.5). However, Water hyacinth alone has surprisingly the highest relaxed density and lowest relaxation ratio. This is probably due to high shrinkage (reduction in volume) with corresponding heavy loss in weight probably as a result of partial decomposition (Figure 4.4 & 4.5).

The other mixtures lost weight by nearly 50% with less than 10% loss in volume.

Anova table (Appendix D10) shows that at∝= 0.05, blending ratio (P-value, 0.0054<∝= 0.05) have significant effect on relaxation ratio and blocking (P-value, 0.0454≈ ∝= 0.05) have no significant effect on relaxation ratio otherwise means of blending ratios 60:30:10,60:20:20,60:10:30,70:20:10, 70:10:20 and 80:10:10 are not significantly different using Duncan's Multiple Range Test (Appendix E3)

4.1.2.6 Durability index (%)

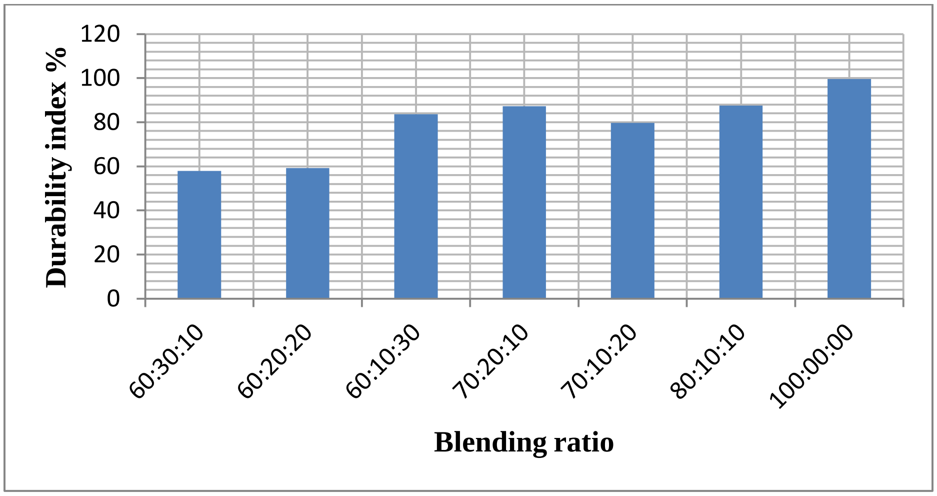

Figure 4.6: Durability index against blending ratios

Durability is a function of bond strength between constituent parts of briquette. Durability index of 80-90% is considered good and anything above 90% is very good. Mean durability index for this experiment is ranging from 57.88% to 99.6% (Figure 4.6). The ratios 60:30:10 and 60:20:20 are exhibiting poor index probably due to high charcoal dust content which has low bonding as confirmed by Eriksson *et al.*, (1990). The rest of mixtures have 80% and above, with water hyacinth (100:0:0 ratio) showing the highest durability index of 99.63% probably because of partial decomposition which increases the binding effect of biomass.

Anova table (Appendix D11) shows that at $\propto = 0.05$, blending ratio (P-value 0.0001 $<\propto = 0.05$) and blocking (P-value,0.3433$>\propto = 0.05$) have significant effect on durability otherwise means of blending ratios 60:10:30, 70:20:10, 70:10:20 and 80:10:10 are not significantly different using Duncan's Multiple Range Test (Appendix E4)

4.1.2.7 Water resistance (%)

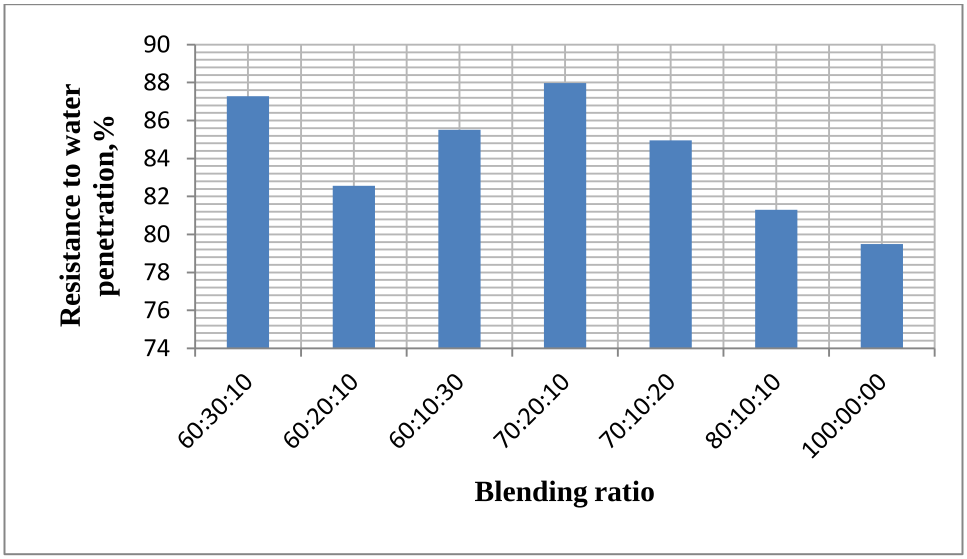

Figure 4.7: Resistance to water penetration against blending ratios.

Mean percentage Resistance to water penetration for 2minutes range from 75.29% to 88.09% and therefore the briquettes have very low absorptive capacity (Figure 4.7). The relatively high resistance of the briquettes to water penetration may be due to the presence of water hyacinth in the briquettes. Water hyacinth is known to have a high cellulose content of range of 17.1 to 31% according to Frank *et a*l., (2013). However, mixtures 60:30:10 and 70:20:10 have highest resistance to water penetration whereas water hyacinth alone shows the least resistance most likely because of partial decomposition which softens the cellulose.

Anova table (Appendix D12) shows that at ∝= 0.05, blending ratio has no significant effect on water resistance (P-values 0.0922>∝= 0.05) and blocking has significant effect on water resistance (P-values 0.7092>∝= 0.05), otherwise means of blending ratios 60:30:10,60:10:30, 70:20:10 and 70:10:20 are not significantly different using Duncan's Multiple Range Test (Appendix E5).

4.2 Combustion and Emission characteristics of briquette

4.2.1 Combustion characteristics

4.2.1.1 Ignition time (Minutes)

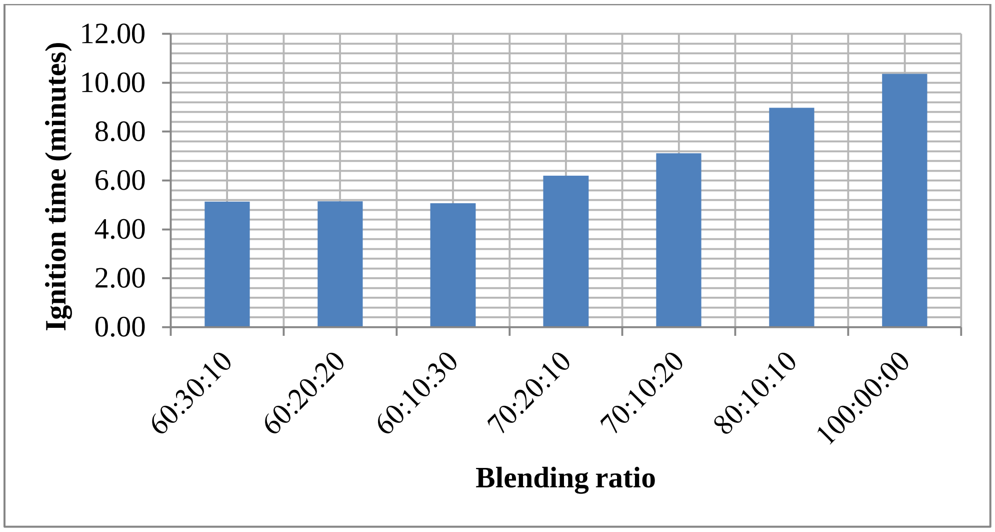

Figure 4.8: Ignition time (Minutes) against blending ratio

There is a steady rise in ignition time as the amount of water hyacinth is increased probably due to its high density caused by partial decomposition and therefore high shrinkage. The ignition time is ranging from 5.07 minutes to 10.37 minutes and it can also be said that briquettes with high charcoal content ignite faster (Figure 4.8).Charcoal is found by Davies *et al.*, (2013) to have higher ignition time compared to other farm residues, however, this scenario differ with the composite briquette tested and therefore importance of blending.

Anova table shows (Appendix D4) that at$\propto = 0.05$, blending ratio (P-value, $0.001 < \propto = 0.05$) and blocking (P-values, $0.6746 > \propto = 0.05$) have significant effect on ignition time. Means of some blending ratios of water hyacinth are not significantly different using Duncan's Multiple Range Test (Appendix E7). Blending ratio 100:0: 0 of water hyacinth has the highest ignition time probably due its high density.

4.2.1.2 Boiling time (Minutes)

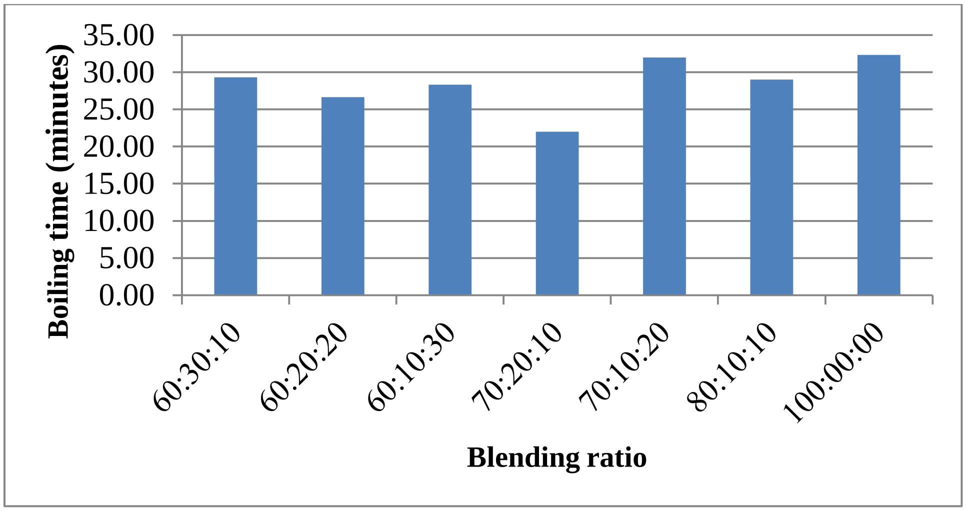

Figure 4.9: Boiling time (Minutes) against blending ratio

Boiling time ranges between 22minutes to 32.33minutes (Figure 4.9). There is no specific trend that exists from the experimental results. It could be inferred that biomass having highest calorific value does not guarantee shortest water boiling time and this is compatible with results obtained by confirmed Davies *et al.*, (2013). However, blending ratio of 70:20:10 has shortest boiling time and blending ratio 100:0: 0 of water hyacinth having the highest boiling time implying general low heat value.

Anova table shows (Appendix D3) that at ∝= 0.05, blending ratio(P-value,0.1696 >∝= 0.05), and blocking (P-value,0.3638 >∝= 0.05), have significant effect on boiling time otherwise means of blending ratios 60:30:10,60,20,20,60:10:30, and 80:10:10 are not significantly different using Duncan's Multiple Range Test (Appendix E6)

4.2.1.3 Burn rate (g/minutes)

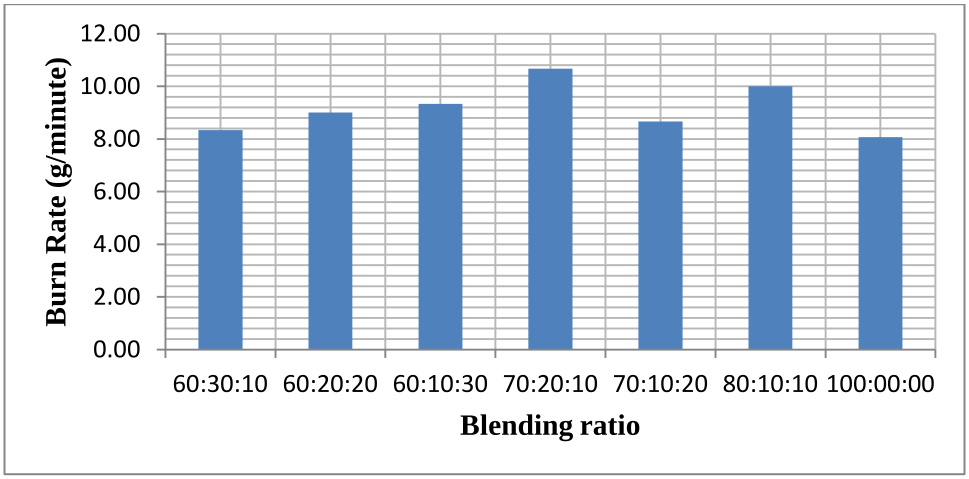

Figure 4.10: Burn rate against blending ratio

Mean burn rate figures vary from 8.33 g/min to 10.67g/min (Figure 4.10) .The trend is very clear with 60:30:10,60:20:20 and 60:10:30 an indication that burn rate decreases with increasing charcoal dust or increases with increasing cow dung value. 60:30:10 briquette ratios have low burn rate which implies it has high energy density and therefore good quality, whereas 70:20:10 has the highest burn rate. This latter observation could be adduced to porosity exhibited between inter and intra–particles which enable easy infiltration of oxygen and out flow of combustion briquettes. 100:00:00 briquette ratios (water hyacinth) have given the lowest burn rate probably due to the fact that it has significantly shrunk and become dense.

Anova table (Appendix D2) shows that at ∝= 0.05, blending ratio (P-value,0.1962 >∝= 0.05) and blocking (P-value,0.7377 >∝= 0.05) have significant effect on burn rate otherwise means of blending ratios 60,20,20,60:10:30, 70:20:10,70:10:20 and 80:10:10 are not significantly different using Duncan's Multiple Range Test (Appendix E8)).

4.2.2 Emission characteristics

4.2.2.1 Particulate matter (µg/m^3)

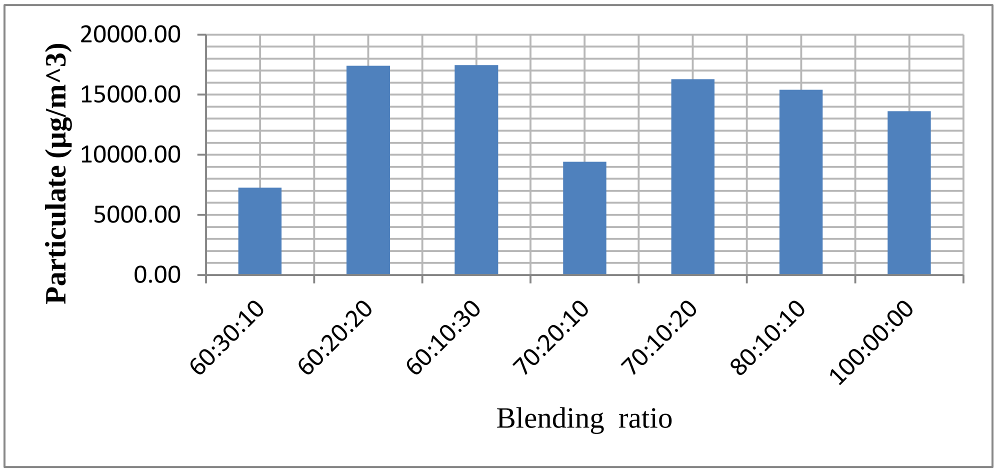

Figure 4.11: Particulate matter (PM$_{2.5)}$ against Blending Ratio

The particulates range between 7264µg/m^3 and 17445.8µg/m^3.There is no particular trend exhibited by the mixtures on particulates but it's clear from the test results that 60:30:10 with 30% charcoal dust and 70:20:10 with 20% charcoal dust have lower particulate matters of 7264µg/ m^3 and 9422µg/ m^{3}respectively (Figure 4.11).Charcoal dust is known to have low particulate matter as confirmed by Pennise *et al.*, (2012) and Njenga *et al.*, (2013). The mixture 60:10:30 has the highest particulate matter most probably due to high cow dung content. Water hyacinth alone (100:00:00) has ranked third which is a good indication on emission characteristics.

Anova table shows (Appendix D5) that at $\propto = 0.05$, blending ratio (P-values 0.0248$\approx \propto = 0.05$) has no significant effect on particulate matter while blocking (P-values 0.1348 $> \propto = 0.05$) has significant effect on particulate matter (Appendix E9).

4.2.2.2 Carbon monoxide (ppm)

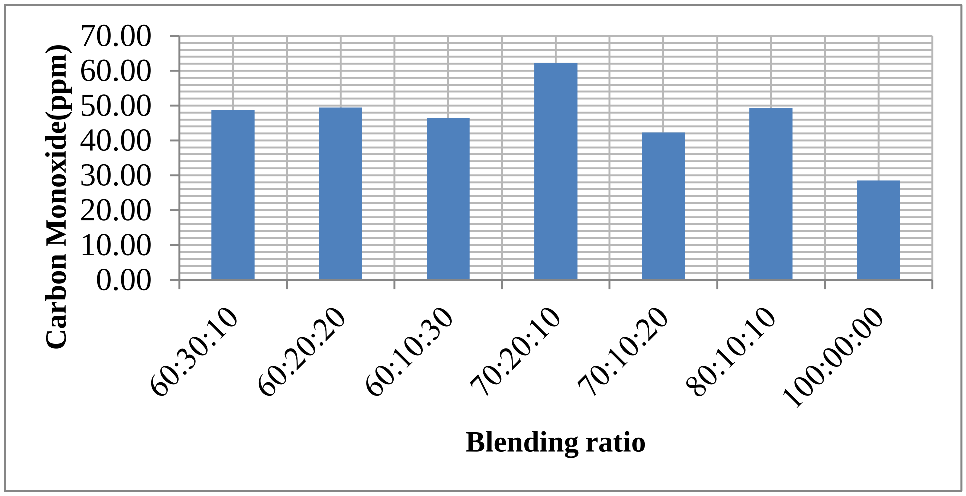

Figure 4.12: Emission characteristics against blending ratios

Mean Carbon monoxide (CO) range from 28.51ppm to 62.21ppm with water hyacinth (100:0:0) having the lowest value and mixture of 70:20:10 having the highest value (Figure 4.12). There is no general trend attached to carbon monoxide .However, it is clear from the graph that briquettes with high carbon (charcoal dust) have high carbon monoxide.

The Anova table (Appendix D6) shows that at $\propto = 0.05$, blending ratio (P-value 0.0022<$\propto = 0.05$) has significant effect on carbon monoxide while blocking (P-values 0.0803 >$\propto = 0.05$) has no significant effect. Means of blending ratios 60:30:10, 60:20:20, 60:10:30, 70:10:20 and 80:10:10 are not significantly different using Duncan's Multiple Range Test (Appendix E10).

4.2.2.3 Carbon dioxide (ppm)

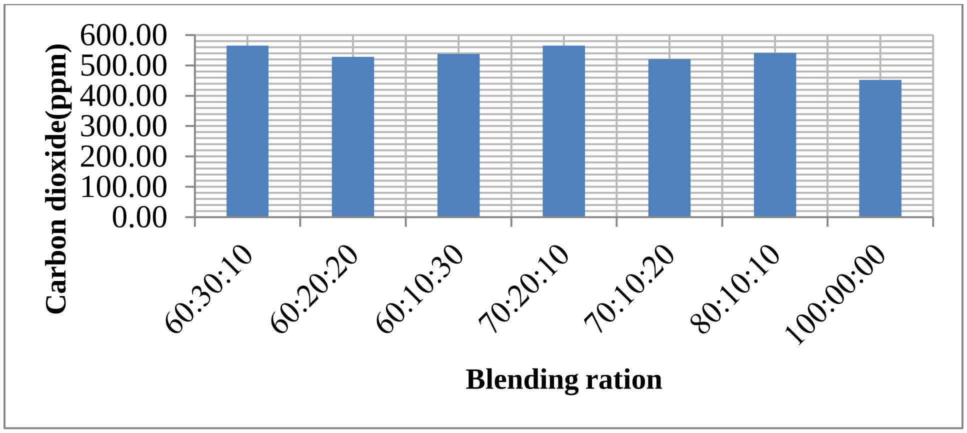

Figure 4.13: Carbon dioxide (ppm) against blending ratio

Mean Carbon dioxide (CO_2) range from 452.80ppm to 564.87ppm with water hyacinth (100:0:0) having the lowest value and mixture of 60:30:10 having the highest value (Figure 4.13). There is no general trend attached to Carbon dioxide.

The Anova table (Appendix D7)shows that at $\propto = 0.05$, blending ratio(P-values $0.0427 \approx \propto = 0.05$) has no significant effect on carbon dioxide while blocking (P-values $0.3223 > \propto = 0.05$) has significant effect though means of blending ratios 60:30:10, 60:20:20, 60:10:30, 70:20:10,70:10:20 and 80:10:10 are not significantly different using Duncan's Multiple Range Test (Appendix E11)

4.3 Optimal mix

SAS rank based method was used to determine the composition of the briquette mixture that gives optimal combustion, emission and physical characteristics. The treatments were scored one to seven, where one represent the best mixture for the treatment response and seven represent worst mixtures for the same treatment response. The averages for all the treatment response scores were then obtained and ranking done (Table 4.14, 4.15, 4.17). The mixture of 60:30:10 was found to be the optimal combustion mixture followed by 60:20:20 and 70:20:10. Similarly, 100:0:0 was found to be the mixture that gave optimal emission characteristics and therefore environmentally friendly, it is also the mixture that gave optimal physical characteristics followed by 70:20:10 and then 60:30:10. This can be attributed to the high density of water hyacinth as a result of partial decomposition which increases the bonding effect.

Table 4.2: Results of combustion/emission characteristic

Blending Ratio	Boiling time (min)	calorific value (MJ/Kg)	Burn Rate (g/min)	Ignition Time (min)	CO (ppm)	CO2 (ppm)	Particulate (μg/m^3)
60:30:10	29.33	20.835	8.33	5.13	48.71	564.94	7264.93
60:20:20	26.67	19.160	9.00	5.15	49.46	528.44	17394.05
60:10:30	28.33	17.585	9.33	5.07	46.54	537.62	17445.80
70:20:10	22.00	21.585	10.67	6.20	62.21	564.87	9422.69
70:10:20	32.00	18.420	8.67	7.12	42.30	520.61	16284.01
80:10:10	29.00	18.990	10.00	8.98	49.28	540.95	15420.27
100:00:00	32.33	16.215	8.07	10.37	28.51	452.80	13622.66

Table 4.3: Rank based method for assessing combustion characteristics

	Boiling time (min)	calorific value MJ/Kg	Burn Rate (g/min)	Ignition Time (min)	Mean rank	Variance	Rank
60:30:10	5	2	2	2	2.75	2.25	1
60:20:20	2	3	4	3	3	0.67	2
60:10:30	3	6	5	1	3.75	4.92	4
70:20:10	1	1	7	4	3.25	8.25	3
70:10:20	6	5	3	5	4.75	1.58	5
80:10:10	4	4	6	6	5	1.33	6
100:00:00	7	7	1	7	5.5	9.00	7

Table 4.4: Rank based method for assessing Emission characteristics

Blending ratio	CO (ppm)	CO2 (ppm)	Particulate (µg/m^3)	Mean rank	Variance	Rank
60:30:10	4	7	1	4.00	9.00	3
60:20:20	6	3	6	5.00	3.00	6
60:10:30	3	4	7	4.67	4.33	4
70:20:10	7	6	2	5.00	7.00	6
70:10:20	2	2	5	3.00	3.00	2
80:10:10	5	5	4	4.67	0.33	5
100:00:00	1	1	3	1.67	1.33	1

Table 4.5: Results of Physical characteristics

Blending Ratio	Bulk density	Condensed density	Relaxed density	Relaxed ratio	Durability index	Resistance to water Penetration %
60:30:10	0.424	1.014	0.498	2.036	57.88	87.28
60:20:20	0.424	1.004	0.480	2.092	59.23	82.56
60:10:30	0.440	1.003	0.479	2.094	83.62	85.52
70:20:10	0.419	1.042	0.483	2.157	87.23	87.98
70:10:20	0.431	1.024	0.468	2.188	79.66	84.95
80:10:10	0.413	1.063	0.475	2.238	87.61	81.29
100:00:00	0.469	1.020	0.574	1.777	99.63	79.49

Table 4.6: Rank based method for assessing Physical characteristics

Blending Ratio	Bulk density	Condensed density	Relaxed density	Relaxed ratio	Durability index	Resistance to water Penetration %	Mean rank	Variance	Rank
60:30:10	2	5	2	2	7	2	3.33	4.67	3
60:20:20	4	6	4	3	6	5	4.67	1.47	4
60:10:30	5	7	5	4	4	3	4.67	1.87	4
70:20:10	3	2	3	5	3	1	2.83	1.77	2
70:10:20	6	3	7	6	5	4	5.17	2.17	6
80:10:10	7	1	6	7	2	6	4.83	6.97	5
100:00:00	1	4	1	1	1	7	2.50	6.30	1

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusions

This study demonstrates that water hyacinth can be utilized alone or as composite briquette instead of other traditional fuel energy for domestic application. The mixture that gives optimal combustion characteristics was found to be 60:30:10 and this was followed closely by 60:20:20.Water hyacinth alone (100:0:0) gave the best emission characteristics and therefore environmentally friendly.

For quality control, the water hyacinth composite briquette gave good indications on physical parameters that were measured e.g. shattering index, densities, relaxation ratio. The water hyacinth briquettes possess high material strength (shattering index) as well as high value combustible fuel as can be seen from the experiment.

5.2 Recommendation

Based on the findings of this study and the conclusions made ;the production of water hyacinth composite briquettes and its utilization could be advocated since its usage as solid biofuel, will alleviate the menace caused by this aquatic plant.

A possibility of combining water hyacinth and a material of good combustion (to enhance its calorific value) and emission characteristics can be explored due to the good emission characteristics exhibited by the weed**.**

Utilization of water hyacinth as a composite briquette could also enhance: rural economic development, farm income, and market diversification, reduction in agricultural surplus, reduced negative environmental impact and creation of employment opportunities in the area of production, harvesting and utilization.

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APPENDIX

Appendix A: Estimated animal wastes by Region

Appendix A1: Estimated annual production of animal wastes by Regions in Kenya in Millions of tons dry weight.

Regions	Cattle	Sheep and Goats	Poultry	Donkeys	Camel
Nyanza	1.66	0.06	0.07	0.01	0.00
Western	1.44	0.20	0.05	0.00	0.00
Central	1.33	0.07	0.02	0.00	0.00
Nairobi	0.03	0.00	0.00	0.00	0.00
Eastern	0.10	0.22	0.06	0.02	0.29
Coast	0.22	0.05	0.02	0.00	0.00
Rift valley	4.31	0.37	0.02	0.07	0.29
N. Eastern	0.22	0.02	0.00	0.00	014
Total	**9.31**	**0.99**	**0.24**	**0.10**	**072**

Source: (Energy and Development in Kenya, 2000)

Appendix B: Calorific value and ash content of various fuels

Appendix B1: Calorific value and ash content of various fuels. (Barnard 85)

Material	**Ash Content %**	**HCV MJ/kg (oven dry)**	**Material**	**Ash Content %**	**HCV MJ/kg**
Alfalfa straw	6.0	18.4	Olive pits	3.2	21.4
Almond shell	4.8	19.4	Pigeon pea stalks	2.0	18.6
Cassava stem	-	18.3	Rice straw	-	15.2
Coconut shell	0.8	20.1	"	19.2	15.0
Coconut husk	6.0	18.1	Rice husks	-	15.3
Cotton stalks	17.2	15.8	"	16.5	15.5
"	3.3	17.4	"	14.9	16.8
Groundnut shells	-	19.7	Soybean stalks	-	19.4
"	4.4	20.0	Soybean stalks	-	19.4
Maize stalks	6.4	18.2	Sunflower straw	-	21.0
"	3.4	16.7	Walnut shells	1.1	21.1
Maize cobs	1.5	18.9	Wheat straw	-	18.9
"	1.8	17.4	"	8.5	17.2

Source: The briquetting of Agricultural wastes for fuel.FAO Rome, Italy by Erikssion,S, and M.Prior,(1990).

Appendix C: Arrangement for downloading Emission data

Appendix C1: downloading emission data

UCB Particle and Temperature Sensor
(UCB-PATS), Particulate (µg/m3)

Thermocouple-Temperature
measurement

Carbon
Monoxide (CO)
Data Logger

Lap top

Indoor air quality
Meter-CO_2 (ppm

Source: Author, 2016

Appendix D: Anova tables

Appendix D1: Calorific value

SOURCE	DF	SS	MS	F-VALUE	Pr>F
TERATMENT	6	60.4911	10.08185	6.46	0.0031
BLOCK	2	3.87165171	1.93582586	1.24	0.3237
ERROR	12	18.71952229	1.55996019		

Coeff Var 6.58399

Appendix D2: Burn rate

SOURCE	DF	SS	MS	F-VALUE	Pr>F
TERATMENT	6	15.41573333	2.56928889	1.73	0.1962
BLOCK	2	0.92460952	0.46230476	0.31	0.7377
ERROR	12	17.77432381	1.48119365		

Coeff Var 13.2962

Appendix D3: Boiling time

SOURCE	DF	SS	MS	F-VALUE	Pr>F
TERATMENT	6	220.5714286	36.7819048	1.86	0.1696
BLOCK	2	43.5238095	21.7619048	1.17	0.3638
ERROR	12	237.1428571	19.7619048		

Coeff Var 15.585

Appendix D4: Ignition

SOURCE	DF	SS	MS	F-VALUE	Pr>F
TERATMENT	6	79.27525714	13.21254286	34.46	<.0001
BLOCK	2	0.31202857	0.15601429	0.41	0.6746
ERROR	12	4.60157143	0.38346429		

Coeff Var 9.028774

Appendix D5: Particulate matter

SOURCE	DF	SS	MS	F-VALUE	Pr>F
TERATMENT	6	79.27525714	13.21254286	34.46	<.0001
BLOCK	2	0.31202857	0.15601429	0.41	0.6746
ERROR	12	155575561.6	12964630.1		

Coeff Var 26.02308

Appendix D6: Carbon monoxide

SOURCE	DF	SS	MS	F-VALUE	Pr>F
TERATMENT	6	1826.604114	304.434019	6.97	0.0022
BLOCK	2	273.671771	136.835886	3.13	0.0803
ERROR	12	523.892029	43.657669		

Coeff Var 14.14384

Appendix D7: Carbon dioxide

SOURCE	DF	SS	MS	F-VALUE	Pr>F
TERATMENT	6	25996.89353	4332.81559	3.16	0.0427
BLOCK	2	3420.27527	1710.13763	1.25	0.3224
ERROR	12	16470.61707	1372.55142		

Coeff Var 6.989742

Appendix D8: Bulk density

SOURCE	DF	SS	MS	F-VALUE	Pr>F
TERATMENT	6	79.27525714	13.21254286	34.46	<.0001
BLOCK	2	0.31202857	0.15601429	0.41	0.6746
ERROR	12	0.00243524	0.00020294		

Coeff Var 3.302684

Appendix D9: Relaxed density

SOURCE	DF	SS	MS	F-VALUE	Pr>F
TERATMENT	6	0.02416724	0.00402787	7.87	0.0013
BLOCK	2	0.00193457	0.00096729	1.89	0.1933
ERROR	12	0.00613876	0.00051156		

Coeff Var 4.57982

Appendix D10: Relaxation ratio

SOURCE	DF	SS	MS	F-VALUE	Pr>F
TERATMENT	6	0.43138429	0.07189738	5.66	0.0054
BLOCK	2	0.10286752	0.05143376	4.05	0.0454
ERROR	12	0.15250114	0.01270843		

Coeff Var 5.40149

Appendix D11: durability index

SOURCE	DF	SS	MS	F-VALUE	Pr>F
TERATMENT	6	0.42746362	0.07124394	16.3	<.0001
BLOCK	2	0.01023038	0.00511519	1.1	0.3433
ERROR	12	0.05244695	0.00437058		

Coeff Var 8.340748

Appendix D12: % water resistance

SOURCE	DF	SS	MS	F-VALUE	Pr>F
TERATMENT	6	347.0045905	57.8340984	2.41	0.0922
BLOCK	2	17.0059714	8.5029857	0.35	0.7092
ERROR	12	288.4806952	24.0400579		

Coeff Var 5.868522

Appendix E: SAS results

Appendix E1: SAS results for bulk density (g/cm^3)

No.	Mixture	No. of trials	Mean Bulk density	Duncan grouping
1	100:00:00	3	0.46900	A
2	60:30:10	3	0.44000	B
3	70:20:10	3	0.43033	B
4	60:20:20	3	0.42433	B
5	60:10:30	3	0.42433	B
6	70:10:20	3	0.41867	B
7	80:10:10	3	0.41267	B

NB: **Means with the same letter are not significantly different**.

Appendix E2: SAS results for relaxed density (g/cm^3)

No.	Mixture	No. of trials	Mean relaxed density	Duncan grouping
1	100:00:00	3	0.57433	A
2	60:30:10	3	0.49800	B
3	70:20:10	3	0.48267	B
4	60:20:20	3	0.48000	B
5	60:10:30	3	0.47900	B
6	80:10:10	3	0.47500	B
7	70:10:20	3	0.46800	B

NB: **Means with the same letter are not significantly different**.

Appendix E3: SAS results for relaxation ratio

No.	Mixture	No. of	Mean Relaxation	Duncan
1	80:10:10	3	2.25667	A
2	70:10:20	3	2.18900	A
3	70:20:10	3	2.16167	A
4	60:10:30	3	2.09600	A
5	60:20:20	3	2.09333	A
6	60:30:10	3	2.03600	A
7	**100:00:00**	**3**	**1.77667**	**B**

NB: **Means with the same letter are not significantly different**

Appendix E4: SAS result for durability index (%)

No.	Mixture	No. of	Mean Durability index	Duncan
1	100:00:00	3	99.600	A
2	80:10:10	3	87.600	B
3	70:20:10	3	87.233	B
4	60:10:30	3	83.633	B
5	70:10:20	3	79.667	B

Appendix E4: SAS result for durability index (%) -continued

6	60:20:10	3	59.233	C
7	60:30:10	3	57.867	C

NB：Means with the same letter are not significantly different

Appendix E5: SAS result for water resistance (%)

No.	Mixture	No. of trials	Mean % water resistance	Duncan grouping
1	70:20:10	3	88.090	A
2	60:30:10	3	87.203	A
3	60:10:30	3	85.693	A
4	70:10:20	3	84.927	A
5	60:20:20	3	82.510	BA
6	80:10:10	3	81.130	BA
7	100:00:00	3	75.287	B

NB: Means with the same letter are not significantly different

Appendix E6: SAS result for Burn rate (g/min)

No.	Mixture	No. of trials	Mean Burn rate	Duncan grouping
1	70:20:10	3	10.6667	A
2	80:10:10	3	10.0000	BA
3	60:10:30	3	9.3333	BA
4	60:20:20	3	9.0000	BA
5	70:10:20	3	8.6667	BA
6	60:30:10	3	8.3333	BA
7	100:00:00	3	8.0733	B

NB：Means with the same letter are not significantly different

Appendix E7: SAS result for Boiling time (Minutes)

No.	Mixture	No. of trials	Mean Boiling time	Duncan grouping
1	100:00:00	3	32.333	A
2	70:10:20	3	32.000	A
3	60:30:10	3	29.333	BA
4	80:10:10	3	29.000	BA
5	60:10:30	3	28.333	BA
6	60:20:20	3	26.667	BA
7	70:20:10	3	22.000	B

NB：Means with the same letter are not significantly different

Appendix E8: SAS result for Ignition time (Minutes)

No.	Mixture	No. of trials	Mean Ignition time	Duncan grouping
1	100:00:00	3	10.3667	A
2	80:10:10	3	8.9800	B
3	70:10:20	3	7.1167	C
4	70:20:10	3	6.2000	DC
5	60:20:20	3	5.1467	D
6	60:30:10	3	5.1300	D
7	60:10:30	3	5.0700	D

NB：Means with the same letter are not significantly different

Appendix E9: SAS result for particulate matter (µg/m^3)

No.	Mixture	No. of trials	Mean Particulate matter	Duncan grouping
1	60:10:30	3	17,446	A
2	60:20:20	3	17,394	A
3	70:10:20	3	16,284	BA

Appendix E9: SAS result for particulate matter (μg/m^3) -continued

4	80:10:10	3	15,420	BA
5	100:00:00	3	13,623	BAC
6	70.20:10	3	9,423	BC
7	60:30:10	3	7,265	C

NB: **Means with the same letter are not significantly different**

Appendix E10: SAS result for carbon monoxide (ppm)

No.	Mixture	No. of trials	Mean Carbon monoxide	Duncan grouping
1	70:20:10	3	62.207	A
2	60:20:20	3	49.463	B
3	80:10:10	3	49.277	B
4	60:30:10	3	48.707	B
5	60:10:30	3	46.540	B
6	70:10:20	3	42.303	B
7	100:00:00	3	28.513	C

NB: **Means with the same letter are not significantly different**

Appendix E11: SAS result for carbon dioxide (ppm)

No.	Mixture	No. of trials	Mean Carbon dioxide	Duncan grouping
1	60:30:10	3	564.94	A
2	70:20:10	3	564.87	A
3	80:10:10	3	540.95	A
4	60:10:30	3	537.62	A
5	60:20:20	3	528.44	A
6	70:10:20	3	520.61	A
7	100:00:00	3	452.80	B

NB: **Means with the same letter are not significantly different**

Appendix F: Gas emission measuring instruments

Appendix F1: IAQ-CALC-Indoor Air Quality Meter (Model 7545)

Specifications

Specifications are subject to change without notice.

CO2:

- Range: 0 to 5000 ppm
- Accuracy1: ±3% of reading or ±50 ppm, whichever is greater
- Resolution: 1 ppm
- Sensor type: Non-Dispersive Infrared (NDIR)

Temperature:

- Range: 32 to 140°F (0 to 60°C)
- Accuracy2: ±1.0°F (±0.6°C)
- Resolution: 0.1°F (0.1°C)
- Response time: 30 seconds (90% of final value, air velocity at 2 m/s)
- Display units: °F or °C (user selectable)
- Type: Thermistor

Humidity*:*

- Range: 5 to 95% RH
- Accuracy2: ±3.0% RH (includes ±1% hysteresis)
- Resolution: 0.1% RH
- Response time: 20 seconds (for 63% of final value)
- Sensor type: Thin-film capacitive

Instrument Temperature Range:

- Operating (Electronics): 40 to 113°F (5 to 45°C)
- Storage: -4 to 140°F (-20 to 60°C)

Instrument Operating Conditions:

- Altitude up to 4000 meters
- Relative humidity up to 80% RH, non-condensing
- Pollution degree 1 in accordance with IEC 664
- Transient over voltage category II

Appendix F2: UCB Particle and Temperature Sensor (UCB-PATS)-Particulate (μg/m3).

Capabilities

- Lower detection limit 30 to 50 µg/m3 (PM2.5)
- Upper detection limit ~25,000 µg/m3 (PM2.5)
- Data logging
- Logs PM concentration, temperature, and battery voltage
- Logging interval 1 to 240 minutes
- Storage capacity 32,768 records
-

Appendix F3: EL-USB-CO-Carbon Monoxide (CO) Data Logger with USB Interface

- 0 to 1000 ppm CO Measurement Range
- Stores up to 32,510 Measurements
- USB Interface for Set-up and Data Download
- Expected sensor life: 4 years
- Replaceable Internal Lithium Battery

Appendix G: Project photos

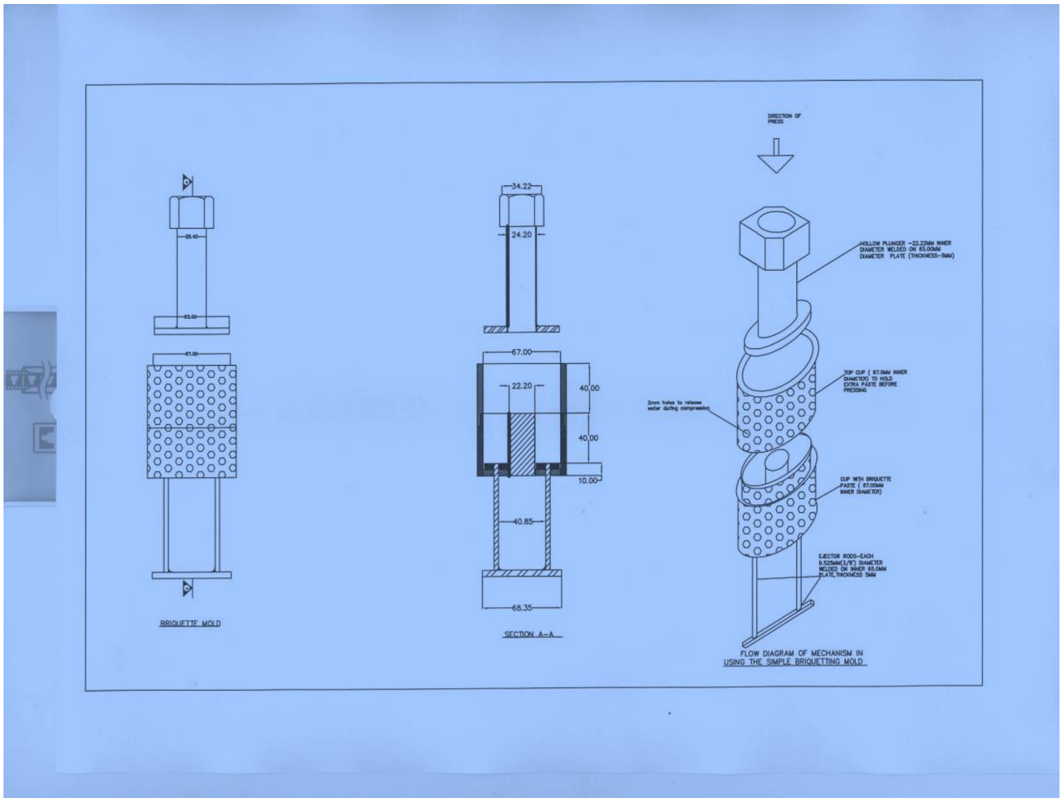
Appendix G1: Author and others harvesting Water hyacinth (Source: Author, 2015)

Appendix G 2: Transporting water hyacinth by boat (Source: Author, 2015)

Appendix G 3: Crushing cow dung using pestle and mortar (Source: Author, 2015)

Appendix G 4: Measuring weight of Briquette materials before pressing (Source: Author, 2015)

Appendix G 5: Briquetting (Source: Author, 2015)



Appendix G 6: Briquetting mold (Source: Author, 2015)

Appendix G 7: Weighing briquette using laboratory electronic balance (accuracy of 0.01g) (Source: Author, 2015)

Appendix G 8: Mounting Emission gas meters (Source: Author, 2016)