KTH Industrial Engineering and Management

APPRAISAL OF FOOD RESIDUE (WASTE) BASED FUEL BRIQUETTES IN DOMESTIC COOKING APPLICATIONS: A CASE STUDY OF UGANDA

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ABSTRACT

The research focuses on developing and evaluating the performance of low cost, low technology food residue based fuel briquettes as an alternative to the widespread use of wood fuels (charcoal and firewood) for domestic cooking applications.

In view of the declining accessibility of wood fuels, inadequate electrification coverage and ever-rising prices of cooking gas and kerosene in Uganda, harnessing energy from within reach, alternative sustainable energy sources such as food residues has been regarded as a viable solution to domestic cooking energy.

In this research, both desktop reviews of earlier studies and laboratory investigations of the developed food residue based fuel briquettes have been considered. Carbonized sweet potato, banana (matooke) and cassava peelings were mixed in different proportions with either sweet potato or banana stem pulp (1 or 2kgs) and later densified using a hand operated molder to develop the food residue based briquettes. The drop test method was used to determine the resilience of the produced briquettes to disintegrating forces in particular during transportation and storage. An oxygen bomb calorimeter was used to determined the Higher Heating Value (HHV) of the briquettes and it ranged from 13.6 – 26 MJ/kg with cassava peelings char: sweet potato peelings char: sweet potato stem pulp 1kg giving the lowest HHV and cassava peelings char: sweet potato peelings char: banana stem pulp 2kg giving the highest HHV. Generally the tests results revealed that the type of natural binder used had an effect on both the higher heating value (HHV) and mechanical strength of the produced briquettes.

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CHAPTER ONE: INTRODUCTION

1.1 Background

Uganda has a total primary energy consumption of 6.256481×10^7 Giga Joules (GJ) [1] [2] which equals 14.94 million tons of oil equivalent (2012) and this consumption is partially met by a number of energy resources including fossil fuels, biomass and solar power. About 90% of the total primary energy consumption is generated through biomass, which can be separated in firewood (78.6%), charcoal (5.6%) and crop residues (4.7%). Electricity is contributing only 1.4% to the national energy balance while fossil fuels (petroleum products), which are mainly used for vehicles and thermal power plants, account for the remaining 9.7%. [1]

The energy consumption pattern shows that residential related activities account for 70.3 % of total use yet the rest is accounted for by commercial use (13.6 %), Industrial use (10.7%), transport use (5%) and other uses (0.4%). Most of the energy consumed for residential activities (in particular during household cooking) is woody biomass energy, which often cannot be used in large scale industries in its raw form [3]. With the majority of Ugandans (about 88% of the population) living in rural areas [1], most households use wood biomass (wood fuels) in form of either firewood and / or charcoal to supply energy during cooking tasks. Significant use of wood biomass energy also occurs in rural small-scale and modern industries with the aim of generating process heat and electricity respectively. Other important users of wood energy include the service sector for large and small-scale cooking and heating applications [4].

Currently, access to electricity at national level in Uganda is still very low at about 15% (1991: 5.6%; 2006: 9%; 2010: 10%; 2013: 15%) with a mere less 7% of the rural population [1,5] having access to electricity. The scanty (low level) access to electricity, high electricity tariffs and insufficient generation capacity could explain why the majority of Ugandans still use woody biomass energy as a source of fuel.

Uganda's population has continued to grow rapidly over time from 24 million people in 2002 to approximately 35 million people in 2014 representing an average annual growth rate of 3.0 percent [6]. Consequently, in an effort to sate the ever-growing demand for wood fuels and agricultural land by the rapid population growth, the country has endure widespread deforestation in the recent past with the total deforestation rate per year between 1990 and 2005 reaching 1.8 percent per annum, while that between 2005 and 2010 was 5.4 percent per annum [6]. By 2020, it is predicted that Uganda will be in a wood biomass deficit [7]. This decline in forest cover has in sequence triggered significant adverse effects of climate change (change in rainfall patterns, prolonged droughts etc) since no substantial measures had been were put in place to deter these effects in a timely manner.

In 2014, the proportion of households according to the type of cooking fuel households was captured as per table below. Woodfuel still emerged as the main energy source for cooking with 71.2 percent and 22.9 percent corresponding to firewood and charcoal users respectively [8].

Table 1: National Population and Housing Census 2014

Source [8]

	1991			2002			2014		
Fuel Type	Rural	Urban	Total	Rural	Urban	Total	Rural	Urban	Total
Electricity (All forms)	0.14	6.31	0.93	0.3	4.3	0.8	1.2	4.4	1.9
Electricity_ Grid	-	-	-	-	-	-	1.0	4.2	1.7
Electricity_ Solar	-	-	-	-	-	-	0.2	0.2	0.2
Gas	0.01	0.16	0.03	0.1	0.7	0.2	0.5	2.3	0.9
Charcoal	2.72	60.79	10.16	7.0	66.8	15.4	11.8	58.2	22.9
Firewood	96.78	29.78	88.19	91.3	22.1	81.6	85.2	31.0	71.2
Paraffin	0.25	2.92	0.60	0.9	4.0	1.3	-	-	-
Other	0.09	0.03	0.09	0.4	2.0	0.6	1.3	4.1	3.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

The above statistics recurrently exhibit heavy reliance on wood fuels as the main source of fuel for household cooking over the past years and thus households can significantly alter the country's energy consumption trend by reducing the amount of wood fuels required to meet their daily cooking needs. Considering that agriculture is still the most widely practiced economic activity in Uganda with nearly two thirds (64 percent) of the working population engaged in subsistence agriculture in 2014 and the predominant household based enterprises were in Agriculture (43 percent) [8], the large amount of by-products and / or wastes typically generated by this activity could be upgraded and used to produce energy for household cooking tasks and at the same time contribute to the agricultural waste minimization and disposal system in use. The common practice is often to leave these agricultural residues to decompose and at times, use them to supplement animal feeds in subsistence farms.

Three common readily available agricultural residues in Uganda are banana, cassava and sweet potatoes. Annual crop production of banana, cassava and sweet potatoes is 4,297.07kt, 2,893.74kt, 1,817.66kt. Estimates of the total energy potential available from the utilization banana, cassava and sweet potatoes agricultural residues in Uganda are 16.44, 7.58 and 9.31 PJ per year respectively [9].

Figure 1: Dried Food residues

Similarly within the Country's vision 2040 [10], emphasis has been laid on achieving faster socio-economic transformations through strengthening fundamentals for harnessing opportunities such as promoting and facilitating of the use of renewable energy technologies among others. Energy from food waste is renewable and therefore its exploitation is aligned with Uganda's vision 2040.

Consequently, to address the current domestic cooking situation, it is worthwhile to further develop the work previously done on different types of fuel briquettes particularly agro-waste based fuel briquettes to evaluate whether low cost, low technology, energy efficient fuel briquettes can be developed from free, readily available household food waste (peelings) whilst creating an opportunity to convert food residue into useful products for the most wide-reaching consumer of wood fuels (households).

Furthermore, bearing in mind that the average Ugandan household survives on approximately US$ 2 per day (average consumption expenditure per household) [8], the use of food residue based briquettes would offer the population a much-needed opportunity to not only easily access an eco-friendly, energy – efficient and low technology fuel for daily cooking tasks but also reduce unmanaged decomposing waste especially in urban households yet living within one's means. Due to their eco- friendly attribute, food waste based fuel briquettes could be perceived as a cleaner energy source compared to wood fuels which are often linked to Household Air Pollution (HAP) and its related health problems.

In view of the aforementioned, a shift to a more sustainable alternative (energy efficient, eco-friendly, affordable solutions) to the prevailing energy system to primarily support domestic cooking applications is quite beneficial and crucial in activating and promoting long-term conscientious alleviation of environmental degradation.

1.2 Problem statement

The dwindling accessibility of wood fuels in Uganda, particularly firewood and charcoal together with the inadequate electrification coverage and ever-rising prices of kerosene and cooking gas have further underscored the need for food residue (waste) based fuel briquettes which can serve as low cost, low-medium technology, within reach, alternative sustainable energy sources intended for household cooking applications.

1.3 Objectives

1.3.1 Main objective

The research seeks to evaluate the performance of low cost, low technology food residue based fuel briquettes in domestic cooking applications.

1.3.2 Specific objectives

1. Determine the physical proprieties of each of the selected raw materials (food residues) for briquetting as well as the briquettes to be developed.

2. Develop the low – cost, low technology fuel briquettes from individual food residue bio-chars and a few blends of these different bio-chars using at least two natural binders (i.e. sweet potato stem & and banana stem pulp)
3. Determine the performance (thermal properties, durability…..) of the developed food residue based fuel briquettes for domestic cooking applications.

1.4 Justification

Given that wood fuels (charcoal and firewood) which represent the bulk of domestic fuel in Uganda are acquired from a declining natural resource (forests) and substitution fuels such as LPG (cooking gas) and kerosene are not widely utilized for household cooking tasks due to their cost, inaccessibility and lack of awareness (unfamiliarity), there is need to address the persistent need for an eco-friendly, sustainable, low cost and broadly spread cooking energy source (fuel) to reduce wood fuel consumption.

1.5 Scope

The scope of this research will be limited to harnessing energy from food residues of three main staple foods in Uganda i.e. sweet potatoes, banana (matooke) and cassava peelings by developing fuel briquettes. These particular food residues were chosen because they are habitually generated in all Ugandan households in reasonable amounts and most often they are dumped.

CHAPTER TWO: LITERATURE REVIEW

2.1 Fuel briquette

A fuel is any material that can be made to react with other substances so that it releases chemical or nuclear energy as heat or to be used for work.

Fuel briquette is then defined as a compressed block of coal dust or other combustible biomass material such as charcoal, sawdust, peat or paper used for fuel and firewood to start a fire.

Densified products with diameters and lengths ranging from 3 to 12mm and 6 to 25mm respectively are called pellets while those which are 25 to 100mm in diameter and 50 to over 100mm lengths are called briquettes [11]. Briquetting can be done with or without a binder. Doing without the binder is more convenient but it requires sophisticated and costly presses and drying equipment which makes such processes non attractive to a developing country. As observed by Wamukonya and Jenkins (1995)[12], for the briquetting industry to be successful in the less industrialized countries, the equipment should consist of locally designed simple, low-cost machines.

Briquetting of biomass not only improves its volumetric heating value but also lowers the associated transportation costs and makes agricultural residues available for a variety of applications [13][14].

Briquettes are frequently classified into various categories based on their constituent fuel type and occasionally, the shape of the briquette itself (i.e. rectangular and cylindrical shape). Common types of briquettes as per constituent fuel include among others; - biomass briquettes, residential and / or municipal waste briquettes, agro-waste briquettes, coal briquettes…etc.

2.2 Briquette production technology

Globally, there are two commonly used briquetting production (and densification) technologies and these are; -

2.2.1 Carbonization and Zero to low pressure densification

This carbonization technology relies on pyrolysis of often sun-dried raw materials or feedstock (e.g. agro-waste, food residue waste,) to produce bio-char that is then bound into a solid fuel using a binding agent (often a natural binder e.g. pulp/cassava starch, cow dung, anthill soil...) and then made into briquettes by casting and pressing (applying zero to low / or medium pressure) depending on the tool (device) at one's disposal to mould the fuel briquette into a desired shape. Often these kinds of briquettes are laid out to dry again before they are used as an energy source.

There are various binding agents in use which can be divided into two main groups: organic and inorganic binders. Organic binders include; - molasses, starch and resin while inorganic binders may include; - clay, cement, lime and sulphite liquor.

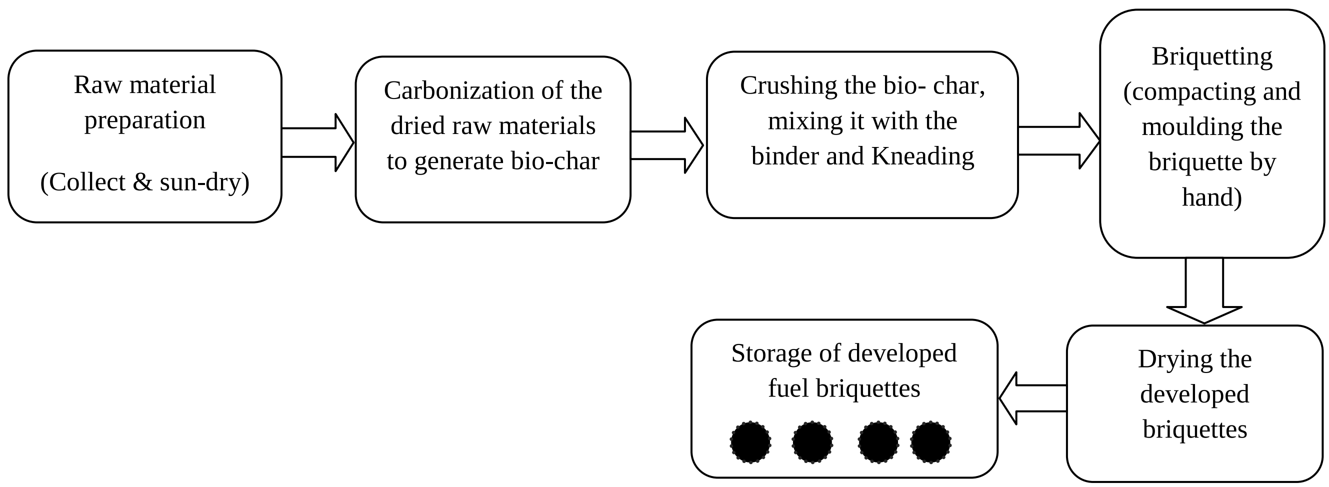

Figure 2: Carbonized Briquette production process

2.2.2 Direct extrusion or High pressure briquette production

This technology of producing fuel briquettes is by the process of compacting dry finely crushed raw materials or feedstock (e.g. agro-waste, residential waste, municipal waste…) into a solid fuel using high pressure and heat minus the use of a binding agent or binder. Often rectangular briquettes are produced using a hydraulic press, through a high pressure 300 - 400 bar while cylindrical ones are produced with or without a radial hole either using a hydraulic or mechanical press through the high pressure of 400-600 bars.

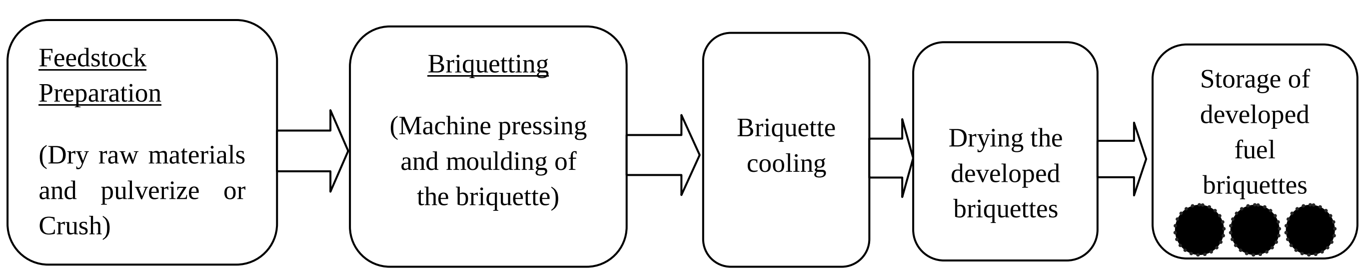

Figure 3: Non - Carbonized Briquette production process

(A) Rectangular: Briquettes **B) cylindrical without a radial hole** **C) Cylindrical with a radial hole**

Figure 3: Common Shapes of Briquettes

The advantages of both these technologies of briquettes production include; - affordability and minimum requirements for the organization of production while the disadvantages include;- briquettes are not resistant to moisture and mechanical damage, which adversely affects its condition after a long transport [15].

Globally, research has been conducted on different briquettes produced from a particular feedstock or blends of feedstock; at times with varying percentages of binder material majorly for the purpose of determining the following;-

1. Thermo-physical properties and elementary composition of the materials used for briquette making.
2. Combustion characteristics of the briquettes developed.
3. Comparing the heating values of the selected feedstock or blend with conventional fossil fuels.

2.3 Properties of briquettes developed from agricultural waste

A number of studies have been performed on the assessment of properties of briquettes from agricultural wastes.

J.T. Oladeji et al., (2010) studied the characteristics of briquettes produced from corncobs and rice husk residues in Nigeria. Ultimate and proximate analyses were carried out to determine the average composition of their constituents. A simple prototype briquetting machine was fabricated to facilitate densification of these residues into briquettes. This study showed that corncob briquettes have more positive attributes as a biomass fuel than rice husk briquettes. Corncob briquettes had moderate moisture content of 13.47%, higher density of 650 kg/m3 and lower relaxation ratio of 1.70. Other positive attributes of corncob briquette over rice husk were long after glow time of 370 seconds and slow propagation rate of 0.12 cm/s. It also has higher volatile matter of 86.53%, higher heating value of 20,890 kJ/kg and compressive strength of 2.34 kN/m2 compared to rice husk which are 67.98%, 13,389 kJ/kg, and 1.07 kN/m2, respectively. The study also concluded that, both briquettes will not crumble during transportation and storage because the values obtained for their relaxed densities are closed to the maximum densities of the briquettes from the two residues [16].

J. Werther et al., (2000) investigated the combustion of different agricultural wastes. Agricultural wastes have low bulk densities. Therefore densification may be required for effective transportation, storage and firing the point of generation, in which case densification may only be considered with respect to firing, i.e. to enable easier feeding and a more efficient combustion process. The decision to densify would therefore depend on the type of residues and the local situation. Agricultural residues are characterized by high contents of volatile matter. Devolatilization of biomasses has been found to start at very low temperatures for instance 160°C - 200°C for coffee husks and between 200°C - 500°C, the devolatilization is rapid and significant weight loss is recorded whereas above 500°C, the weight is remains more or less constant. The volatiles released consist mainly of combustible gases such as CO, H2 and C_xH_y and this is due to the decomposition of the biomass constituents at various temperatures [17].

M.M. Roy, K.W. Corscadden et al..., (2012) conducted an experimental study of combustion and emissions of biomass briquettes in a domestic wood stove to investigate the potential use of hay and switch grass briquettes as an alternative source of combustible biomass. The combustion and emission results were obtained using an Environmental Protection Agency (EPA) phase two wood stove for 15 biomass briquettes produced from a range of feedstock including hay and switch grass. Fuel property, gas emissions, particulate emissions and stove efficiency were compared. In regard to fuel properties, proximate analysis, ultimate analysis and heating values are determined and emissions of carbon monoxide (CO), nitrogen oxides (NO_x) and sulfur dioxide (SO_2) are measured and compared. In this study, particulates were also sampled, measured and compared using an iso-kinetic particulate analyzer. The results suggest that hay and switch grass briquettes can successfully be combusted in domestic wood stoves with similar or better performance and emissions when compared to a range of biomass (other woody) briquettes currently available in the market [18].

A.Yank et al... (2016) performed a study on Physical properties of rice husk and bran briquettes under low pressure densification for rural applications. A manual press generating a pressure of 4.2 MPa was developed and used. The influence of the briquette formulation (type of binder, binder content, water addition, and bran content) was studied. The binders investigated were cassava wastewater, rice dust, and okra stem gum. The physical properties(density, moisture content, calorific value, durability, and compressive strength) were tested to identify the briquettes with the highest quality, i.e. greatest physical integrity. The briquettes made with rice dust had the highest durability (91.9%) and compressive strength (2.54 kN), while the briquettes made with cassava starch wastewater had the greatest density (441.18 kg m3). Water added to the rice husk before densification positively influenced the briquette quality while bran seemed to mostly increase the density, but not necessarily the briquette quality. The briquette formulation did not significantly influence the calorific value. With a higher heating value of 16.08 MJ kg dry basis, rice husk is a suitable biomass for low pressure densification to produce briquettes as an alternative cooking fuel to wood fuels. The risk husk briquettes presented adequate characteristics namely physical integrity (durability and compressive strength) as well as low moisture content (below 7.5%) and high calorific value. Further studies would be required to assess the overall life-cycle energy requirement of the low pressure densification system. If more time or energy is required for briquette preparation and production compared to fuel-wood collection from the surrounding, the technology may be faced with low adoption rates compared to the immediate need to reduce fuelwood consumption. Overall, biomass briquettes, either from rice husk or other potential raw material, remain an interesting solution to provide an alternative fuel for rural Africa [19].

Idah P.A et al... (2013) conducted a comparative assessment of the heating values of briquettes produced from four of these biomass materials (ground nut husks, Rice husks, maize cobs, sugarcane bagasse) and two different types of agricultural byproduct binders (banana peel and cassava peel gel). The briquettes were subjected to energy evaluation test using the Fulton XRY-1B Oxygen Bomb Calorimeter. The mean bulk densities of the briquettes produced from rice husk, maize cob, groundnut shell and sugar cane bagasse were 0.75g/cm3, 0.69g/cm3, 0.81g/cm3and 0.65g/cm3, respectively. The results obtained showed that the average energy values of the briquettes produced using cassava peel as binder from rice husk, maize cob, groundnut shell and sugarcane bagasse were 26.612MJ/Kg, 28.255MJ/Kg, 33.703MJ/Kg and 32.762MJ/Kg, respectively. The corresponding average values for those produced using banana peel as binders were 29.980MJ/kg, 28.981MJ/kg, 32.432MJ/kg, 31.508MJ/g for rice husk, maize cob, groundnut shell and sugarcane bagasse respectively. The results indicate that briquettes produced from groundnut shell using cassava peel gave the highest energy value of 33.70 MJ/kg while those obtained from rice husk using cassava peel gave the lowest heating value of 26.61MJ/kg and these were significantly different($p \leq 0.05$). The briquette from groundnut shell is therefore more suitable for starting and maintaining fire for cooking and other domestic heating. The study concluded that briquettes made from groundnut shells using cassava peel as binder gave the highest energy value during combustion while the least energy was produced by briquettes produced from rice husk using cassava peel as binder. The briquettes from these by-products in terms of energy values are ranked as follows: groundnut shell > sugar cane bagasse > maize cob > rice husk. The effective utilization of these agricultural by-products as high grade solid fuel can reduce the popular use of charcoal which has an adverse effect on our environment (deforestation) and also help in minimizing the energy crisis resulting from non- renewable energy sources like petroleum products as domestic fuel [20].

Anak Agung Kencana et al … (2014) carried out an investigation about how the alternative energy from food waste can be produced in the form of briquette by a cheap method and process (roasting, drying and carbonizing). The main material for the research was food waste i.e. rice, chicken bones and vegetables collected from the neighbourhood. The binder which was used was adhesive powder which came from synthetic diesel residue (from polypropylene and polyethylene terephthalate plastics) and it was available for free as well. The results were 3,076.76 kJ/kg and 2,051.17 kJ/kg of energy on wet and dry basis (of food waste) respectively yet in an organic briquette form; it was 29,056.26 kJ/kg of energy. With a weight of the roasted food waste of 0.1 kg and the adhesive powder of 0.1 kg, the developed briquette had 33.5 g of weight, 45 min of combustion time, 2.44% of moisture contents, 8.88% of ash, 26.45% of volatile matter, 62.23% of fixed carbon. The time to boil 1 L of water is examined and comparing the developed food waste briquettes to coal briquettes and LPG, the time taken for the water to boil were 4.09 min, 5 min and 6.32 min respectively. The NPV for 6 year is IDR 2,171,010.90 (approximately US$ 162.4), the IRR is 154%, and the Payback Period is 0.64 year. The resultant briquette is gives a lower energy unit cost than those given by coal briquette and LPG. Therefore, this research shows a potential low cost, renewable and environmentally friendly energy source which remains viable as long as people continue to need energy [21].

In conclusion, the above referenced studies do reveal that worldwide there has been limited research conducted on fuel briquettes produced using only at hand, affordable (relatively free) and eco-friendly agricultural food residues (i.e. peelings, stems...etc) with an aim of discovering the feasibility of using these briquettes as an alternative to the conventional household cooking fuels (charcoal, firewood, cooking gas, electricity).

CHAPTER THREE: METHODOLOGY

3.1 Feedstock/Raw Material Preparation

Banana (matooke), sweet potato and cassava peelings were collected from Mulago market in Kampala.

The peelings were spread and dried using direct sunlight so as to reduce the moisture content to about 10% to 15% according to Mishra et al., 1998 [22]. Thereafter, the dried raw material was loaded into a carbonizing drum (see Figure 4); ignited using a lighter fire and the drum was covered. The function of the holes around the carbonizing drum is to facilitate control of the combustion air. This is achieved by plugging the holes (with mud) during the carbonizing process as and when the need arises (i.e. immediately smoke is observed, the hole is blocked with mud so that the material is progressively carbonized from the top to the bottom of the carbonizing enclosure. This is also referred to as slow pyrolysis.

Figure 4: Carbonization process

After the carbonization process, the bio char (see figure 6) was removed from the drum and ground into very fine particles so that particles have more contact points with the binder as recommended by Chaney, J. (2010) [23].

Figure 5: Bio Char

<u>Briquetting trial</u>

The material was tested if it could make a good briquette by soaking it in water, and a handful of wet material was grabbed and pressed into the hands. The material formed into a ball which retained its shape and did not fall apart and this demonstrated that this type of material can form a good solid briquette when mixed with a binder that increases the binding capacity of the mixture [23].

3.2 Binder preparation

The natural binders used include; - sweet potato stems sap and banana stem pulp (L-R)

Figure 6: Sweet potato stems and Banana stem

Method

1000ml volume of water was mixed with 1000g and 2000g portions of banana stem and sweet potato stem and the mixture was boiled to approximately 100 ^{o}C. The result was pulp which contained sufficient starch for making the fuel briquettes.

3.3 Briquette production process

An assortment of the selected raw materials, their blends and each of the chosen natural binders in different proportions (1- 2kgs) and at room temperature were bonded together to develop the briquettes to be investigated.

With binder from banana stem pulp; -

i) Banana peelings char
ii) cassava peelings char
iii) sweet potato peelings char
iv) cassava peelings char & banana peelings char
v) sweet potato peelings char & Banana peelings char
vi) cassava peelings char & sweet potato peelings char

With binder from sweet potato stem sap;-banana peelings char

i) Banana peelings char
ii) cassava peelings char
iii) sweet potato peelings char
iv) cassava peelings char & banana peelings char
v) sweet potato peelings char & banana peelings char
vi) cassava peelings char & sweet potato peelings char

The following mixing ratios produced the desired briquette qualities as summarized in the table below:

Table 2: Mixing Proportionality

Mixture	**Proportionality(grams)**
Banana peelings char: Banana stem pulp	1000:1000
Banana peelings char: Banana stem pulp	1000:2000
cassava peelings char: banana stem pulp	1000:1000
cassava peelings char: banana stem pulp	1000:2000
sweet potato peelings char: banana stem pulp	1000:1000
sweet potato peelings char: banana stem pulp	1000:2000
Banana peelings char: sweet potato stem pulp	1000:1000
Banana peelings char: sweet potato stem pulp	1000:2000
cassava peelings char: sweet potato stem pulp	1000:1000
cassava peelings char: sweet potato stem pulp	1000:2000
sweet potato peelings char: sweet potato stem pulp	1000:1000
sweet potato peelings char: sweet potato stem pulp	1000:2000
cassava peelings char: Banana peelings char: banana stem pulp	1000:1000
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cassava peelings char: Banana peelings char: sweet potato stem pulp	1000:2000
sweet potato peelings char: Banana peelings char: sweet potato stem pulp	1000:1000
sweet potato peelings char: Banana peelings char: sweet potato stem pulp	1000:2000
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp.	1000:2000
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp.	1000:1000

Each mixture was hand fed into the molder (mould of 5cm in diameter by 8.3cm in height was made from mild steel by milling to the required diameter and properly polished to achieve smooth internal surfaces. In the mould, the briquette mixture was in contact with a piston-like compressive metal with a plunger that was 12cm long (see figure 7). The force that was applied to compact and densify the produced briquettes was that of a human arm.

Figure 7: Molder

Figure 8: Developed briquettes

3.4 Evaluating the briquette properties

Proximate analysis was applied when evaluating the produced briquettes.

The purpose of the proximate analysis is to indicate the percentage by weight of the Fixed Carbon (FC), Volatile matter (VM), Ash and Moisture Content in the briquettes.

3.4.1 Proximate Analysis

Physical properties of the raw material and developed briquettes

Werther et al. 2000 used the Conventional Oven Method.

i) Measurement of Moisture content

The following procedure was used to determine the moisture content.

1. The ceramic weighing dishes were pre-dried by placing then in a drying oven at 105±3^{0}C for four hours. The pre-dried dish was then weighed to the nearest 0.1mg. This weight was recorded.
2. An approximate amount from the briquette sample was then weighed out to the nearest 0.1mg into the weighing dish.
3. The briquette sample was then placed in a conventional oven at 105±3^{0}C for a minimum of four hours. The sample was then removed from the oven to cool to room temperature in desiccators. The dish containing the oven dried sample was weighed and the weight recorded.
4. The sample was placed back into the conventional oven at 105±3^{0}C and dried to constant weight. Constant weight is defined as ±0.1 percent change in weight percent solids upon one hour of re-heating the sample. The weight was then recorded.

<u>*Calculations*</u>

$$\%\text{Total solids} = \left\{\frac{\text{Weight of dry pan and dry sample - Weight of dry pan}}{\text{Weight of sample as received}}\right\} \text{x} 100$$

$$\%\ \text{Moisture} = (100 - \%\text{Total solids})$$

ii) Measurement of Volatile Matter

The following procedure was used to determine the volatile matter:

- The weight of the container was determined.
- The weight of the container and the briquette was determined.
- The briquette was put in the oven and heated to 700 ^{0}C and then held for 4 hours.
- The briquette was then removed and weighed.

The volatile matter content was calculated from the following expression:

$$\%\text{Volatile matter} = \left[100 - 100\,\text{x}\left(\frac{\text{Weight of container and fuel after heating - Weight of container}}{\text{Weight of briquette alone}}\right)\right]$$

iii) Measurement of Ash content

The following procedure was used to determine the ash content:

1. Crucibles were marked and then placed in a furnace set to 575±25°C for a minimum of four hours, after which the crucibles were cooled for a recommended time of one hour. The weight of the crucible and the briquette sample was then recorded to the nearest 0.1mg.
2. The sample was then placed back into the muffle furnace at 575±25°C and dried to constant weight. Constant weight is defined as less than ±0.3mg change in the weight upon one hour of re-heating the sample. If the sample being analysed was a 105°C dried test specimen, the sample was used immediately after the moisture analysis test to obtain the ash content.
3. The crucibles with the samples were then placed into the furnace and the ramping operation described below was used to ash the samples.

   - Ramp from room temperature to 105°C
   - Hold at 105°C for 12 minutes
   - Ramp to 250°C at 10°C/minute
   - Hold at 250°C for 30 minutes
   - Ramp to 575°C at 20°C/minute
   - Hold at 575°C for 180 minutes
   - Allow temperature to drop to 105°C
   - Hold at 105°C until samples are removed

4. The crucible was then carefully removed from the furnace and the crucibles and the ash were weighed to the nearest 0.1mg and the weight was recorded.

Calculations

$$\text{Oven dry weight} = \left[\frac{\text{Weight of air dry sample x \%Total solids}}{100}\right]$$

$$\text{\%Ash content} = \left[\frac{\text{Weight of crucible plus ash - Weight of crucible}}{\text{Oven dry weight}}\right]\text{x100}$$

iv) Heating value of the raw material bio-char and developed briquette (Idah P.A et al…2013)

The higher heating value was determined using an oxygen bomb calorimeter connected to an industrial size oxygen supply. The apparatus comprises of the bomb calorimeter housing with thermometers. The bomb cover with crucible holder and circuit was removed and placed on the stand. The samples were weighed in the crucible using an electrical digital weighing scale to masses ranging between 0.8g to 1.2g. The sample within the crucible was then placed on to the holder and a resistance wire (platinum wire) connected across to complete the circuit. A cotton wick was then secured onto the centre of the resistance wire and connected to the sample in the crucible.

The whole set up was put into the bomb after cleaning it with distilled water. The cover was tightened, then after placed into the calorimeter housing. The samples were numbered in the control and the experiment was started. After about 20 minutes, the lower heating value was displayed on the control panel display screen.

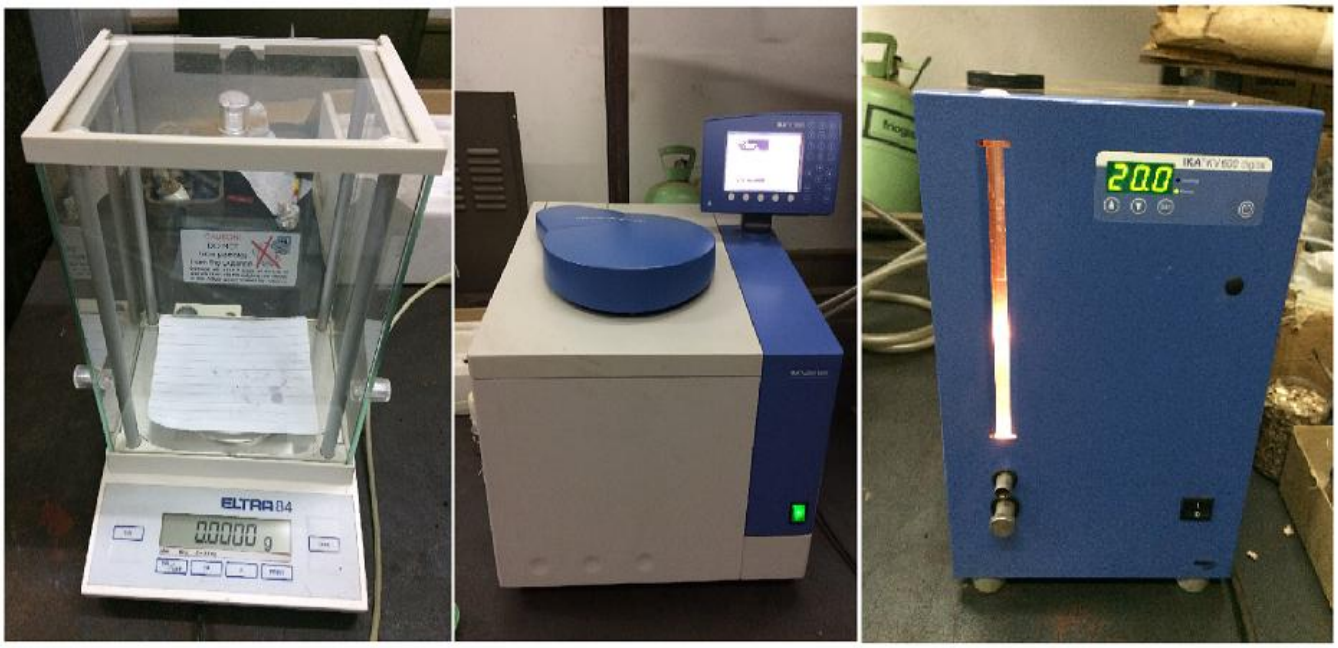

Figure 9: Bomb calorimeter

v) Determination of Particle Density

Particle density of the briquettes was determined from actual measurements of the mass, diameter and length of the developed briquettes [24]. The mass was obtained by using a digital weighing scale, while the volume was calculated by taking the linear dimensions (length and diameter) of the briquette by means of a vernier caliper.

3.4.2 Performance Tests

i) Determination of briquette integrity using drop strength

The drop test was used to estimate the integrity or impact resistance of the produced briquettes under shattering forces. In order to determine the drop strength, the briquettes were elevated up to 2m and then dropped onto a thin steel plate. The ratio of the weight after dropping to the weight before dropping was recorded as the drop strength.

Calculations

$$\text{Shattering index (\%)} = \left[\frac{\text{Weight of briquette retained on the thin steel plate after being dropped}}{\text{Weight of briquette before being dropped}}\right] \text{x}100$$

This is useful in order to gauge the maximum force that the produced briquettes can withstand (without disintegrating) during handling, transportation and storage. [25]

ii) Water boiling test

The water boiling test was used to determine how long it would take 120g of briquettes to boil 0.5 litres of water in an improved stove. The flame after boiling the water was observed and the highest temperature of the briquettes at this point was recorded using a DT-8865 non-contact infrared thermometer gun (Dual laser up to 1000 ºC; 30:1 D/S ratio) for each category of briquettes developed. [26]

Figure 10: Non-contact infrared thermometer gun

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Physical Properties

The results for physical properties are shown in table 2.

Generally, briquettes made with banana stem pulp have fixed carbon percentages compared to those made with sweet potato stem binder. The results for fixed carbon content correlate with the heating value. The increase in the fixed carbon percentages after carbonization means that carbonization might have had a thing to do with the increase from the 33.1%, 33.4% and 50.6% for cassava peelings, sweet potato peelings and matooke peelings raw material [33]

The moisture content results in the briquettes greatly reduced after carbonization of the raw materials. The combination of the carbonization process and the presence of banana stem and sweet potato pulp binder had a positive effect on reducing moisture content of the raw material before the formation of briquettes. The carbonization process inhibits moisture adsorption which is a very important result for increased shelf life and storage of the briquettes by preventing rotting and decomposition. [24]

Generally, the volatile matter results for the developed briquettes are much lower than those of the raw materials. This could be because of the carbonization process and the influence of the sweet potato pulp and banana pulp binder. Higher volatile matter eases ignition and enhances combustion due to increased chemical reactivity.

The developed briquettes produced more ash content than the raw materials from which they were made. High ash content levels reduce heating value, increase thermal resistance to heat transfer, generate slag deposits and require more equipment maintenance [34]

Table 3: Physical Properties of the Developed Briquettes

SAMPLE	**% Fixed carbon**	**% volatile matter**	**% Moisture content**	**% Ash content**
matooke peelings char: Banana stem pulp 1kg	54.5	20.49	6.54	18.47
matooke peelings char: Banana stem pulp 2kg	44.2	29.76	6.34	19.7
sweet potato peelings char: banana stem pulp 1kg	70.2	4.01	6.86	18.93
sweet potato peelings char: banana stem pulp 2kg	80.1	1.59	6.35	11.96
cassava peelings char: banana stem pulp 1kg	47.3	24.05	9.70	18.94
cassava peelings char: banana stem pulp 2kg	42	33.43	9.40	15.16
cassava peelings char: sweet potato peelings char: banana stem pulp 1kg	68.2	8.63	8.43	14.74

cassava peelings char: sweet potato peelings char: banana stem pulp 2kg	60.8	16.82	8.12	14.26
cassava peelings char: matooke peelings char: banana stem pulp 1kg	54.5	23.00	7.00	15.51
cassava peelings char: matooke peelings char: banana stem pulp 2kg	47.5	28.18	7.55	16.77
sweet potato peelings char: matooke peelings char: banana stem pulp 1kg	69.3	2.27	13.50	14.9
sweet potato peelings char: matooke peelings char: banana stem pulp 2kg	58.9	14.48	13.01	13.6
matooke peelings char: sweet potato stem pulp 1kg	58.1	19.69	9.50	12.71
Matooke peelings char: sweet potato stem pulp 2kg	47.3	28.66	9.12	14.92
sweet potato peelings char: sweet potato stem pulp 1kg	47.3	27.48	13.44	11.78
sweet potato peelings char: sweet potato stem pulp 2kg	47.3	27.69	12.97	29.77
cassava peelings char: sweet potato stem pulp 1kg	54	21.66	9.50	14.84
cassava peelings char: sweet potato stem pulp 2kg	58.5	13.79	8.98	18.73
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 1kg	38.3	33.72	9.50	18.75
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 2kg	59	18.31	8.99	13.69
cassava peelings char: matooke peelings char: sweet potato stem pulp 1kg	46.3	22.82	14.21	16.67
cassava peelings char: matooke peelings char: sweet potato stem pulp 2kg	51.3	20.00	13.43	15.27
sweet potato peelings char: matooke peelings char: sweet potato stem pulp 1kg	62.8	9.74	12.09	15.37
sweet potato peelings char: matooke peelings char: sweet potato stem pulp 2kg	29.7	43.04	11.94	15.32
Matooke peelings	50.6	21.60	14.90	12.89
Cassava peelings	33.1	45.82	15.80	5.28
Sweet potato peelings	33.4	44.21	17.20	5.19

The moisture content remains ideally the same because even though 2kgs or 1kg of sweet potato stem or banana stem is used to make the pulp, the same liquid proportions were mixed with the respective bio-chars and this means that the only difference between the pulp from the 1kg and that of 2kgs is that the latter is thicker. The thicker pulp implies increased starch content that would result into an increased heating value, as seen in the results below.

4.2 Heating Value

Figure 11 shows the heating value of the developed briquettes. An increase in the amount of banana and sweet potato stem pulp binder used generally presents an increasing heating value content of the developed briquettes with the exception of a few composite briquettes made from cassava/banana bio-char/ sweet potato pulp and banana bio-char/banana stem pulp] which presented an opposite trend (increase in the binder content led to a reduction in the heating value of the briquettes). As well, it was noted that a reasonable range of the developed briquettes with sweet potato stem pulp had lower heating values than those made with banana stem pulp.

However regardless of the type and amount of binder, briquettes made from sweet potato bio-char and its blends with other bio-chars generally had the highest heating value (26 MJ/kg) while those from cassava bio-char had the second highest.(24MJ/kg). A wider range of lowest heating values was observed with briquettes made from banana (matooke) bio-char. The heating values of the briquette types were found to be in range with the 18.89 MJ/kg obtained in banana peel briquette by Wiliapon, 2008 [27].

Table 4: Heating Value of the Developed Briquettes

SAMPLE	**Heating value (MJ/kg)**
matooke peelings char: Banana stem pulp 1kg	22.5
matooke peelings char: Banana stem pulp 2kg	22.1
sweet potato peelings char: banana stem pulp 1kg	23.3
sweet potato peelings char: banana stem pulp 2kg	25.7
cassava peelings char: banana stem pulp 1kg	21
cassava peelings char: banana stem pulp 2kg	21.6
cassava peelings char: sweet potato peelings char: banana stem pulp 1kg	23.2
cassava peelings char: sweet potato peelings char: banana stem pulp 2kg	26
cassava peelings char: matooke peelings char: banana stem pulp 1kg	18.2
cassava peelings char: matooke peelings char: banana stem pulp 2kg	23.4
sweet potato peelings char: matooke peelings char: banana stem pulp 1kg	19.3
sweet potato peelings char: matooke peelings char: banana stem pulp 2kg	20
matooke peelings char: sweet potato stem pulp 1kg	15.7
Matooke peelings char: sweet potato stem pulp 2kg	16.6
sweet potato peelings char: sweet potato stem pulp 1kg	21.7
sweet potato peelings char: sweet potato stem pulp 2kg	23.1

cassava peelings char: sweet potato stem pulp 1kg	18
cassava peelings char: sweet potato stem pulp 2kg	24
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 1kg	13.6
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 2kg	25.4
cassava peelings char: matooke peelings char: sweet potato stem pulp 1kg	23.3
cassava peelings char: matooke peelings char: sweet potato stem pulp 2kg	17.5
sweet potato peelings char: matooke peelings char: sweet potato stem pulp 1kg	17.3
sweet potato peelings char: matooke peelings char: sweet potato stem pulp 2kg	17.6

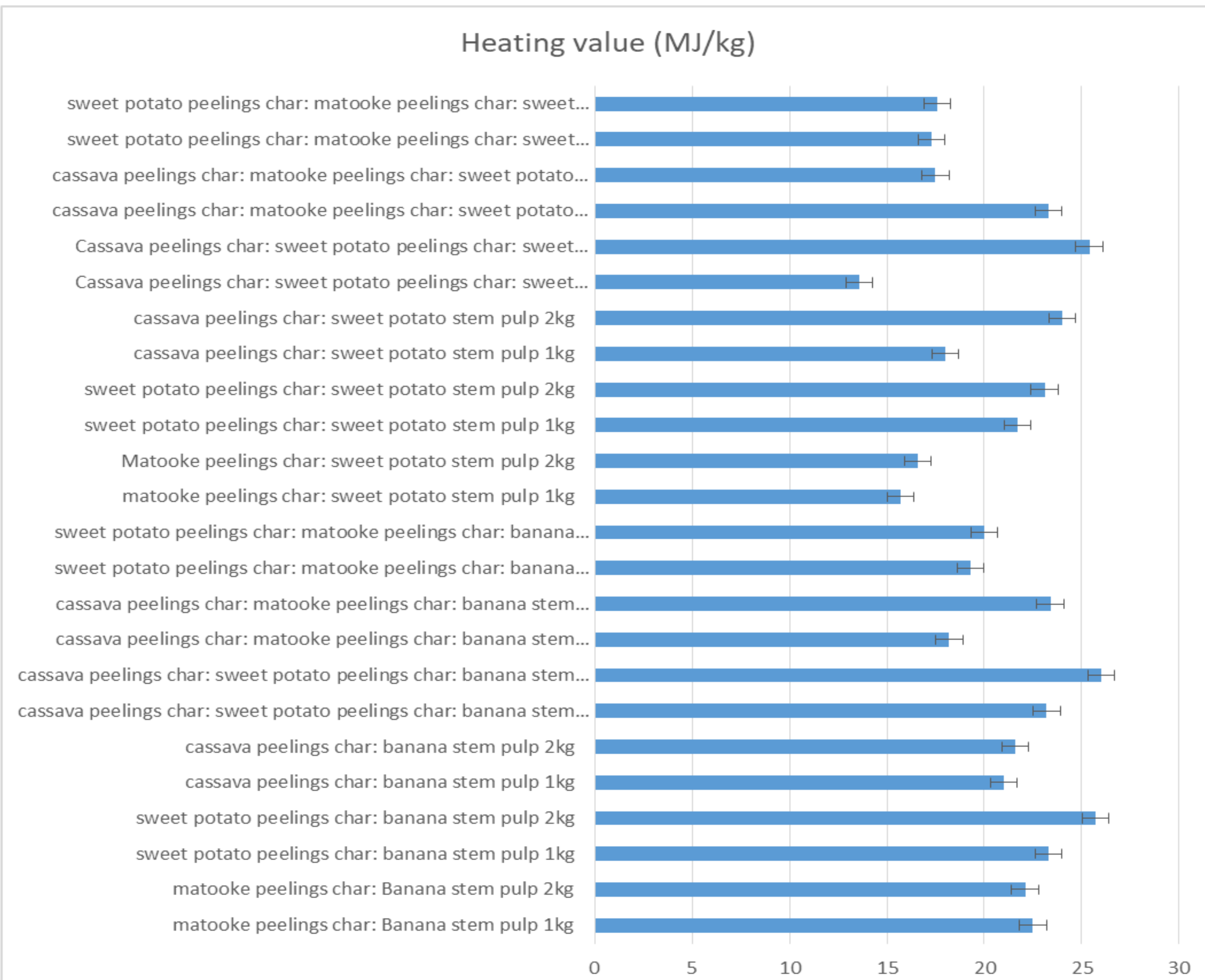

Figure 11: Heating value of the developed briquettes

ANOVA: Single Factor

HHV of developed Individual and Composite briquettes

Groups	*Count*	*Sum*	*Average*	*Variance*
matooke peelings char: Banana stem pulp 1kg	2	45	22.5	2
sweet potato peelings char: banana stem pulp 1kg	2	46.6	23.3	0.5
sweet potato peelings char: matooke peelings char: banana stem pulp 1kg	2	42	21	3.38
cassava peelings char: sweet potato peelings char: banana stem pulp 1kg	2	46.4	23.2	1.28
cassava peelings char: matooke peelings char: banana stem pulp 1kg	2	36.4	18.2	0.18
cassava peelings char: banana stem pulp 1kg	2	38.6	19.3	3.38

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*
Between Groups	45.47	5	9.094	5.089925	0.036173
Within Groups	10.72	6	1.786667		
Total	56.19	11			

Groups	*Count*	*Sum*	*Average*	*Variance*
matooke peelings char: Banana stem pulp 2kg	2	44.2	22.1	5.12
sweet potato peelings char: banana stem pulp 2kg	2	51.4	25.7	0.18
sweet potato peelings char: matooke peelings char: banana stem pulp 2kg	2	43.2	21.6	0.72
cassava peelings char: sweet potato peelings char: banana stem pulp 2kg	2	52	26	2
cassava peelings char: matooke peelings char: banana stem pulp 2kg	2	46.8	23.4	3.92
cassava peelings char: banana stem pulp 2kg	2	40	20	2.42

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*
Between Groups	56.22667	5	11.24533	4.698607	0.043138
Within Groups	14.36	6	2.393333		
Total	70.58667	11			

Groups	*Count*	*Sum*	*Average*	*Variance*
cassava peelings char: matooke peelings char: sweet potato stem pulp 1kg	2	31.4	15.7	16.82
sweet potato peelings char: sweet potato stem pulp 1kg	2	43.4	21.7	27.38
cassava peelings char: sweet potato stem pulp 1kg	2	36	18	24.5
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 1kg	2	27.2	13.6	2.42
sweet potato peelings char: matooke peelings char: sweet potato stem pulp 1kg	2	46.6	23.3	13.52
matooke peelings char: sweet potato stem pulp 1kg	2	34.6	17.3	3.92

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	132.9867	5	26.59733	1.801987	0.246704
Within Groups	88.56	6	14.76		
Total	221.5467	11			

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
cassava peelings char: matooke peelings char: sweet potato stem pulp 2kg	2	33.2	16.6	1.62
sweet potato peelings char: sweet potato stem pulp 2kg	2	46.2	23.1	23.12
cassava peelings char: sweet potato stem pulp 2kg	2	48	24	5.12
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 2kg	2	50.8	25.4	74.42
sweet potato peelings char: matooke peelings char: sweet potato stem pulp 2kg	2	35	17.5	2.88
matooke peelings char: sweet potato stem pulp 2kg	2	35.3	17.65	4.205

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	150.1842	5	30.03683	1.618291	0.28602
Within Groups	111.365	6	18.56083		
Total	261.5492	11			

Single factor analysis of variance (ANOVA) was used to determine the statistical significance of the effect of briquette composition on the HHV. The statistical analysis showed that at a 95% confidence interval, there was a high statistical significance ($p<0.05$) in the relationship between the briquette composition and HHV for briquettes bound with banana stem pulp binder. However, a low statistical significance was observed for HHV of the briquettes bound with sweet potato stem pulp. This is probably because the results for the latter are comparable.

4.3 Particle Density

Particle density results are shown in figure 12.

Generally, the briquettes particle density increases with an increase in binder content (banana stem pulp) with the exception of the composite briquettes of cassava bio-char & banana bio-char and matooke char & sweet potato peelings char which confirmed an opposite trend.

For briquettes made with sweet potato stem binder, the particle density generally reduced when the amount of binder present was increased apart from composite briquettes from cassava bio-char & banana bio-char as well as matooke char & sweet potato peelings char whose particle density increased with increasing binder content.

Particle density affects the drop strength (because the briquettes will have more mass as compared to the volume they hold) and consequently the transportation and storage of the briquettes.

Table 5: Particle Density for the Briquettes

SAMPLE	Density (kg/m^3)
Banana peelings char: Banana stem pulp 1kg	281.6
Banana peelings char: Banana stem pulp 2kg	300.3
sweet potato peelings char: banana stem pulp 1kg	312.6
sweet potato peelings char: banana stem pulp 2kg	315
Cassava peelings char: banana stem pulp 1kg	331.6
cassava peelings char: banana stem pulp 2kg	425.3
cassava peelings char: sweet potato peelings char: banana stem pulp 1kg	312.6
cassava peelings char: sweet potato peelings char: banana stem pulp 2kg	345.3
cassava peelings char: Banana peelings char: banana stem pulp 1kg	382.6
cassava peelings char: Banana peelings char: banana stem pulp 2kg	366.1
sweet potato peelings char: Banana peelings char: banana stem pulp 1kg	376.9
sweet potato peelings char: Banana peelings char: banana stem pulp 2kg	367.3
Banana peelings char: sweet potato stem pulp 1kg	374.5
Banana peelings char: sweet potato stem pulp 2kg	426.3
sweet potato peelings char: sweet potato stem pulp 1kg	357.3
sweet potato peelings char: sweet potato stem pulp 2kg	352

cassava peelings char: sweet potato stem pulp 1kg	405.1
cassava peelings char: sweet potato stem pulp 2kg	361.7
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 1kg	390.1
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 2kg	352
cassava peelings char: Banana peelings char: sweet potato stem pulp 1kg	301.1
cassava peelings char: Banana peelings char: sweet potato stem pulp 2kg	318.3
sweet potato peelings char: Banana peelings char: sweet potato stem pulp 1kg	373.5
sweet potato peelings char: Banana peelings char: sweet potato stem pulp 2kg	390.7

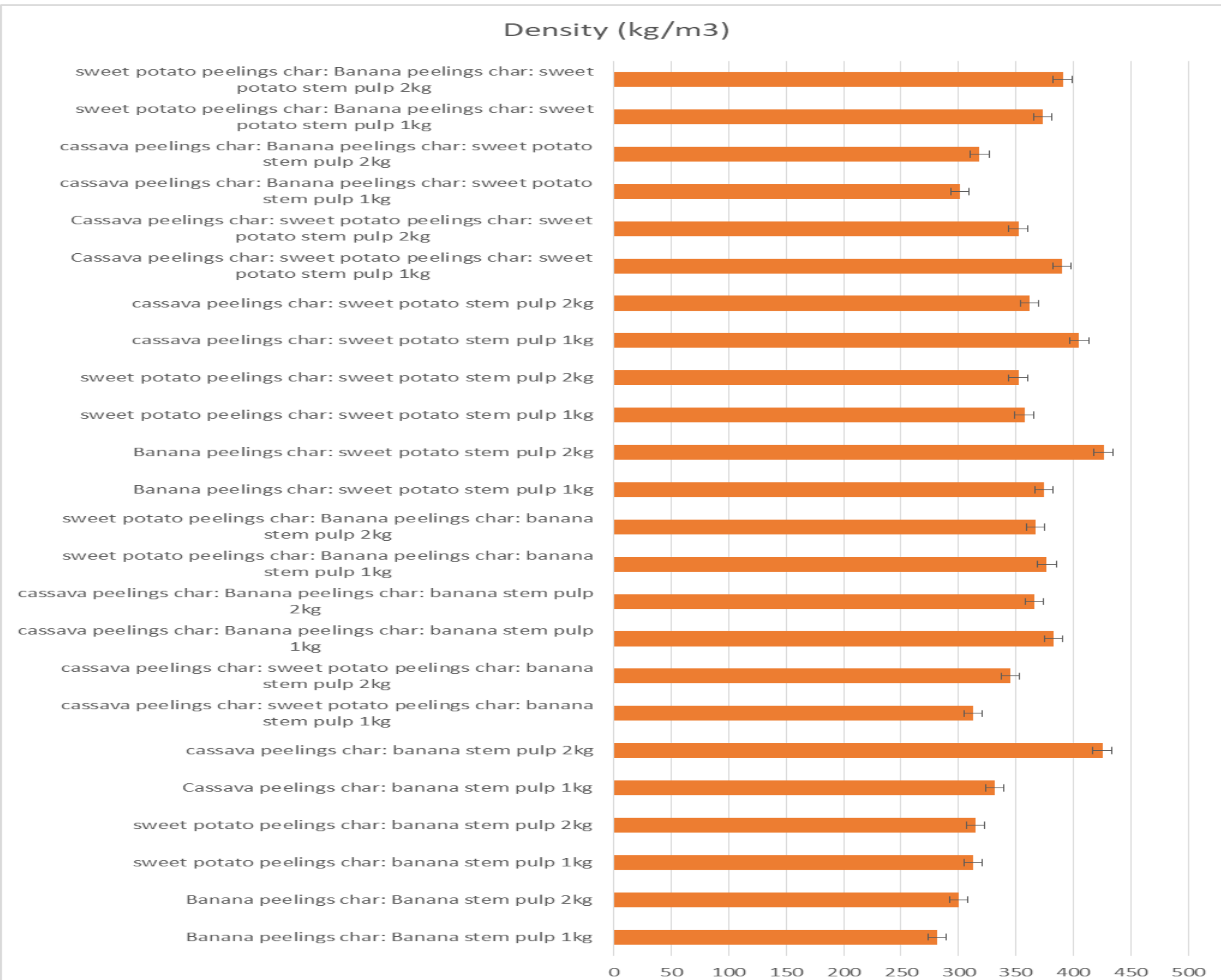

Figure 12: Particle density of the developed briquettes

ANOVA: Single Factor

Particle Density of developed Individual and Composite briquettes

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
matooke peelings char: Banana stem pulp 1kg	2	563.2	281.6	1.28
sweet potato peelings char: banana stem pulp 1kg	2	625.2	312.6	1.62
sweet potato peelings char: matooke peelings char: banana stem pulp 1kg	2	663.2	331.6	0.32
cassava peelings char: sweet potato peelings char: banana stem pulp 1kg	2	625.2	312.6	0.02
cassava peelings char: matooke peelings char: banana stem pulp 1kg	2	765.2	382.6	4.5
cassava peelings char: banana stem pulp 1kg	2	753.8	376.9	7.22

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	15727.22	5	3145.443	1261.541	5.63E-09
Within Groups	14.96	6	2.493333		
Total	15742.18	11			

Groups	*Count*	*Sum*	*Average*	*Variance*
matooke peelings char: Banana stem pulp 2kg	2	600.6	300.3	1.62
sweet potato peelings char: banana stem pulp 2kg	2	630	315	13.52
sweet potato peelings char: matooke peelings char: banana stem pulp 2kg	2	850.6	425.3	5.78
cassava peelings char: sweet potato peelings char: banana stem pulp 2kg	2	690.6	345.3	0.18
cassava peelings char: matooke peelings char: banana stem pulp 2kg	2	732.2	366.1	0.18
cassava peelings char: banana stem pulp 2kg	2	734.6	367.3	14.58

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	19767.38	5	3953.475	661.485	3.89E-08
Within Groups	35.86	6	5.976667		
Total	19803.24	11			

Groups	*Count*	*Sum*	*Average*	*Variance*
cassava peelings char: matooke peelings char: sweet potato stem pulp 1kg	2	749	374.5	24.5
sweet potato peelings char: sweet potato stem pulp 1kg	2	714.6	357.3	0.18
cassava peelings char: sweet potato stem pulp 1kg	2	810.2	405.1	1.62
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 1kg	2	780.2	390.1	131.22
sweet potato peelings char: matooke peelings char: sweet potato stem pulp 1kg	2	602.2	301.1	2
matooke peelings char: sweet potato stem pulp 1kg	2	747	373.5	5.78

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	13041.19	5	2608.237	94.67286	1.27E-05
Within Groups	165.3	6	27.55		
Total	13206.49	11			

Groups	*Count*	*Sum*	*Average*	*Variance*
cassava peelings char: matooke peelings char: sweet potato stem pulp 2kg	2	852.6	426.3	4.5
sweet potato peelings char: sweet potato stem pulp 2kg	2	704	352	115.52
cassava peelings char: sweet potato stem pulp 2kg	2	723.4	361.7	3.38
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 2kg	2	704	352	25.92
sweet potato peelings char: matooke peelings char: sweet potato stem pulp 2kg	2	636.6	318.3	58.32

matooke peelings char: sweet potato stem pulp 2kg	2	781.4	390.7	89.78

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	13855.59	5	2771.117	55.90311	5.95E-05
Within Groups	297.42	6	49.57		
Total	14153.01	11			

ANOVA was also used to determine the statistical significance of the effect of briquette composition on the particle density. The statistical analysis showed that at a 95% confidence interval, there was a high statistical significance ($p<0.05$) in the relationship between the briquette composition and particle density for all the developed briquettes.

4.4 Drop strength

Figure 13 shows results for the drop strength of the developed briquettes.

Generally there was an increase in the drop strength with an increase in the amount of binder present in the briquette. This implies that the briquettes developed will better withstand disintegrating forces during handling, storage...etc if the binder content is increased. However drop strength reduced with an increase in binder content in composite briquettes (cassava /matooke peelings char and sweet potato / matooke peelings char) made using sweet potato stem pulp. The inverse behaviour could probably be attributed to the chemical composition of the individual bio-chars of either cassava or sweet potato peelings when mixed with banana peelings char and bound together using sweet potato pulp.

The increase in drop strength is expected when the amount of binder is increased since the total composition of the briquette will also have increased. The presence of Protein in starch has also been found to enhance bonding due to its ability to plasticize under application of heat. This generally results in an increase in bonding and strength of the densified bio-char or briquettes. [28, 29, 30]

The raw materials were carbonized before making briquettes. During carbonization, 'natural binders' are softened as temperatures increase which enhances the bonding of carbonized briquettes [31]. The bonding in briquettes developed after carbonization are characterized by short range forces such as hydrogen bridges and 'van der Waals' forces, which are generally weak in nature [30, 32]. This explains why more binder is required to obtain higher drop strengths.

Additionally, during formation of the binder, water addition and heating results into the formation of intermolecular hydrogen bonds between the amylose and amylopectin components of starch. This is followed by loss of crystallinity in the structure of the two components which leads to the formation of a viscous solution that undergoes retro-gradation. When the starch binder is mixed with the bio-char to form a briquette, the briquettes attain a higher strength at room temperature [35].

Table 6: Drop Strength of the Briquettes

SAMPLE	**Drop strength (%)**
Banana peelings char: Banana stem pulp 1kg	80.9
Banana peelings char: Banana stem pulp 2kg	82.4
sweet potato peelings char: banana stem pulp 1kg	69.1
sweet potato peelings char: banana stem pulp 2kg	74
cassava peelings char: banana stem pulp 1kg	48.3
cassava peelings char: banana stem pulp 2kg	59.2
cassava peelings char: sweet potato peelings char: banana stem pulp 1kg	72.7
cassava peelings char: sweet potato peelings char: banana stem pulp 2kg	76.8

cassava peelings char: Banana peelings char: banana stem pulp 1kg	49.7
cassava peelings char: Banana peelings char: banana stem pulp 2kg	70.1
sweet potato peelings char: Banana peelings char: banana stem pulp 1kg	50
sweet potato peelings char: Banana peelings char: banana stem pulp 2kg	50.2
Banana peelings char: sweet potato stem pulp 1kg	50.7
Banana peelings char: sweet potato stem pulp 2kg	57.8
sweet potato peelings char: sweet potato stem pulp 1kg	47.4
sweet potato peelings char: sweet potato stem pulp 2kg	47.8
cassava peelings char: sweet potato stem pulp 1kg	78.3
cassava peelings char: sweet potato stem pulp 2kg	95
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 1kg	44.1
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 2kg	67.6
cassava peelings char: Banana peelings char: sweet potato stem pulp 1kg	74.3
cassava peelings char: Banana peelings char: sweet potato stem pulp 2kg	74
sweet potato peelings char: Banana peelings char: sweet potato stem pulp 1kg	80
sweet potato peelings char: Banana peelings char: sweet potato stem pulp 2kg	69.7

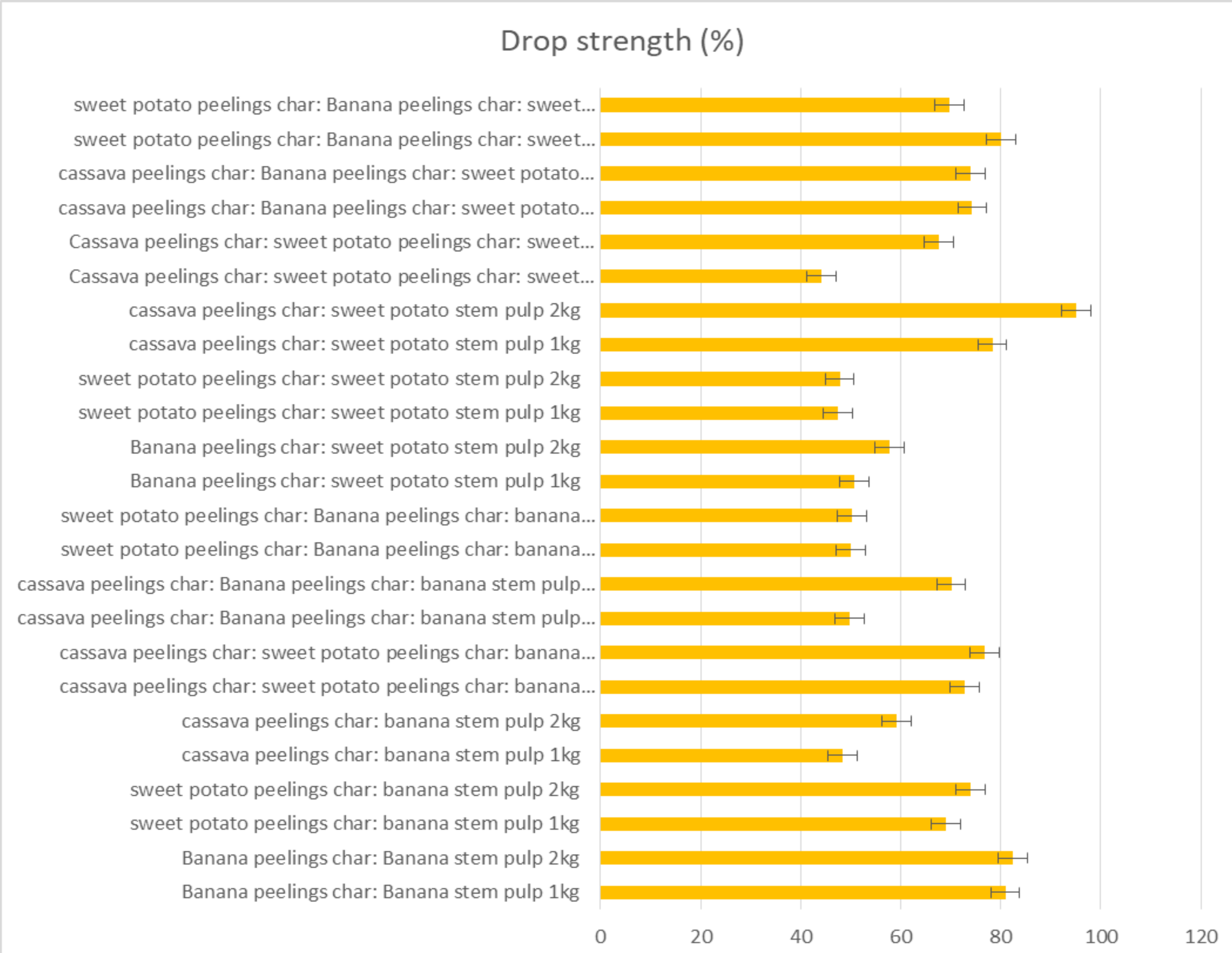

Figure 13: Drop strength of the developed briquettes

The values in Table 6 indicate the impact or shattering resistance of the produced briquettes that have been dropped from a 2m height above the ground level. To obtain a drop strength of 100%, the weight of the briquette before and after the drop should be the same; meaning that the briquette remains intact and doesn't disintegrate after the drop. However the above results reveal that indeed all the produced briquettes did disintegrate to varying extents after the drop due to both the type and amount of raw materials (including natural binder type)

4.5 Boiling Test

Results for the time it takes to boil 0.5 litres of water using 120g of briquettes are shown in figure 14.

The composite briquettes made from sweet potato peelings char: matooke peelings char with sweet potato stem binder of 2kg cooked for the longest time (13 minutes) while briquettes made with composite material of cassava peelings char and matooke peelings char with 1kg of banana stem pulp binder took the least time to boil (5 minutes). It is considered that the time taken to boil the water is generally low because of the high amount of volatiles therein. Due to the high content of volatile matter, during combustion the developed briquette will ignite more readily (with a proportionate increase in flame length) and burn faster than another briquette with a lesser volatile matter content.

Therefore, it is reasoned that the time taken to boil the water is dependent on how fast the developed fuel briquette ignites (ignitibility) and how much heat is released (heating value) to prolong combustion. Considering that these two factors jointly contributed to the water boiling time, this would explains why the composite briquette of sweet potato peelings char and banana stem pulp 2kg (25.7MJ/kg, 80.1% fixed carbon, 1.59% volatile matter) took 11 minutes to boil the water yet the composite briquette of cassava peelings char, sweet potato peelings char and banana stem pulp 2kg (26MJ/kg, 60.8%fixed carbon, 16.82% volatile matter) took only 6 minutes. This means that the heating value alone doesn't control thermal efficiency but burning rate is equally important.

Table 7: Water Boiling Time for each Developed Briquette

SAMPLE	Time to boil 500mls of water (Minutes)
Banana peelings char: Banana stem pulp 1kg	10
Banana peelings char: Banana stem pulp 2kg	10
sweet potato peelings char: banana stem pulp 1kg	6
sweet potato peelings char: banana stem pulp 2kg	11
cassava peelings char: banana stem pulp 1kg	8
cassava peelings char: banana stem pulp 2kg	6
cassava peelings char: sweet potato peelings char: banana stem pulp 1kg	6
cassava peelings char: sweet potato peelings char: banana stem pulp 2kg	6
cassava peelings char: Banana peelings char: banana stem pulp 1kg	5
cassava peelings char: Banana peelings char: banana stem pulp 2kg	9
sweet potato peelings char: Banana peelings char: banana stem pulp 1kg	6
sweet potato peelings char: Banana peelings char: banana stem pulp 2kg	7
Banana peelings char: sweet potato stem pulp 1kg	10
Banana peelings char: sweet potato stem pulp 2kg	13
sweet potato peelings char: sweet potato stem pulp 1kg	6
sweet potato peelings char: sweet potato stem pulp 2kg	6
cassava peelings char: sweet potato stem pulp 1kg	10

cassava peelings char: sweet potato stem pulp 2kg	7
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 1kg	10
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 2kg	6
cassava peelings char: Banana peelings char: sweet potato stem pulp 1kg	6
cassava peelings char: Banana peelings char: sweet potato stem pulp 2kg	10
sweet potato peelings char: Banana peelings char: sweet potato stem pulp 1kg	8
sweet potato peelings char: Banana peelings char: sweet potato stem pulp 2kg	13

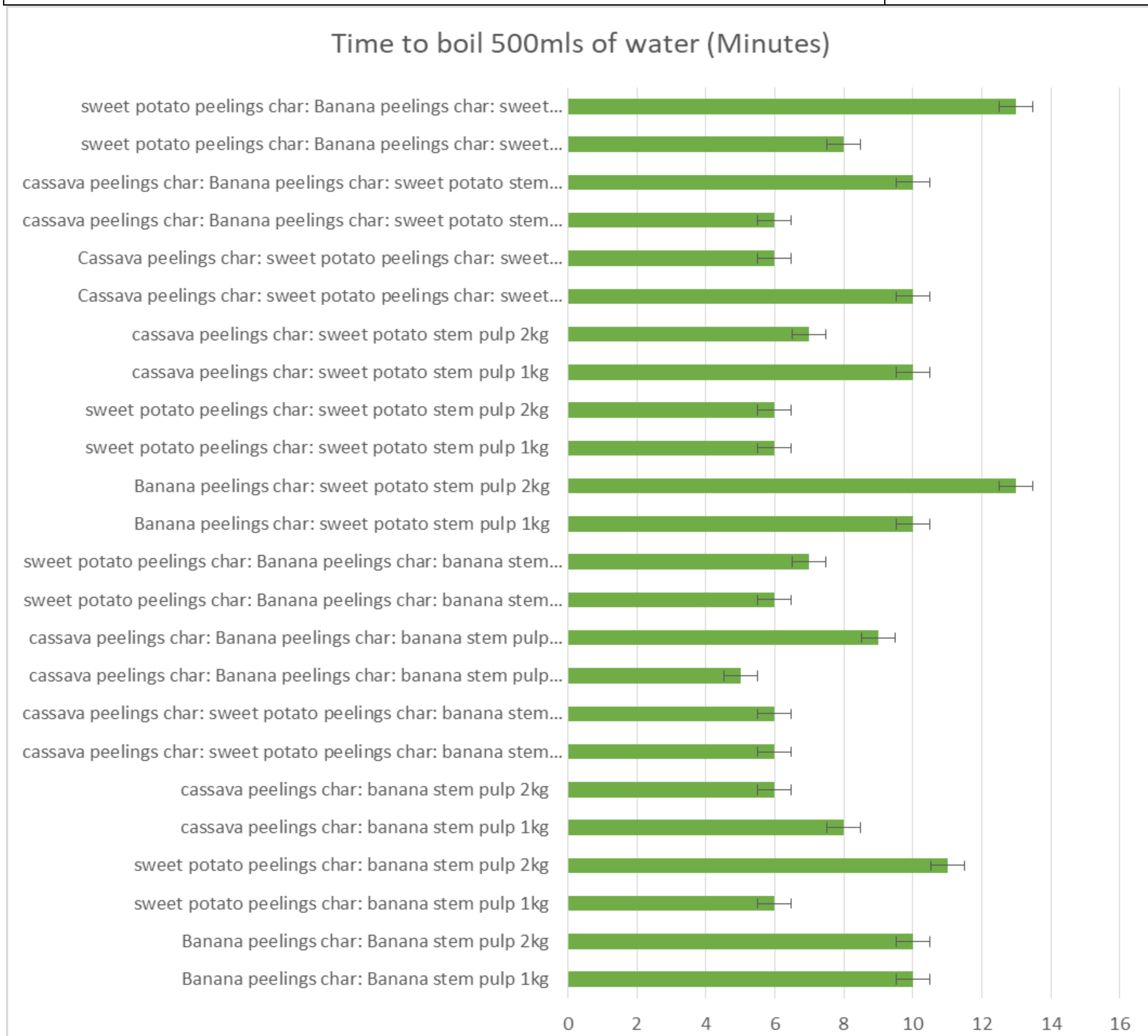

Figure 14: Time to boil 0.5 litres of water using 120g of the developed briquettes

4.6 Maximum attainable flame temperature

Figure 15 shows results for the maximum attainable flame temperature of the briquettes after the water has been boiled.

The flame temperature generally increased with an increase in the amount of binder present in the briquette. The flame temperature however reduced when binder was increased in matooke peelings char: banana stem pulp binder, matooke peelings char: sweet potato pulp binder, cassava peelings char: sweet potato peelings char and the composite briquettes of cassava peelings char: matooke peelings char: banana stem pulp, sweet potato peelings char: matooke peelings char: banana stem pulp,

The results show that an increase in binder proportionally leads to an increase in the maximum attainable flame temperature. Clearly there must be something in the banana stem pulp and sweet potato stem pulp that causes the trend. The results are in line with heating value results shown in figure 11. This shows that when the heating value increases, the flame temperature also increases. This therefore means it will take less time to cook.

Table 8: Maximum Attainable Flame Temperature

SAMPLE	^{o}C
Banana peelings char: Banana stem pulp 1kg	799.5
Banana peelings char: Banana stem pulp 2kg	703.4
sweet potato peelings char: banana stem pulp 1kg	750.9
sweet potato peelings char: banana stem pulp 2kg	785.8
cassava peelings char: banana stem pulp 1kg	805.3
cassava peelings char: banana stem pulp 2kg	828.6
cassava peelings char: sweet potato peelings char: banana stem pulp 1kg	815.5
cassava peelings char: sweet potato peelings char: banana stem pulp 2kg	852.3
cassava peelings char: Banana peelings char: banana stem pulp 1kg	808.5
cassava peelings char: Banana peelings char: banana stem pulp 2kg	790.8
sweet potato peelings char: Banana peelings char: banana stem pulp 1kg	855.4
sweet potato peelings char: Banana peelings char: banana stem pulp 2kg	794
Banana peelings char: sweet potato stem pulp 1kg	640.7
Banana peelings char: sweet potato stem pulp 2kg	609.7
sweet potato peelings char: sweet potato stem pulp 1kg	732.1

sweet potato peelings char: sweet potato stem pulp 2kg	810.1
cassava peelings char: sweet potato stem pulp 1kg	741.4
cassava peelings char: sweet potato stem pulp 2kg	678.4
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 1kg	722.9
Cassava peelings char: sweet potato peelings char: sweet potato stem pulp 2kg	773.4
cassava peelings char: Banana peelings char: sweet potato stem pulp 1kg	702.1
cassava peelings char: Banana peelings char: sweet potato stem pulp 2kg	713.4
sweet potato peelings char: Banana peelings char: sweet potato stem pulp 1kg	718.2
sweet potato peelings char: Banana peelings char: sweet potato stem pulp 2kg	775.4

Figure 15: Maximum attainable flame temperature

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, bio-char from cassava, banana and sweet potato peelings was densified into briquettes using two different types of natural binders, namely banana stem and sweet potato stem pulp; at room temperature using the compressive strength of a human arm.

Most of the food residues from homes in Uganda are simply put to waste. Given the amount of wastes generated from individual households in Uganda annually and the amount of heating value these contain, a shift from the use of charcoal/ firewood use to fuel briquettes; made from the agricultural food residues in particular cassava, sweet potatoes and bananas (matooke) will aid in securing a low cost, low to medium technology, within reach, alternative to daily cooking fuels such as kerosene, LPG and fuel wood.

The average heating value ranged from 13.6 – 25.7 MJ/kg with cassava peelings char: sweet potato peelings char: sweet potato stem pulp 1kg giving the lowest heating value and cassava peelings char: sweet potato peelings char: banana stem pulp 2kg giving off the highest heating value.

Generally the briquettes had good durability characteristics in terms of drop strength (44.1%-80.9%) and particle density (281.6kg/m^3 - 426.3 kg/m^3)

5.2 Recommendations

More research on energy from food residues in Uganda should be carried out as Uganda is a predominantly agricultural country. There are many more residues that could provide even better energy and physical properties. The carbonizer used in this work should be modified so that the exhaust fumes from it during the carbonisation process can be cleaned and purified before they are let to the atmosphere.

Further studies related to the variables involved in the briquetting process are recommended so as to get a clearer picture of what fully affects the energy in briquettes.

Survey or cost analysis has to be carried out to show the acceptability and future market potential for briquettes among households in Uganda.

Small to medium scale entrepreneurs should take up this clean energy fuel production technology by producing fuel briquettes from the agricultural food residues (waste) which were originally not being utilized. In this way, less of the common household costs will be attributed to purchase of foreign fuels for example kerosene and cooking gas in Uganda. Besides, this kind of fuel briquette production would promote both job and value creation from these agricultural food residues.

More research is needed in the use of other binder types and briquetting raw materials material to reduce on the smoke and gas emissions produced during carbonization and combustion (actual use) of the developed fuel briquettes.

BIBLIOGRAPHY

[1] https://energypedia.info/wiki/Uganda_Energy_Situation

[2] http://www.iea.org/statistics/resources/unitconverter

[3] http://www.gov.ug/topics/power-energy-0

[4]http://www.irena.org/DocumentDownloads/events/2015/Bioenergy%20Statistics%20Presentations/Household%20energy%20surveys/Uganda_household%20energy%20surveys.pdf

[5] http://www.eia.gov/beta/international/analysis.cfm?iso=UGA

[6] UBOS 2015 Statistical Abstract

[7] Charlotte Kanabahita, December 2001. Forestry Outlook Studies in Africa (FOSA) – Uganda.

[8]National Population and Housing census 2014
https://unstats.un.org/unsd/demographic/sources/census/wphc/Uganda/UGA-2016-05-23.pdf

[9] Okello C, Pindozzi S, Faugno S, Boccia L. 2013. Bioenergy potential of agricultural and forest residues in Uganda. Biomass and Bioenergy 2013.

[10] Uganda's Vision 2040 http://npa.ug/wp-content/themes/npatheme/documents/vision2040.pdf

[11] Olorunnisola .A (2007). Production of Fuel Briquettes from Waste Paper and Coconut Husk Admixtures. Department of Agricultural & Environmental Engineering, University of Ibadan, Nigeria

[12] Wamukonya L. and B. Jenkins 1995. Durability and relaxation of sawdust and wheat – straw briquettes as possible fuels for Kenya.

[13] Samson R., Mani, S., Boddey, R., Sokhansanj, S., Quesda, D., Urquiaga, S., Reis, V. & Lem, C.H., (2005). The potential of C4 perennial grasses for developing a global Bioheat industry. Critical Reviews in Plant Sciences, Vol. 24.

[14] Demirbas, A., Sahin-Demirbas, A. & Demirbas, A.H., (2004). Briquetting properties of biomass waste materials. Energy Sources, Vol. 26.

[15] http://piroliz.org/clients/articles/2013-05-21-13-35-08/eng/

[16] J.T. Oladeji, (2010). Fuel Characterization of Briquettes Produced from Corncob and Rice Husk Resides. M.Sc. Department of Mechanical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria.

[17] J. Werther , M. Saenger , E.U. Hartge , T. Ogada , Z. Siagi (2000). Combustion of Agricultural residues. Chemical Engineering I, Technical University Hamburg, Department of Production Engineering, Moi University, Eldoret, Kenya

[18] Murari Mohon Roya, Kenny W. Corscadden (2012). An experimental study of combustion and emissions of biomass briquettes in a domestic wood stove.

[19] A.Yank, M. Ngadi, R. Kok (2016). Physical properties of rice husk and bran briquettes under low pressure densification for rural applications. McGill University, Department of Bioresource Engineering

[20] Idah, P. A1, Mopah, E. (2013). Comparative Assessment of Energy Values of Briquettes from Some Agricultural By-Products with Different Binders. Department of Agricultural and Bio-resources Engineering, Federal University of Technology, Niger State, Nigeria.

[21] Anak Agung Kencana, Aqli Mursadin (2014). Fuel Briquette based on Food Waste Energy.
Department of Mechanical Engineering Lambung Mangkurat University

[22] Mishra, S.K., Grover, P.D. 1996. Biomass Briquetting: Technology and Practices. Regional Wood Energy Development Programme in Asia: Bangkok, Thailand; FAO. Field Document No.46.

[23] Chaney, J. (2010). Combustion Characteristics of Biomass Briquettes. PhD thesis. University of Nottingham, MSc Physics.

[24] Fernandez RG, Garcia CP, Lavin AG, Bueno de las Heras J.L. 2013. Influence of physical properties of solid biomass fuels on the design and cost of storage installations. Waste Management 2013; 33(5): 1151 -1157

[25] Fengmin L, Mingquan Z. 2011. Technology Parameters of Biomass Briquetting of Macrophytes in Nansi Lake, Energy Procedia 2011; 5: 2449-2454

[26] Chen Y, Shen G, Su S, Du W, Huangfu Y, Liu G, Wang X, Xing B, Smith KR, Tao S. 2016. Efficiencies and pollutant emissions from forced-draft biomass-pellet semi-gasifier stoves: Comparison of International and Chinese water boiling test protocols. Energy for Sustainable Development. 2016; 32: 22-30

[27] Wilaipon P. 2008. Density Equation of Bio-Coal Briquettes and Quantity of Maize Cob in Phitsanulok, Thailand. Am. J. App. Sci., **5**(12): 1808−1811.

[28] Kaliyan N, Morey VR. 2009. Factors affecting strength and durability of densified biomass products. Biomass and Bioenergy 2009; 33(3) 337-359.

[29] Kaliyan N, Morey VR. 2009. Constitutive model for densification of corn stoves and switch grass. Biosystems Engineering 2009; 104(1) 47-63

[30] Mani S, Tabil LG, Sokhansanj .S. 2006. Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. Biomass and Bioenergy 2006; 30(7): 648-654

[31] Dureja H, Khatak S, Khatak M, Kalra M. 2011. Amylose Rich Starch as an aqueous based pharmaceutical coating Material - Review. International Journal of Pharmaceutical Sciences and Drug Research 2011; 3(1) 8-12

[32] Liu Z, Jiang Z, Cai Z, Fei B, Yu Y, Liu X. 2013. Effects of carbonization conditions on properties of bamboo pellets. Renewable Energy 2013; 51: 1-6

[33] Amaya A, Medero N, Tancredi N, Silva H. Deiana C. 2007. Activated Carbon Briquettes from Biomass Materials. Bioresource Technology 2007; 98(8): 1635-1641

[34] Fernandez RG, Garcia CP, Lavin AG, Bueno de las Heras JL. 2014. Spanish Biofuels heating value estimation. Part II: Proximate analysis data. Fuel 2014; 117: 1139-1147.

[35] Tako M., Hizukuri S. 2002. Gelatinization mechanism of potato starch, Carbohydrate Polymers 2002; 48(4) 397-401