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Development of charcoal briquettes using Sehalahala (Seriphium plumosum and Felicia filifolia)

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Abstract

Introduction: Production of charcoal briquettes using invasive shrubs found on Lesotho's rangelands can provide alternative sustainable biomass energy for household heating and cooking applications in rural Lesotho.

Objectives: To develop briquettes using the two species of *Sehalahala (Seriphium plumosum and Felicia filifolia*) and evaluate the performance properties of charcoal briquettes made from the two shrubs.

Methods: *Sehalahala* feedstock was harvested and dried for five days to reduce the moisture content. Dried materials were cut and carbonised using a 200L steel drum. Wheat and clay binders were added at 5% (w/w) with charcoal powder and mixed together. Puck shaped briquettes were developed using a car jack driven briquetting machine. Four treatments (2 species and 2 binders) were developed and compared with a briquette purchased from the local supermarket for benchmarking.

Proximate analysis was conducted using ASTM standards. Caloric value (MJ/Kg) was calculated using an empirical formula. Ultimate analysis was undertaken using a LECO CHNS 628 Determinator.

Results: The mean percentage value of the four manufactured briquettes for the respective parameters evaluated were found to be as follows: moisture content (6.83 ± 2.72) m %,volatile matter content (30.53 ± 5.93) m %, ash content (3.77 ± 1.10) m %, fixed carbon (58.88 ± 6.51) m %, and higher heating value (25.66 ± 1.28) MJ/kg**.** In addition, the results indicated that the clay binder yields higher calorific value compared to the boild wheat flour suspention mix. Results of the ultimate analysis showed total carbon (35.14 ± 4.13) %, total nitrogen (1.01 ± 0.20) %, hydrogen (2.13± 0.26)% and sulphur (0.34 ± 0.08) %.

Conclusion: Based on the results, it can be concluded that *Sehalahala* is suitable for production of bio-char briquettes. The newly produced briquettes have a higher energy content, less indoor air pollution and burns longer than traditional biomass (cow dung, agro-residues, shrubs, wood, etc) used in rural Lesotho for cooking and laughing applications. However, the results also indicate an opportunity for optimising production methods in order to achieve better results for mass production.

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1. INTRODUCTION

1.1. Background

Energy is an important input in modern economies (Bhattacharyya, 2011). It is used in many sectors as intermediary good for production of different final products and services. As a result, energy security is one of the prominent challenges facing governments globally (Liao et al., 2013). This is further exacerbated by global warming, which require the world to shift towards cleaner energy sources. Thus, it is imperative for the governments and private sector to invest in the harvesting of renewable energy resources in order to meet domestic energy needs and mitigate against climate change (Eberhard et al., 2017).

Renewable energy is derived from natural sources that are replenished constantly (Department of Energy, 2017). Renewable energy has been used across the world to replace conventional energy sources such in four distinct areas; (i) electricity generation, (ii) air and water heating/cooling, (iii) petroleum products, (iv) rural (off-grid) energy services (Eberhard et al., 2017). There are different forms of renewable energy, namely; (i) solar PV, (ii) solar thermal, (iii) hydropower, (iv) bioenergy, (v) geothermal, and (vi) tidal energy.

Bioenergy is a form of renewable energy which is derived from biomass (Amaducci and Perego, 2015). The term "biomass" is the general term used to include phytomass (plant biomass) and zoomass (animal biomass) (Abbasi et al., 2011). The sun's energy when intercepted by plants and converted by a process of photosynthesis into chemical energy, is stored in the form of terrestrial and aquatic vegetation(Abbasi et al., 2011). The vegetation when consumed by animals is converted into zoomass and excreta. The excreta from terrestrial animals can be used as energy – biomass energy. Biomass energy refers to all substances of organic origin that includes: (i) phytomass and zoomass (plants and animals), (ii) resulting residues (animal manure), (iii) dead (but not yet fossilized) phytomass and zoomass (straw), and (iv) in the broader sense all substances which arose from a technical conversion and/or material use (black liquor, pulp and paper, organic waste,…) (Young et al., 2011) The differentiation of biomass from fossil fuels starts with peat, the fossil secondary product of rotting (Young et al., 2011). However, peat cannot be regarded as renewable since it is not being formed within the lifetime of a human but takes approximately 10.000 years (Young et al., 2011).

Biomass can be used for production of biofuels, bioheating and bioelectrity. There are different types of biofuels, namely; (i) liquid biofuels (methanol, ethanol, butanol and biodiesel etc), (ii) solid biofuels (firewood, charcoal, wood pellets, briquettes, biochar briquettes etc) and gases (methane and hydrogen) (Promdee et al., 2017). The biofuels are converted into bioenergy using different conversion pathways; (i) anaerobic digestion and fermentation for gaseous biofuels, (ii) gasification, combustion, pyrolysis and hydrolysis for solid biofuels and, (iii) Transesterification for liquid biofuels (Promdee et al., 2017).

This study contributes on the production of solid biofuels. using two invasive plant biomass that found in Lesotho's rangelands, known as Sehalahala (*Seriphium plumosum and Felicia filifolia*).

1.2. Problem statement

Charcoal briquettes can be produced using several materials, namely; municipal waste , agricultural residues, invasive shrubs and wood chips (Abdullahi et al., 2017; Allesina et al., 2018; Ji et al., 2018; Sahoo et al., 2019). With regard to municipal waste, feedstock such as paper and saw dust are widely used across literatrure for development of charcoal briquettes (Fuwape and Sobanke, 1998; Roy et al., 2015; Yang et al., 2016). In addition, charcoal briquettes have been produced using agricultural residues such as; plant shells, cobs, husks and straw (Jittabut, 2015; Muazu and Stegemann, 2015; Roy et al., 2015; Rahaman and Salam, 2017; Rominiyi et al., 2017a; Wang et al., 2017b). Wood chips from different trees such as eucalyptus, palm, pine have also been used for production of briquettes.

However, the focus of this thesis is on the production of charcoal using invasive plant biomass. Previously, invasive shrubs such as water hyacinth (Oroka and Thelma, 2013; Munjeri et al., 2016; Bandara and Kowshayini, 2018; Carnaje et al., 2018), mikania (Shuma et al., 2017) and Japanese knotweed (Brunerova et al., 2017) have been used for production of charcoal briquettes. However, there is no research which has been undertaken using these feedstocks; *Seriphium plumosum* and *Felicia filifolia* shrubs. These are the most dangerous and prevalent invasive shrubs found in Lesotho's rangelands (Hae, 2016).Thus, the study will contribute to existing literature by characterisation of charcoal briquettes produced from *Seriphium plumosum* and *Felicia filifolia.*

It is against this background that this study seeks to provide an innovative solution for integrated catchment management; creating charcoal briquettes from invasive shrubs cleared from rangelands during *fato-fato* government programmes. The goal of the research is to create a new energy product out of the waste material.

1.3. Objectives of the study

The main objective of the study is to investigate the potential of selected woody invasive shrubs found in Lesotho's rangelands for production of bio-char briquettes with the following specific objectives.

- Develop charcoal briquettes using different woody biomass invasive shrubs (*Seriphium plumosum and, Felicia filifolia)* locally known as *Sehalahala*.
- Evaluate the physicochemical properties of sample charcoal briquettes and respective suitability for domestic use.
- To evaluate the impact of clay and wheat as binder on calorific value of *Sehalahala* briquettes.

1.4. Rationale of the study

The challenge of energy access for cooking, water heating and space heating in the rural areas of Lesotho is huge, hence the need to research on the use ofthe available materials (invasive shrubs) for alternative clean energy products. Carbonised briquettes produced from invasive shrubs can be used to mitigate the effects of traditional use of biomass in Lesotho; deforestation, indoor air-pollution, time consumed collecting wood and open fire related injuries

The rationale for this study is to develop a combustible energy product made from local (waste) materials which will be used in rural areas for heating and cooking applications.It is envisaged that the newly produced briquette will serve as an alternative to traditional usage of biomass (cow dung, agro-residues, shrubs, wood). The study adopted Sehalahala as a waste material from the Public Works Programme of the Ministry of Forestry and Soil Conservation

1.5. Motivation of the study

Rangelands are an important source of livelihood to nearly two thirds of Basotho (Ministry of Forestry and Soil Conservation, 2014). Rangelands contribute to Lesotho's economy in three-fold: (i) being a grazing sites for livestock, rangelands serve as an input for major commercial agricultural commodities such as milk, meat, wool and mohair; (ii) rangelands provides non-agricultural benefits such as wildlife habitat and (iii) it provides biomass that can be used for household energy needs, thatch and medicinal plants.

However, over the past decades, there has been a significant decline in the productivity of rangelands in Lesotho due to encroachment of invasive shrubs (Hae, 2016). The effects of encroachment of invasive shrubs are both ecological and economical. With the former, research has shown that invasive shrubs affect rangelands by using excessive amounts of resources, notably, water, light, and oxygen (Hae, 2016; Lesoli et al., 2013). With the latter, they decrease rangeland productivity which is a major source of forage for grazing animal which in turn influences the quality of animal production in Lesotho (Lesoli et al., 2013).

Over the past two decades, Lesotho has implemented several projects with the aim of reversing encroachment of invasive species on rangelands. These programmes, commonly known as *fato-fato* have focused on the control of invasive plants encroachment on rangelands through employing communities to physically cut and uproot woody invasive shrubs on rangelands (Ministry of Forestry and Soil Conservation, 2014)). This method of manually uprooting invasive plants is known to be the most effective yet, the least sustainable (Ministry of Forestry and Soil Conservation, 2014)). According to the Ministry of Forestry and Land Reclamation (MFLR) (2014), the programmes are not sustainable due to heavy labour costs which are mostly sponsored through donor by government.

Among other factors mentioned, this study was further motivated by recent policy statements of the Governments of Lesotho, which seek to engage youth in the harvesting of *Seriphium plumosum* and *Felicia* on Lesotho's rangelands. The Government has envisaged to employ 3000 youth from the 10 districts of Lesotho to harvest the invasive shrubs in order to save rangelands. However, there is no clear plan on what will be done with the harvested material. Previously, this material has been burnt into pits. It is against this backdrop that the current study investigates the potential of producing bio-char briquettes using the harvested material.

In addition, the success of the South African Department of Environmental Affair's (DEA) Working for Water (WfW) programme which used harvested invasive shrubs for production of eco-furniture (Mugido et al., 2014) has also motivated this study. However, this study considers value addition through conversion of invasive shrubs into solid biofuels namely charcoal briquettes. Conversion of woody invasive species in to biofuels has been widely studied in literature (Munalula and Meincken, 2009; Smit, 2010; Young et al., 2011; Liao et al., 2013; Mugido et al., 2014; Amaducci and Perego, 2015). But, none have explored the potential of invasive species found on Lesotho's rangelands for charcoal briquette production, hence the motivation for this study.

1.6. Structure of the dissertation

This study is structured into five chapters. Chapter one provides an introduction while chapter two discusses the literature review and chapter three the methodology and materials used for undertaking physico-chemical analysis of charcoal briquettes. Chapter four presents the results of the study and further discusses them. Chapter five conclude the study with a set of recommendations.

2. LITERATURE REVIEW

2.1 Solid biomass and sustainable energy

Solid biomass refers to wood, charcoal, leaves, agricultural residue, animal/human waste and urban wastes. It can be used for cooking, heating and co-combustion applications in residential and industrial settings either in traditional or improved and modern way of utilisation...

Traditional use of solid biomass refers to the direct combustion of solid biomass such as wood, charcoal, briquettes, agro-waste, animal and human waste, and municipal waste, for cooking and space heating (Murdock et al., 2019). The direct use of solid biomass as primary fire wood is associated with rural households in developing countries for cooking and heating in simple and inefficient devices (Murdock et al., 2019). However, this method of using solid biofmass is still the largest contributor of bioenergy in global energy mix. The amount of traditional biomass used in 2017 is estimated at 27.5 EJ from a total of 46 EJ contributed by bioenergy in the global supply mix (Murdock et al., 2019). Yet, it is worth noting that the share of traditional use of solid biofuels has been declining for several years, from 8.8% in 2006 to 7.6% in 2017 (Murdock et al., 2019). This is due to adoption of; (i) improved traditional use of solid biomass and (ii) modern use of solid biomass.

Improved traditional use of biomass refers to direct combustion of solid biomass using improved and efficient technologies. These technologies improve the combustion properties (improved cookstoves) and thermal properties of solid biomass (densification and fuel characterisation) (Wu et al., 2011). Modern use of solid biomass refers to the use of solid biomass for production of advanced non-solid fuels for bioheating and bioelectricity (Bazargan et al., 2014). Solid biomass is considered a sustainable energy source if it is not used in a traditional method.

2.1.1. Use of biomass in developed countries

Solid biomass is used in different methods for different applications in the world. In developed countries, solid biomass is used in a modern method for applications such as heating and production of electricity (Goldemberg and Coelho, 2004). For this, there are several entities which are responsible for growing, harvesting, transportation and processing of solid biomass. These entities range from local companies which provide small scale heating applications to regional and national entities which provide large scale district heating and power generation applications (Nikulin et al., 2016).

In developed countries, pellets are produced for residential heating, large scale heating and power generation. However, the bulk of supply in power generating plants is imported from places outside the European Union. The United states is still the largest manufacturer and exporter of wood pellets at a capacity of 10.6 million tonnes in 2018 (Murdock et al., 2019). This is approximately 30% of the global production and trade of pellets, estimated at 35 million tonnes (Murdock et al., 2019). The US exports an estimated 5.4 million tonnes of pellets to Europe - primarily United Kingdom, Denmark, Italy and Netherlands (Murdock et al., 2019). Russia and Canada are also large scale exporters to European countries with an estimated 3.6 million tonnes and 2.7 million tonnes respectively in 2018 (Murdock et al., 2019). Japan is also exported an estimated 0.6 million tonnes of pellets to Europe in 2018 (Murdock et al., 2019).

Demand for pellets, for biomass fired Combined Heat Power (CHP) plants, in European Countries is estimated to increase over the next decade due to the policy directive stipulated in the EU Renewable Energy Directive targets for 2020 to 2030 (Murdock et al., 2019). The United Kingdom in 2019 commissioned a 27 MW capacity CHP plant fuelled by pellets and locally sourced wood in Sandwich (Murdock et al., 2019). The plant delivers heat and power to 50 000 households (Murdock et al., 2019) In the Netherlands, a 15 MW plant s under construction at Duiven and it is envisaged to be fuelled by pellets, municipal waste and wood waste (Murdock et al., 2019).

In the Latin America, agricultural wastes are the most used form of solid biomass for production of heat and electricity. For example, in Brazil, a 50 MW plant fuelled by sugar cane waste is used to supply a sugar mill and excess electricity into the grid (Murdock et al., 2019).. In Argentina, a major peanut producer, Prodeman, uses peanut shells to produce 10 MW of electricity for their peanut plant (Murdock et al., 2019).

Forest residues are also being used as an energy source in some developing countries as well. In La Caruna Spain, a 50 MW biomass power plant which is fuelled by locally sourced forest waste was commissioned in 2018 (Murdock et al., 2019). In addition, in South Africa, the Ngondwane Energy Biomass Project, supported under the Renewable Energy Independent Power Producers Procurement Programme has reached financial close and it is expected to commence operations in 2021 (Murdock et al., 2019).

2.1.2. Use of biomass in developing countries

Solid biomass, in the form of wood, animal dung and crop waste, is used in developing countries for residential cooking and space heating, unlike in developed countries where it is used for residential space heating, district heating and CHP plants (Goldemberg and Coelho, 2004). Households in developing countries, particularly in rural areas, use solid biomass in its traditional form in open fires and inefficient heating and cookstoves (Goldemberg and Coelho, 2004). Between 1990 and 2018, the population using solid biomass, traditionally is estimated at around 2.7 and 2.8 billion, respectively (Jafta et al., 2019). The reason being that solid biomass is used for cooking and heating, which account for 90% of household energy needs (WEO, 2017). It is estimated that in 2018, around 2.6 billion rely on traditional biomass, while 400 million use coal as their primary cooking fuel (WEO, 2017). Over 700 million people without access to modern fuels for cooking live in the Least Developed Countries (LDCs) and with a majority of them, estimated at around 600 million, in sub-Saharan Africa (WEO, 2017).

The vast majority of people who rely on solid fuels for cooking are concentrated in Asia and sub Saharan Africa. It is estimated that 75% of people who use solid biomass for cooking live in Asia, with India and China accounting for 27% and 25%, respectively, of all those using solid biomass for cooking (Legros et al., 2009). While sub Saharan Africa makes up 14% of the total population of developing countries, it accounts for more than 20% of people relying on solid biomass as their primary cooking fuel (Legros et al., 2009).

The share of population relying on wood as a cooking fuel is highest in sub-Saharan Africa and South Asia. It is estimated that almost 70% of people in sub-Saharan Africa primarily use wood for cooking (Legros et al., 2009). This is higher than India (58%) and South Asia (49%) (Legros et al., 2009). The reliance on solid fuels in sub-Saharan Africa (82 %) is higher than any other geographic region.

FAO estimates that the global production of wood charcoal was about 53.2 million tons in 2018, of which 34.2 million tons (or around 64%%) were produced in Africa (FAO, 2020). Data from FAOSTAT indicate that around 90% % of the wood removed from the forests and woodlands in Africa are used as fuel, of which about 29 %% are converted into charcoal (FAO, 2020). Due to steady increase in market demand, the production of wood charcoal in Africa has almost doubled in 20 years from 1998 to 2018 and accounted for roughly two-thirds of the global production (FAO, 2020).

2.1.3. Use and abundance in Lesotho

Lesotho like most least developed countries relies on solid biomass for residential cooking and heating applications. Cooking represents one of the most energy-intensive applications in rural households of Lesotho. It is estimated that 72.9% of Lesotho's population (2 million) resides in rural areas (Department of Energy, 2017). Lesotho's rural households' energy consumption is characterised by a reliance on solid biomass such as wood and dung (70%) and paraffin (16%) (Department of Energy, 2017). Only few rural households (14%) continue to depend on electricity, coal and LPG (Department of Energy, 2017). It is estimated that 90% of rural population uses firewood, crop and animal residues for space heating (Department of Energy, 2017). Only 10% of the population uses paraffin and gas for space heating in rural areas (Department of Energy, 2017).

Urban households are less reliant on biomass and mainly use paraffin and gas for heating and cooking. Only 10% of urban households use firewood for cooking and a vast majority use gas (50%), paraffin (30%), and electricity (10%). However, 70% of urban households use paraffin for space heating (Department of Energy, 2017).

Charcoal is another solid biomass which is used in Lesotho for barbecuing applications in urban households and small informal food business. Over the past three years' charcoal production was estimated at 34 tonnes, 38 tonnes and 17 tonnes in 2015, 2016, and 2017 respectively (Bureau of Statistics, 2018). Charcoal is produced by small scale producer in different districts of Lesotho.

2.1.4. Challenges of using solid biomass for cooking and heating

Relying on traditional use of solid biomass possess several challenges for developing countries; (i) health impacts, (ii) burden on women and girls, and (iii) climate change. Worldwide, almost two million deaths annually from pneumonia, chronic lung diseases, and lung cancer are associated with exposure to indoor air pollution resulting from cooking with biomass and coal, and 99%%of them occur in developing countries (Fullerton et al., 2008). Almost half the global population (45%%) still relies on solid fuels for household use, resulting in dramatic impacts on health, especially for children and women (Fullerton et al., 2008). Some 44%% of these deaths occur in children; of the adult deaths, 60%% occur in women in developing countries. In LDCs and sub-Saharan Africa, more than 50%% of all deaths from these three diseases can be attributed to solid fuel use, compared with 38%% in developing countries overall (Fullerton et al., 2008). Given the high burden of these diseases in LDCs and sub-Saharan Africa, household energy interventions clearly have considerable potential to improve health and promote achievement of MDGs, particularly MDG-4 on child survival (Fullerton et al., 2008).

In developing countries, 60 % of all deaths from COPD and lung cancers attributable to solid fuels are amongst women (Fullerton et al., 2008). Since women are generally in charge of cooking and spend a large amount of time in the kitchen, they bear a larger burden of disease as a result of their higher exposure to indoor air pollution. The ratio of death rates in women compared to men are highest in East Asia and the Pacific, where women account for 64 % of all deaths from COPD and lung cancer attributable to solid fuel use (Fullerton et al., 2008). For child pneumonia, no analysis by gender was performed as the available studies do not allow separate estimation of the risk of child pneumonia for boys and girls.

Emissions from burning solid fuels in open fires and traditional stoves also have significant global warming effects, due to incomplete combustion of fuel carbon. Consequently, interventions that improve combustion efficiency and hence reduce emissions and exposure to pollutants can benefit health and mitigate climate change.

2.1.5. Technologies for mitigating adverse effects of solid biomass

2.1.5.1. Combustion Technologies - Improved Cookstoves

Technologies developed to mitigate the adverse effects of solid biomass include; combustion technologies and thermal technologies. Combustion related technologies have focussed on improving the cooking methods through adoption of improved cookstoves. These stoves offer three advantage over traditional open fires; (i) Improved heat-transfer efficiency - the amount of heat is absorbed by the pot, (ii) improved combustion efficiency - the amount of energy and carbon in the fuel is converted to heat and carbon dioxide and, (iii) improved overall thermal efficiency – the amount of energy in the fuel which is absorbed by the pot (Venkataraman et al., 2010). . Many workers argued that the primary goal of improved cookstoves is to reduce the amount of fuel, and deforestation, which is need for cooking purposes. Improved cookstoves were designed primarily to improve the efficiency of heat transfer to the cooking pot, thereby saving fuel and reducing pressure on forest resources. Improved cookstoves can reduce fuel use by 20–50 % relative to the three-stone fire (Venkataraman et al., 2010)

There are various types of improved cookstoves developed across the world. Many are designed with the cook in mind and aim not to change cooking practices but to accommodate a cook's habits, fuel choice, and traditional cuisine (Ekouevi and Tuntivate, 2012). Rocket stoves are the most widely used cookstoves. Rocket stoves are defined by improvements to an insulated, L-shaped combustion chamber that allows for partial combustion of gases and smoke inside the cookstove (Ekouevi and Tuntivate, 2012). Rocket stoves follow 10 design principles to improve heat transfer using insulation and narrow channels that direct the flow of hot gases closer to the pot or griddle. Stoves that incorporate a griddle for cooking flat breads are most prevalent in Latin America, and throughout this region are referred to as plancha stoves. The plancha stove is designed to enclose the fire to heat the griddle surface and to expel through a chimney the particulate matter and toxic vapors resulting from incomplete combustion (Ekouevi and Tuntivate, 2012). Although fuel efficiency was the main concern of designers of fuel-efficient cookstoves, in some parts of the world—notably Latin America and South Asia—some cookstoves were also provided with chimneys or hoods (Ekouevi and Tuntivate, 2012). These help reduce indoor air pollution by diverting wood smoke out of the kitchen, though they do nothing to curb outdoor pollution or climate change (Smith et al., 2009). The reduction of indoor emissions varies significantly. Some fuel-efficient cookstoves deliver little or no reduction, whereas others can reduce particulates and carbon monoxide by up to 90 % in laboratory testing (Smith et al., 2009). Stoves with a well-fitted chimney kept in good condition and regularly cleaned can dramatically reduce indoor air pollution.

2.1.5.2. Densification Technologies - Pellets and briquettes

Technologies used to improve the thermal properties or energy content of solid biomass include; densification and carbonisation. With regard to densification, problems associated with solid biomass such as high bulk volume, which results in high transportation costs and requires large storage capacities, and to the high moisture content which can result in biological degradation as well as in freezing and blocking the in-plant transportation systems are reduced. All these problems may be overcome by densification, which consists in compressing the material to give it more uniform properties. Benefits of densification are; (i) An increased bulk density (from 80-150 kg/m3 for straw or 200 kg/m3 for sawdust to 600-700 kg/m3 after densification), resulting in lower transportation costs, reduced storage volume and easier handling, (ii) A lower moisture content (humidity <10%), favouring a long conservation and minor losses of product during the storage period and (iii) An increased energy density and more homogeneous composition, resulting in better combustion control possibilities and thereby higher energy efficiency during combustion (Tanger et al., 2013). Densified products can be found as briquettes or as pellets. The heating value, moisture content and chemical characteristics are about the same for both but the density and strength are somewhat higher for pellets. The major difference is the size making them easy to use in fully automatic operation, from household appliances to large-scale combined heat and power (CHP) plants.

2.1.5.3. Carbonisation Technologies – Lump Charcoal

A promising alternative form of bioenergy production is via thermochemical conversion—the controlled heating or oxidation of biomass (Demirbas, 2004)). The term covers a range of technologies including pyrolysis, gasification, and combustion which can be configured to produce outputs of heat, electricity, or gaseous or liquid precursors for upgrading to liquid fuels or chemical feedstocks (Demirbas, 2004). Thermochemical technologies show great promise for the production of renewable electricity, both in the context of biomass co-firing in existing coal powerplants and for decentralized electrification projects in developing countries (Demirbas, 2004). Thermochemical produced electricity could help fulfill standards enacted in many US states that require a certain %age of electricity be produced from renewable sources (Demirbas, 2004). In some cases, thermochemical production of renewable electricity or liquid fuels and associated co-products is the most effective use of biomass for fossil energy displacement (Demirbas, 2004).

2.1.5.4. Charcoal briquetting

Briquetting is the process of converting low bulk density biomass into high density and energy-concentrated fuel. Cohesion is achieved by low pressure agglomeration with the use of binders (e.g. molasses), medium pressure compaction with a lower binder percentage or high pressure compaction with little or no binder. The main benefit of compacting biomass is to increase energy density - the amount of useful energy per unit of volume (Mwampamba et al., 2013)..

Energy density can be increased further by carbonizing the biomass before or after compaction (Mwampamba et al., 2013). Carbonisation entails conversion of the biomass into carbon through pyrolysis i.e., subjecting the biomass to high temperature, low oxygen conditions (Mwampamba et al., 2013). Torrefaction is an intermediate option that consists of slow heating of biomass in an inert atmosphere at lower temperatures than for conventional pyrolysis. Carbonization of biomass residues almost doubles the energy value per unit of weight with bio-char having a calorific value of 25–30 MJ/kg, compared to around 15 MJ/kg for unprocessed biomass (Demirbas, 2009) and gives briquettes a charcoal-like appearance, hence the terms “charcoal briquettes” or “ biocoal”.

Charcoal briquettes, just like traditional charcoal, is produced from solid biomass by a process known as carbonization. Carbonisation is also known as pyrolysis. In this process, biomass is heated under oxygen-deprived conditions hence producing a substance known as black carbon or charcoal (Brožek, 2015). The feedstock used to produce charcoal briquettes comes from agricultural, industrial, forest waste whilst the feedstock from traditional charcoal and briquettes is derived from trees (Shuma and Madyira, 2017). Agro waste such as maize stalks, rice husks and twigs can be used for charcoal briquettes production. Through the use of agro, industrial, and forestry waste, the cutting of trees for charcoal production is reduced significantly, thus charcoal is considered as a sustainable renewable energy (Arévalo et al., 2017).

Charcoal briquettes can be considered as a substitute to the use of traditional charcoal since the latter requires the cutting down of trees. On the other hand, charcoal briquettes considered environmentally friendly as it uses waste and converts it to useable energy. Charcoal, produced from waste material, is compressed and densified into briquettes that can eventually be used for provision of heat energy for cooking and space heating.

The use of the charcoal briquettes has several advantages compared to the use of traditional charcoal. Firstly, apart from it substituting the wanton cutting down of trees that would eventually result into the disappearing of forests, use of charcoal briquettes has a direct positive impact on the environment and can be considered a mitigation measure for the causes of climate change (Demirbas, 2009; Liao et al., 2013;Ji et al., 2018; Weaver et al., 2018). Secondly, unlike traditional fuelwood, charcoal briquettes have relatively low moisture content which makes them more energy efficient since less energy is used to drive away the moisture during combustion (Prathomtong et al., 2016). Thirdly, the high %age fixed carbon content in bio-char briquettes relative to wood leads to high heating value per unit mass of bio-char which comes as a result of carbon content due to the carbonization process (Pereira et al., 2012). Fourthly, most of the volatiles (wood extractives) found in wood are driven out of the wood matrix during its carbonization which in turn leads to low volatile matter in charcoal than in wood (Prathomtong et al., 2016). As a result, charcoal briquettes burns with little or no smoke and hence reduced the amount of polycyclic aromatic hydrocarbons released, which as a result minimizes pollution of the environment and health hazard problems (Prathomtong et al., 2016).Bio-char briquettes which are proposed in these study that made from waste materials and invasive shrubs are considered as modern biomass and sustainable energy.

2.2. Charcoal Briquettes Production Process

Charcoal briquettes are briquettes which are not made by cutting trees, but rather using raw materials such as industrial and municipal waste, agricultural residues, invasive shrubs and wood chips. The process involves carbonisation of feedstock, grinding of carbonised feedstock into charcoal powder, mixing charcoal powder with binder, briquetting and drying. Figure 1 illustrates the process of developing charcoal briquettes. The subsequent sub-chapters will discuss each stage of the processes illustrated in Figure 1.

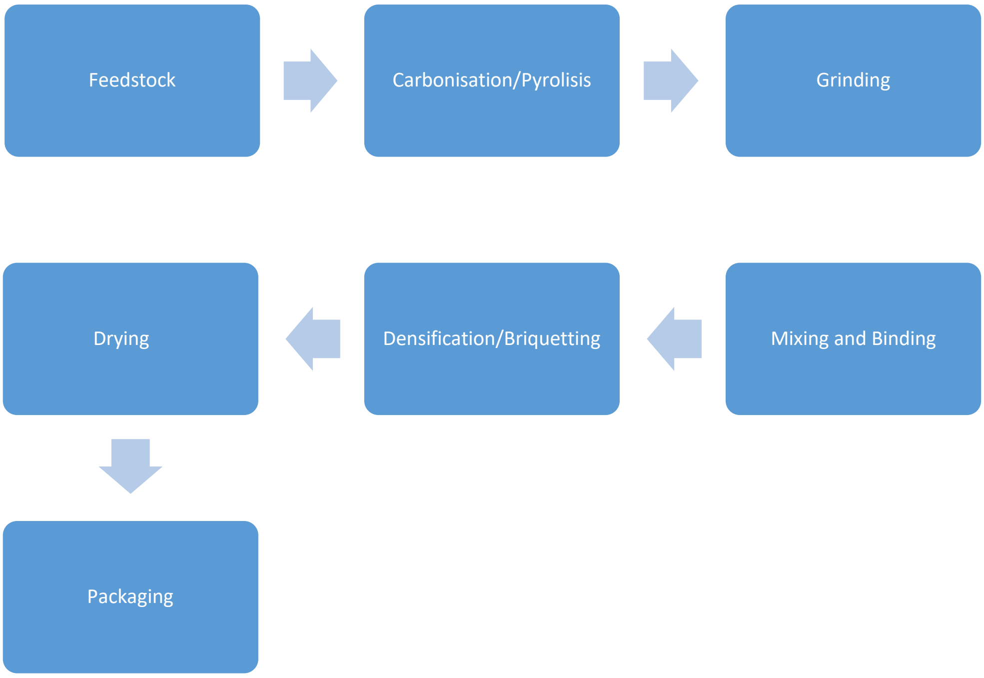

Figure 1: Process of charcoal briquettes production.

2.2.1. Charcoal briquettes feedstock selection

Environmentally friendly charcoal briquettes, also known as modern biomass, can be produced using several feedstocks: solid waste, agricultural residues, invasive shrubs and woodchips. With regard to solid waste, some studies have used paper as feedstock (Mburugu, 1994; Brožek, 2015; Oyelaran et al., 2015a; Roy et al., 2015; Odusote et al., 2016) while some have used saw dust (Fuwape and Sobanke, 1998; Akowuah et al., 2012; Obi, 2015; Antwi-Boasiako and Acheampong, 2016; Lela et al., 2016; Rajaseenivasan et al., 2016; Yang et al., 2016; Rominiyi et al., 2017b; Liu et al., 2018b; Nyaanga et al., 2018). Furthermore, there are studies which used textile waste to form bricks (Avelar et al., 2016; Zhuo et al., 2017) while some studies have used sewage (Panwar et al., 2011; Kim et al., 2016; Yilmaz et al., 2018) and faecal sludge (Kiwana and Naluwagga, 2016; Nyaanga et al., 2018; Atwijukye et al., 2018; Atwijukye, 2019)

However, majority of charcoal briquettes in developing countries have been produced using agricultural residues. Coconut shells were the most used agricultural residues with a calorific value ranging from 17.0-20.7 MJ/Kg (Arellano et al., 2015; Promdee et al., 2017; Yuliah et al., 2017; Dziedzic et al., 2018) Corn cobs, husks, straw and stover were also used by farming communities to produce bio-char briquettes (Jittabut, 2015; Muazu and Stegemann, 2015; Roy et al., 2015; Rahaman and Salam, 2017; Rominiyi et al., 2017a; Wang et al., 2017b). Palm oil fiber had the highest calorific value for agricultural residues estimated at a range of 18.4-35.5 MJ/kg (Sing and Aris, 2013; Faizal et al., 2015; Hamid et al., 2016; Kurnia et al., 2016; Maitah et al., 2016; Abdullahi et al., 2017). Rice husks had the lowest calorific value estimated at a range of 14.2-20.5 MJ/kg (Efomah and Gbabo, 2015a; Jittabut, 2015; Muazu and Stegemann, 2015; Obi and Okongwu, 2016; Rahaman and Salam, 2017; Quispe et al., 2017).

With regard to invasive shrubs, seaweed Japanese Knotweed (Brunerova et al., 2017) and water hyacinth (Davies and Davies, 2013; Oroka and Thelma, 2013; Shyamalee et al., 2015; Munjeri et al., 2016; Bandara and Kowshayini, 2018; Carnaje et al., 2018) are the most used feedstock for producing briquettes, though the calorific value has been low: 12.6-17.4 MJ/kg (Hedman et al., 2005; Haykiri-Acma et al., 2013; Jenkins et al., 2019). Other studies have used wild shrubs (Yumak et al., 2010; Susanti et al., 2015; Ciesielczuk et al., 2016; Raj and Syriac, 2016).

Wood chips and waste in forests are widely used in developing countries for developing bio-char briquettes (Shuma and Madyira, 2017; Han et al., 2018; Sahoo et al., 2019)

2.2.2. Carbonisation process

The production of traditional charcoal from wood is through a process known as carbonization. Carbonization is a term used when complex carbonaceous substances like wood or agricultural residues are broken down by heating into elemental carbon and chemical compounds which may also contain some carbon in their chemical structure (Atwijukye et al., 2018). Under carbonization, the raw material, which is solid biomass in this case, has to be burnt under controlled amount of oxygen to prevent absolute burning (Zaror and Pyle, 1982). The resulting product is black carbon. The process of production can be deemed to be sensitive as any excess amount of air present in the kiln can lead to absolute combustion of the fuel.

Carbonisation can be conducted in four stages. The first stage of the carbonization process is to provide energy for driving out the moisture content from the wood (Jenkins et al., 2019). When harvested, the moisture content in plants is commonly 50% and may be as high as 90% in aquatic algae (Jenkins et al., 2019). The water content is driven off as vapour from the chambers. To save on the energy used during the drying process, it is recommended that the wood is first pre-dried using open sun drying before putting it in the kiln (Abdullahi et al., 2017). The pre-drying phase reduces the amount of moisture in the wood. Materials are considered to be dry when the moisture content reaches about 10% to 15% (Jenkins et al., 2019). During the heating process, when temperatures begin to rise in the kiln, the wood will start losing the moisture up to the maximum temperature of 100^{o}C when it is considered that the higher percentage of water molecules would have all evaporated and the wood can be considered to be very dry. The presence of moisture in biomass fuel often leads to a significant loss in useful thermal output since the evaporation of water requires about 2.3MJ/Kg (Jenkins et al., 2019).

In the second stage, the temperature in the chamber continues to rise as the energy is coming from the wood as it starts to undergo the stages of conversion, the stage is considered as an energy absorbing reaction or endothermic reaction. The temperatures at this stage will rise to about 280°C (Jenkins et al., 2019). At the temperature of around 280°C, the wood begins to spontaneously break down to produce charcoal and entities such as methanol, acetic acid and water vapour and other more complex chemicals (Jenkins et al., 2019). The complex materials are mostly in the form of tars and non-condensable gas consisting mainly of hydrogen, carbon monoxide and carbon dioxide (Jenkins et al., 2019). During the carbonization process, air enters the kiln or pit through properly done air vents so as to allow the burning process to continue during the conversion process. Occasionally, the vents will be opened and closed for observation purposes and air flow control.

The third stage occurs around a temperature of 280°C. At temperatures above 280°C, there is spontaneous breakdown or carbonization of the wood which results in giving out energy, thus this stage of reaction is said to be exothermic in nature (Salema et al., 2017). This process continues until only the carbonized residue remains. The carbonized residue is what is termed as charcoal. The temperature at which the process of carbonization is taking place is of great importance. At a temperature of about 400°C as peak kiln temperature, the process of conversion can be stopped and the raw material would have converted to a desired product. It is important to note that at this maximum temperature, the charcoal produced will still contain appreciable amounts of tarry residue and with the ash content of the original wood.

At the maximum temperature of 400°C, the ash content of the charcoal will be in the range of 3-5% and the tarry residue may amount to about 30% by weight (Jenkins et al., 2019). The rest of the mass of the product is the fixed carbon which is about 65-70%. To increase the fixed carbon content, temperature can be raised by further heating the product. The heating process will facilitate the driving off and decomposing of more of the tars that are still present in the product (Wang et al., 2017a).

The fifth stage occurs above 400°C. Increasing the temperature to 500°C further drives off the tars and gives a typical fixed carbon content of about 85% and a volatile content of about 10% (Yang et al., 2016). The yield of charcoal at this temperature is about 33% of the weight of the oven dry wood carbonized (Liu et al., 2018a)

It is important to note that low carbonization temperatures will give a higher yield of charcoal, but the charcoal produced will be of low grade. This charcoal will be corrosive due to its content of acidic tars, and is not going to burn with a clean smoke-free flame. Thus, for the production of high quality charcoal, the production process has to be followed with great attention in order to ensure that the end product has a fixed carbon content of about 75% (Jenkins et al., 2019). The easiest way to ensure that getting good quality charcoal is attained is to reach the reaction temperature to a maximum of around 500°C (Wang et al., 2017a)

The charcoal quality is also dependent on the type of wood used. The lignin content of the wood is a component of great importance in the quality of the wood, thus trees of high lignin content will show a high inclination of yielding charcoal with high quality (Demirbas, 2009). The more mature a tree harvested for wood is, the better it is for charcoal production. Another type of quality that is preferred for charcoal production is the dense type. Dense wood tends to give strong charcoal, however, very dense woods sometimes produce a friable charcoal because the wood tends to shatter during carbonization (Tanger et al., 2013). Friability is the tendency of a solid substance to break into smaller pieces under duress or contact. With charcoal, it can be noted that the friability increases as carbonization temperature increases and the fixed carbon content increases as the volatile matter content falls (Zhuo et al., 2017). Thus at temperatures between 450 and 500°C an optimum balance between friability and the desire for a high fixed carbon content is achieved (Demirbas, 2004). This makes the conclusion that quality charcoal is produced at a maximum temperature of 500°C.

2.2.3. Types of kilns used during carbonisation

Charcoal production ranges from small to commercial scale. The equipment used in the production process is dependent on the scale. Some equipment is basic and needs little or no control and others can be so sophisticated needing automation. The choice of equipment is mostly governed by the cost involved, the geographical location and the type of feedstock being used.

There are four types of kilns used during carbonisation of feedstock for production of charcoal briquettes. The first type is called the earth mound kilns. They are the most predominant kilns used in low-cost production (Adam, 2009). The process of making the mounds involves biomass gathering, then cutting to suitable sizes and finally placing on the ground. The mound or pile of biomass is then covered with earth. The earth forms the necessary gas-tight insulating barrier behind which carbonization can take place without leakage of air (Promdee et al., 2017). After firing the kiln, the biomass heats up and start to lose its moisture, this stage is important as the biomass could be having a percentage of moisture in it. Some spots are left open so as to allow exhaustion of moisture. Visual observation can be used at this stage, the discharge is white smoke indicating that the moisture is being driven off (FAO, 1985). The carbonization process starts to take place and this can be seen from the change in colour of the fume discharge, the fumes will change from a yellowish to a dark colour, this change in the colour indicates the driving out of the syngases, when the discharge becomes clear, it is an indication that the carbonization process has been complete (FAO, 1985). Generally, the earth kilns are usually large and are common for use when using larges pieces of wood. The main challenge of this system of kiln is the ventilation. Control of the carbonization is difficult to control and in most cases the carbonization is incomplete thus, having low quality charcoal as the end product (Adam, 2009).

Attempts have been done to improve the efficiency of the kilns such as the Casamance kiln which are equipped with a chimney. The purpose of the chimney is to allow a better control of air flow and in the process reducing heat loss during carbonization and improving gas circulation (Adam, 2009). These improvements on the earth kiln (Figure 2) results in giving a higher quality of charcoal.

Figure 2: The structure of Earthen Mount Kiln.

The second type of kilns is the earth pit kiln. The earth pit kilns are similar to earth mound kilns but they use a pit as opposed to a structure constructed on the surface. These kilns are common in many African countries where charcoal production is not sustainably done. The design involves the use of well excavated pits that are properly drained to avoid seepage of water (Adam, 2009). The logs are laid in the pit and the pit is buried with soil and only leaving out small vents that allow for carbonization process.

The third type of kilns are the brick kilns. Brick kilns are constructed as fixed structures using masonry means. The kilns are commonly used by the medium scale producers. The brick kiln is said to be one of the most effective method of the charcoal production (Adam, 2009). However, one of the setbacks on using this type of kiln is its stationary nature, unable to move to other locations that have biomass readily available.

The fourth type of kilns are the steel kilns. Steel kilns come in different shapes and sizes. Some of the common ones include the reuse of 210 litres steel drums that are mainly used for storage of various products such as petroleum and chemicals. The main distinctive qualities of steel kilns is in their capability to carbonize even poor quality wood and their portability (Adam, 2009). The steel kilns do have a much quicker carbonization cycle than others since they allow for easy control and operation, thus allowing air flow management in the kiln which is critical in the carbonization process (Adam, 2009). Depending on the feedstock used, the carbonization process can even last as short as 25 minutes.

2.2.4. Binding and mixing of charcoal powder

Feedstock which cannot densify on its own to formulate bio-char briquettes is bonded using binders. Several types of binders have been used in literature to date. The following binders were found to have good adhesive properties; biodegradable paper soaked in water, subsoil, lignin, fibers, glycerine, char, pitch, molasses, plastics and starch (Davies and Davies, 2013; Hu et al., 2015; Thabuot et al., 2015; Sen et al., 2016; Rahaman and Salam, 2017).

In some studies, wood cells containing high lignin were used as binder (Davies and Davies, 2013). In other studies, addition of slop waste as a binder increased the compressibility strength of the briquettes (Hu et al., 2015; Thabuot et al., 2015). However, majority of literature has proved that including starch in the briquetting process produces strong briquettes.

What is not known in literature is the optimum ratio of starch to char. However, the most recommended amount varies between 6% and 25% of starch should be added to carbonised feedstock (Davies and Davies, 2013; Hu et al., 2015; Thabuot et al., 2015; Sen et al., 2016; Rahaman and Salam, 2017).

Some studies have mixed the charcoal manually using spades and sometimes hands (Faizal et al., 2015; Roy et al., 2015). This method has been applied mostly in projects when there is a need for empowerment through job creating. Other projects used screw customised mixers, for example, a cement mixer was used for a project in Kenya.

2.2.5. Densification of charcoal briquettes

The optimum pressures that have been used for producing charcoal briquettes ranged from 50 MPa to 250 MPa for different feedstock characteristics (Yaman et al., 2001; Suhartini et al., 2011). The optimum compression time ranged between 4 and 25 minutes(Bazargan et al., 2014). The compression time requirement increases with a decrease in the applied pressure. With a pressure of 80 MPa and 150 MPa, briquettes were produced with a compaction time of 25 minutes and 6 minutes, respectively (Yaman et al., 2001). Optimum compression time is necessary for each feedstock due to the reversible nature of plastic deformation, which causes sudden dilation and may create fractures and splits in the briquettes.

Screw press and piston press are the two machines that have been regularly used to produce charcoal briquettes. The screw press operates by extruding feedstock continuously through a heated taper dye. The dye is heated externally to reduce friction. The advantages of using this type of machine are that it generates less noise during operation and can alternatively be used for producing carbonized briquettes(Abakr and Abasaeed, 2006; Wessapan et al., 2010). The disadvantages are the high wear and tear of the screw and large power consumption, and the fact that it requires a particular particle size and homogeneity of the raw material (Wessapan et al., 2010).

2.2.6. Drying and storage of charcoal briquettes

The two main drying types are passive and active drying. The distinction lies in the source of the drying media. The use of these two types is highly influenced by the geographic orientations, the type and state of feedstock to be dried. The other determining factor is the cost implication regarding the selection.

2.2.6.1. Passive Drying

Passive drying can simply be defined as the drying of the biomass material without using any external sources (Vest, 2003). This type of drying is wholly dependent on the prevailing weather conditions. The moisture being driven off the biomass will be determined by the surrounding moisture in the open environment. Such conditions makes the process slow and uncontrollable. For passive drying, the drying process is influenced by two factors, these are:

i. *Vapour pressure and relative humidity*: The presence of vapour in the drying environment will have a direct effect on the drying process. The drying air has the tendency of exerting a saturation vapour pressure when it holds a maximum amount of vapour. The drying process will occur when the water vapour present in the biomass is higher than that in the air. The ratio of actual vapour pressure to the saturation vapour pressure at a given temperature is called relative humidity (RH) and is normally expressed as a percentage form. Exposure of wet biomass is to unsaturated air (>100% RH), results in the evaporation of moisture from its surface hence achieving the drying process (Bujang and Safuan, 2011). The vapour pressure difference between the air closest to the biomass surface and that of the more mobile air above this zone determines the rate of evaporation of moisture from any given surface.

ii. *Air movement*: The movement of air around the biomass being dried is of major significance in the drying process. Stagnation of air around the biomass results in the drying air becoming saturated hence causing the evaporation of moisture from the surface of biomass to stop (Bin Bujang, et,al. 2011). To achieve perfect drying without the effect of stagnant air, it has to insured that the layer of air closest to the surface is not under saturation. Bulk drying of piles of biomass will mainly be affected by the stagnation of the air when put in a closed setup, hence it is important to leave the stacks in the open.

2.2.6.2. Active Drying

Active drying is defined as the drying process that requires the input of energy from an external source to speed up the process and achieve lower ultimate moisture content (Chua and Chou, 2003). The energy input could be inform of fans for air flow and heating elements that would allow for driving away of moisture. To achieve higher efficiency, a large surface area to volume ratio is required of the material to be dried, and good air flow over as much of the surface as possible (Chua and Chou, 2003). The air flow speed is an important factor; it has to be coupled with good ventilation. The surface exposure also plays a critical role in the active drying process. Limited access to the biomass surface can result in wastage of energy thus, moving, turning or spreading the material has to be incorporated in the drying process. The source of the heat can be from process heat from a plant, or a dedicated heating unit. Concentrated solar heating system can be considered as the cheapest source of heating for drying that can be used in the active drying system.

2.2. Performance analysis of charcoal briquettes

There are three methods which are used to investigate the performance of carbonised briquettes; proximate analysis, ultimate analysis, and higher heating value, also known as calorific value. In this section of the literature review; each of the methods will be described and how they affect the suitability of feedstock for production of briquettes.

2.3.1. Proximate Analysis

The proximate analysis provides the potential efficiency and durability of the briquettes that will be produced (Efomah and Gbabo, 2015b). This requires the following organic solid waste properties: moisture content, ash content, volatile matter and fixed carbon of the briquette. The total energy that is needed to bring a briquette up to its pyrolytic temperature is dependent on its moisture content which affects the internal temperature within the briquette due to endothermic evaporation (Adekunle et al., 2015). Moisture content is one of the main parameters that determine briquette quality: a lower moisture content of briquettes implies a higher calorific value (Yin, 2011).

The second property which is analysed through proximate analysis is the volatile matter. This is the part of biomass that may be released when the biomass is heated up, for example, during carbonization (Zaror and Pyle, 1982). On the other hand, high volatile matter may result in the high release of emissions during burning. Therefore, low volatile matter is of importance.

The third component is the ash which is a powdery residue that remains after burning of a material. It is comprised of mineral, which is a non-combustible material. A higher ash content will result in ash slagging (Bandara and Kowshayini, 2018; Ciesielczuk et al., 2016). This inhibits the combustion process by supporting overheating of the burning device and subsequently its corrosion. Therefore, an optimum ash content in feedstock is needed to control the burning process and to maintain the machine parts (Ciesielczuk et al., 2016; Bandara and Kowshayini, 2018).

The fourth component is the percentage of fixed carbon, which determines the amount of solids that remain once the carbonization process has been completed to produce briquettes (Arévalo et al., 2017; Salema et al., 2017; Bandara and Kowshayini, 2018). In this case, a higher carbon content in feedstock is likely to result in long-lasting and mechanically strong carbonized briquettes (Promdee et al., 2017).

2.3.2. Ultimate Analysis

The ultimate analysis involves quantifying elements contained in the bio-char briquettes. These factors influence the combustion behaviour, which is the levels and types of emissions that will be generated during usage of the briquettes especially for indoor use as it determines air quality (Adekunle et al., 2015). Key gases to monitor include the following: Carbon monoxide (CO), Nitrogen oxides (NOx) and Hydrogen. Carbon monoxide (CO) emission is attributed to the excess air factor (the higher the air factor used for combustion, the lower CO emissions (Demirbas, 2009). The CO emissions may also result from low combustion temperature, poor mixing of fuel with combustion air and short combustion time (Demirbas, 2009). Nitrogen oxides (NOx) content is proportional to the nitrogen content in the feedstock. The higher the nitrogen content, the higher NOx emission (Bandara and Kowshayini, 2018; Falemara et al., 2018). The NOx may also be produced at high temperature in boilers/kilns, even in the absence of organic nitrogen. Hydrogen results in water formation after combustion. High oxygen levels improve the burning potential of the briquette and reduce the burning temperature (Oyelaran et al., 2015b) Assessing the concentration of these elements in briquettes is very important.

2.3.3. Determination of calorific value

Generally, the heating value of a fuel may be explained on two bases: as higher heating value or gross calorific value and lower heating value or net calorific value. The higher heating value (HHV) refers to the heat removed from fuel combustion with the original and generated water in a condensed state, while the lower heating value is based on gaseous water as a product (Acar et al., 2016). The higher heating values (HHVs) contain the latent heat of the water vapour products of combustion because the water vapour is allowed to condense to liquid water. The relationship between high and low heating values (HHV): A low heating value (LHV) is the correction to HHV due to moisture in the fuel (biomass) or water vapour formed during combustion of hydrogen in the fuel (Acar et al., 2016).

The heating value of a fuel can be determined experimentally by employing an adiabatic bomb calorimeter, which measures the enthalpy change between reactants and products (Demirbas, 2004). However, the measurement is a complex and time-consuming process that requires the set-up, measurement and calculation procedures. The proximate and ultimate analyses of fuels are necessary for their efficient and clean utilization while the HHV of fuels determine the quantitative energy content of fuels (Demirbas, 2009).

2.4. Summary of Literature review

This chapter highlighted literature on how charcoal briquettes are an important part of bioenergy. Specifically, the literature revealed that; compared to traditional biomass consumption for heating and cooking applications, biochar presents an alternative clean fuel. Secondly, the literature review, indicated that the briquetting process starts with carbonization of feedstock into chartcoal fines. This process revealed that the there are different methods of carbonisation and the steel drums were found to be the most efficient for small scale operations because of their ability to provide airtight environments. Fourthly, the litereature also indicated that the best binder to use for briquetting is starch and clay. Fifthly, compression can be undertaken using any kind compressors as long as it can keep the samples together.

This literature also highlighted the importantance of characterization of briquettes in order to analyse their energy content. Parameters such as moisture content, volatile matter, ash content and fixed carbon content are important in determining the calorific value of the briquettes. In addidition, testing for the amounts of carbon, sulphur, nitrogen, hydrogen and oxygen in the briquettes is important for determining their suitability to the environment and domestic use.

The methodology for this study, presented in the next chapter, is based on the literature reviewed. Specifically, the literature guided the process of; (i) production of briquettes, and (ii) undertaking proximate and ultimate analysis.

3. MATERIALS AND METHODS

3.3. Description of the Study Feedstock

The samples of invasive shrubs, namely *Seriphium plumosum and Felicia filifolia,* were collected at Motheo Two, Masianokeng, Maseru Lesotho (29.3906° S, 27.5619° E). Although *Seriphium plumosum* (also known as bankrupt bush, slangbos, vaalbos or Khoi-kooigoed in the Western Cape) is indigenous to Lesotho, it has naturalised in other countries in Africa (South Africa, Angola, Namibia, Mozambique and Zimbabwe)(Mugido et al., 2014) *Seriphium plumosum*, previously known as *Stoebe vulgaris*, is currently viewed as an aggressive encroacher species in large parts of the Fynbos and Grassland Biomes of South Africa, such as districts of the Eastern Cape, Free State, Mpumalanga, North West and Gauteng provinces (Smit, 2010).

Felicia filifolia, previously *Aster fillifolius*, is a member of the Asteraceae family. It is commonly known as Sehalahala-se-seholo (Sesotho), draaibos (Afrikaans) (Hae, 2018). It is a twiggy shrub (Fig. 1B) that grows moderately fast, is well branched and grows to 1 meter high (Hae, 2018). Its foliage is made up of tufted bunches of needle-like leaves that are clustered in clumps at the end of branch tips. It bears large numbers of daisy-like attractive flowers that have a unique aroma from October to December (Hae, 2018). Felicia filifolia has a high reproductive capacity and reproduces both by seeds and root division (Hae, 2018). It grows moderately fast and has a low water requiremen (Hae, 2018)t. Felicia filifolia is relatively tolerant to droughts and high temperatures. Thus it is one of the most invasive bushes in Lesotho’s rangelands.

3.4. Sample collection

Harvesting entails cutting the shrubs and haulage to the point of use. A single man can harvest shrubs’ culms using a machete and/or a handsaw. A plastic bag was used for transportation before they were dried at site.

3.5. Sample Preparation

A total of 20kg from each of the plant species were collected to carry on the experiment. he uprooted plant material including the roots were chopped into smaller pieces and sun dried for one week. Soil was removed from the dried materials and were further cut to approximately a length less than 20 cm in preparation for the carbonization process.

Figure 3: Dried feedstock (Seriphium plumosum) before carbonisation.

3.6. Development of bio-char briquette samples

3.6.1. Carbonization of invasive plants

Charcoal can be produced in kilns manufactured from standard 200L oil drums. This method has been operated successfully using fast burning raw materials such as coconut palm timber, coconut shells and scrub wood (Adam, 2009). However, when operated with dense hardwoods, complete carbonization is difficult to achieve and the resulting charcoal is likely to have a high volatile content(Adam, 2009). Compared with traditional methods of production the conversion efficiency obtained in oil drum kilns is comparatively high with reported yields of up to 23% (dry basis)(Promdee et al., 2017).

The dried samples of the IAPs were carbonized using a carbonizer designed by the author. The carbonizer is made of cylindrical 200L oil drum with a chimney at the side for removal of smoke (Fig. 1). The feedstock is a low densitiy biomass, thus the steel drum kiln is the most appropriate as compared to other traditional methods. Biomass was tightly packed into the inner drum and carbonised for 45 minutes (Figure 4).

Figure 4: A steel drum (200L) for carbonisation (Courtesy: Kanono Thabane, 2020)

3.6.2. Char Grinding and mixing with binder

After the biomass was converted into char, the char was grinded to a smaller size (< 0.5 cm less than). This was meant to promote easy mixing with binders and a smooth surface of the desired shape. Grinding was done by hand into a basin.

In this study, four treatment combinations of binders mixed at a ratio of 1:2 with water:

i. Plant A + wheat flour
ii. Plant A + clay
iii. Plant B + wheat flour
iv. Plant B + clay
v. Charcoal briquette from shop as a "control' were used.

The mixture of wheat (starch) and water was heated until it gelatinizes without becoming too thick. Clay was also prepared as binder with water. Binder was mixed with charcoal powder as a ratio of 5% weight to weight (w/w)..The experiment was done in duplicate and repeated once.

3.6.3. Briquetting and drying

A doughnut-shaped briquette was developed using 110mm PVC drain pipe and a 2 tonne hydraulic car jack. A 500 grams of blended mould was placed into the PVC pipe. A hydraulic car jack was used for compacting the solids. The pressure applied to each mould (120 psi or 8.27 bar) was set constant by allowing the jack to travel the same distance from the reference to the final point. The manufactured briquettes were then dried in the sun for 5 days at the lab. Figure 5A shows the Patterson press method to be applied and Figure 5B shows the final output.,the charcoal briqueet.

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Three methods: proximate analysis, ultimate analysis and higher heating value, also known as calorific value. were used to investigate the performance of carbonised briquettes. For each treatment a total of five trials weighting 2grams were extracted and placed in crucible for proximate and ultimate analysis.

3.7.1. Proximate Analysis

The proximate analysis provides the potential efficiency and durability of the briquettes that will be produced. This requires the following organic solid waste properties:

3.7.1.1. Moisture content determination

Each sample was taken into a pre-weighed crucible and kept in an oven at a temperature of 105 ^{o}C for 1 hour. The crucible was then taken out of the oven and left to cool in a desiccator for 1 hour after which its mass was measured using an analytical balance. Percentage moisture content was calculated from the weight loss using Equation 1.

$$\%\ Moisture\ Content\ (PMC) = \frac{sample\ mass\ loss}{initial\ sample\ mass} \times 100 \qquad \text{(Equation 1)}$$

3.7.1.2. *Volatile matter content determination*

The samples used for moisture content determination were taken into a furnace and temperature set to 950 ^oC. The samples were left in the furnace at 950 ^oC for 7 min and thereafter removed from the furnace and left to cool in a desiccator for 1 hour. Volatile matter content was then calculated from the sample weight loss using Equation 2 (Figure 7).???

$$\%\ Volatile\ Matter\ Content\ (PVC) = \frac{moisture\ free\ sample\ mass\ loss}{moisture\ free\ sample\ mass} \times 100 \qquad \text{(Equation 2)}$$

Figure 6: Samples were cooled in desiccators for an hour before measurements were undertaken

3.7.1.3. *Percentage ash content determination*

Samples used for volatile matter content determination were heated at 750 ^oC (with the crucibles lids in place) until no significant change in mass was observed (i.e heating results in mass loss less than 0.0005 g). Percentage ash content was calculated from the sample weight loss using Equation 2 (Figure 7)..

$$\%\ Ash\ Content\ (PAC) = \frac{mass\ of\ ash\ residue}{moisture\ free\ sample\ mass} \times 100 \qquad \text{(Equation 3).}$$

Figure 7: Muffle furnace.

3.7.1.4. Percentage fixed carbon content

It was calculated indirectly by subtraction of the sum of volatile matter, moisture and ash contents from 100 as shown in Equation 3.

$$\%\ Fixed\ Carbon\ Content\ (PFC) = 100 - (PMC + PAC + PVC) \qquad \text{(Equation 4)}$$

3.7.2. Ultimate Analysis

Percentage total content for both carbon and nitrogen were determined directly by use of LECO Carbon and Nitrogen Determinator (CN 628). Nearly equal weight of sample for each run were wrapped in a tin foil and taken to CN 628 for direct determination of percentage total carbon and nitrogen. Percentage total oxygen was indirectly by subtraction of the sum of the percentage total carbon, hydrogen and nitrogen from 100.

3.7.3. Determination of Higher Heating Value

The higher heating value of the charcoal was calculated using an empirically derived equation 5 which correlates the proximate analysis results to the energy content (Demirbaş, 1997).

$$HHV = 0.196(FC) + 14.119 \quad (Equation\ 5)$$

4. RESULTS AND DISCUSSION

4.3. Proximate Analysis

4.3.1. Moisture Content

The results displayed in Table 1 illustrate that the mean percentage moisture content for all four treatments was found to be 6.83 ± 2.72 m %. According to literature, percentage moisture content for briquettes should be less than 10% otherwise, will produce smoke during combustion (Food and Agriculture Organisation (FAO, 1985). However, the results indicate that the manufactured charcoal briquettes have a higher moisture content as compared to market briquettes with exception to one treatment (Plant A+ Wheat), which has a moisture content comparable to the market briquette. Plant A+ Wheat treatment had the lowest average percentage of moisture content of 3.5±1.22 m %. which is an important determinant burning characteristics of solid biofuels. High moisture (>10%) content reduces the calorific value of charcoal briquettes. In addition, moisture content above 10% increases the heating purpose and lengthens the time of heating for briquettes.

Table 1: Percentage of moisture content for five charcoal briquettes treatment samples

	Percentage of Moisture Content				
	Plant A	**Plant A**	**Plant B**	**Plant B**	**Market**
Trials	**Wheat**	**Clay**	**Wheat**	**Clay**	**Briquette**
1	2.5±	7.5±	7.5±	7.5	4±
2	5±	10±	10±	5±	3±
3	2.5±	9±	10±	5±	2.5±
4	5±	8±	10±	5±	3.5±
5	2.5±	9.5±	10±	5±	3.5±
Mean	**3.5**	**8.8**	**9.5**	**5.5**	**3.3**
SD	**1.22**	**0.93**	**1**	**1**	**0.51**

Legend: Plant A= *Felicia filifolia*; **Plant B=** *Seriphium plumosum*

The results from four treatments indicate that there is an opportunity to lower the moisture content through optimisation of drying techniques. A lower moisture content is suitable for combustion of briquettes. This implies that the briquettes undergo combustion with minimum CO emissions. Moreover, the briquettes with low moisture content release more energy since a minimum amount of energy is wasted trying to drive the moisture away from the briquettes during combustion.

In this study, the moisture content analysis indicates that for Plant A, the most appropriate binder which yields the lowest moisture content is wheat (see Table 1). Contrarily, for Plant B, the most appropriate binder is clay: it yields the lowest moisture content.

4.3.2. Volatile Matter content

The desirable amount of percentage of volatile matter is estimated to be between 5%-40% m (Food and Agriculture Organisation (FAO), 1985). A lower volatile matter is associated with high carbonisation temperature during the production of briquettes. The results of the percentage of volatile matter from the four treatments of charcoal briquettes was found to be 30.53 ± 5.93m %, which is lower than that of the market briquette (46.92 ±0.99). This indicates that the market briquettes are carbonised at a lower temperature than the four charcoal briquettes. It has been observed that charcoal with higher volatile matter content ignites easily but may burn with a smoky flame in the absence of oxygen and has lower calorific value (Yin, 2011; Efomah and Gbabo, 2015b; Veeresh and Narayana, 2012). However, high volatile matter charcoal is preferable for some purposes such as barbecue while other utilizations such as chemical purification and metal manufacture need charcoal with low volatile matter content (Makara, 2017). Lower level of volatiles in charcoal is associated with high level of lignin and low level of extractives in wood.

Table 2: Percentage of volatile matter for five charcoal briquette treatment samples

	Percentage of Volatile Matter				
	Plant A	**Plant A**	**Plant B**	**Plant B**	**Market**
Trials	**Wheat**	**Clay**	**Wheat**	**Clay**	**Briquette**
1	24±	24.32±	35.1±	24±	46.77±
2	34.21±	28.89±	35.44±	29±	45.87±
3	30.76±	21.98±	30.76±	26.3±	46.15±
4	36.8±	21.74±	36.11±	26.3±	47.15±
5	43.58±	28.18±	38.88±	34.21±	48.7±
Mean	**33.87±**	**25.022±**	**35.258±**	**27.962±**	**46.928±**
SD	**6.48188**	**3.01504**	**2.61285**	**3.50248**	**0.99387**

Legend: Plant A= *Felicia filifolia*; **Plant B=** *Seriphium plumosum*

The results further indicate that the treatments with clay had the lowest percentage of volatile matter as compared to the treatments with starch. At higher temperatures, typically above 850^{o}C, the residue formed in charcoal production becomes volatile, therefore elevated temperatures can be used for carbonization to give low volatile matter content charcoal (Makara, 2017). This helps to minimize the levels of polycyclic aromatic hydrocarbons in the smoke which increase the risk of food contamination on grilling (Makara, 2017). For this reason, care must be taken when using this charcoal for grilling.

4.3.3. Ash Content

The desirable amount of ash content in briquettes should range between 0.5% and 5% depending on the feedstock used. In this study, the mean percentage ash content for all four treatments was found to be 3.77 (± 1.10) %m. The results indicate that the four treatments are within the desirable range whilst the market briquette is above the desirable range, estimated at 6.17 (±0.36) %m. A low ash content in briquettes is an indication of higher heating value since the briquette does not contain non-combustible materials. From the four treatments, briquettes produced from plant A had the lowest ash content as compared to the other plant tested**.**

Table 3: Percentage of ash content rfor five charcoal briquette treatment samples

	Percentage of Ash Content				
	Plant A	**Plant A**	**Plant B**	**Plant B**	**Market**
Trials	**Wheat**	**Clay**	**Wheat**	**Clay**	**Briquette**
1	5.08±	3.11±	3.83±	3.46±	5.68±
2	4.47±	2.87±	3.98±	4.28±	6.23±
3	1.45±	2.8±	6.79±	4.54±	6.23±
4	2.47±	2.61±	3.78±	4.7±	6.77±
5	4.44±	3.58±	3.35±	3.82±	5.95±
Mean	**3.582**±	**2.994**±	**4.346**±	**4.16**±	**6.172**±
SD	**1.38208**	**0.33386**	**1.23982**	**0.45957**	**0.36213**

Legend: Plant A= *Felicia filifolia*; **Plant B=** *Seriphium plumosum*

4.3.4. Fixed carbon

Better quality of briquettes and higher levels of fixed carbon, is associated with high levels of lignin and low level of holocelluloses (hemicellulose and cellulose) and extractives in wood

(Makara, 2017). The desirable amount of fixed carbon in briquettes should range 50% to 90% (Food and Agriculture Organisation (FAO), 1985). In this experiment, all the four treatments were found to be within the desirable range with a mean percentage fixed carbon of 58.88 ± 6.51 m %. The market briquette on the other hand was found to be below the desirable range with average percentage 43.6 ± 1.27 of fixed carbon. The fixed carbon gives an indication of the proportion of char that remains after volatile matter has removed. It gives a rough estimate of the heating value of a fuel and acts as the main heat generator during burning (Falemara et al., 2018). Briquettes with clay binder have a higher percentage of fixed carbon as compared to briquettes with wheat binder (Table 4).

Table 4: Percentage of Fixed Carbon for five charcoal briquette treatment samples

	Percentage of Fixed Carbon				
	Plant A	**Plant A**	**Plant B**	**Plant B**	**Market**
Trials	**Wheat**	**Clay**	**Wheat**	**Clay**	**Briquette**
1	68.42±	65.07±	53.57±	65.04±	43.55±
2	56.32±	58.24±	50.58±	61.72±	44.9±
3	65.29±	66.22±	52.45±	64.16±	45.12±
4	55.73±	67.65±	50.11±	64.00±	42.58±
5	49.48±	58.74±	47.77±	56.97±	41.85±
Mean	**59.048**±	**63.184**±	**50.896**±	**62.378**±	**43.6**±
SD	**6.88178**	**3.92203**	**2.00273**	**2.91795**	**1.27325**

Legend: Plant A= *Felicia filifolia*; **Plant B=** *Seriphium plumosum*

4.4. Ultimate Analysis

The ultimate analysis includes an assessment of the levels of carbon, hydrogen, nitrogen and sulphur (Table 5). Among many charcoal properties, contents of energy-carrying chemical bonds between the most abundant ultimate elements, together with total ash content, represent the most important readings (Fuwape and Sobanke, 1998). Firstly, Carbon and oxygen react during combustion in an exothermic reaction, generating CO2 and H2O; thus, they contribute in a positive way to the charcoal's calorific value and the combustion process itself (Pastor-Villegas et al., 2006). Carbon is one of the most important elements in the combustion process. Favourable carbon content in charcoal composition is exceptionally important because its increased presence boosts the heating value of charcoal (Okot et al., 2018). The results indicate that the samples have a very low carbon content (29% to 38%) compared to the recommended levels (57%) by FAO.

Secondly, low levels of hydrogen content may represent a problem because, hydrogen is essential for determining energy properties of charcoal (Wang et al., 2017b). The results indicate a low nitrogen percentage (1.98% to 2.48%) which is very low compared to the ma Thirdly, since nitrogen content, together with sulfur, influences the emissions of harmful gases (NOx and SO2) during biomass combustion concentrations of these gases should be as low as possible (Roy et al., 2015). Sulfur is a gas with the lowest presence in biomass, but, together with nitrogen are the most important elements regarding the environmental impact (Han et al., 2018). The results indicate that results indicate that the composition of nitrogen and sulphur are favourable to the recommended levels and thus the samples are not harmful for indoor applications and the environment.

Table 5: Ultimate Analysis Results from the three trials

Samples	**C (%)**	**H (%)**	**N (%)**	**S (%)**
FAO Recommended	50-90	<5	<3	<1
Plant A +Wheat	38.94	1.98	1.12	0.29
Plant + Clay	35.54	1.88	1.19	0.29
Plant B + Wheat	36.77	2.18	1.28	0.32
Plant B + Clay	29.31	2.48	0.8	0.46
Market Briiquette	57.17	3.17	0.77	0.27

4.5. Determination of Higher Heating Value

The desirable range of higher heating value for briquettes is 17-30 MJ/kg (Food and Agriculture Organisation (FAO), 1985). In this study, all the four biochar treatments had a higher heating value towards the upper limit of the range with a mean higher heating value of 25.66 ± 1.28.MJ/kg (Table 6). In addition, all the four treatments had a higher heating value as compared to the market briquetteIn this study briquettes produced with clay as binder had shown higher specific heat of combustion than those produced with wheat as binder.

Table 6: Heating Value of the charcoal briquettes produced

	Determination of Higher Heating Value (MJ/Kg)				
	Plant A	**Plant A**	**Plant B**	**Plant B**	**Market**
Trials	**Wheat**	**Clay**	**Wheat**	**Clay**	**Briquette**
1	27.52±	26.87±	24.61±	26.86±	22.65±
2	25.15±	25.53±	24.03±	26.21±	22.91±
3	26.91±	27.09±	24.39±	26.69±	22.96±
4	25.04±	27.37±	23.94±	26.66±	22.46±
5	23.81±	25.63±	23.48±	25.28±	22.32±
Mean	**25.69**±	**26.50**±	**24.09**±	**26.34**±	**22.66**±
SD	**1.34883**	**0.76872**	**0.39254**	**0.57192**	**0.24956**

Legend: Plant A= *Felicia filifolia*; **Plant B=** *Seriphium plumosum*

4.6. Discussion of the results

4.6.1. Key Findings

The briquettes produced in this study have a low percentage moisture content which is below 5%. This implies that they do not produce smoke during combustion. In addition, the volatile matter is less than 40%, which implies that the briquettes are properly carbonised and can burn for longer. This implies that the briquettes are suitable for domestic applications such as barbecuing, cooking and heating. The results further indicate that the ash content is below 5% which implies that they do not have non-combustible materials. This implies that the briquettes are ideal for domestic use and not for industrial use: which require the percentage of ash content to be less than 1%. The percentage of fixed carbon is greater than 50% which implies that the briquettes has lots of energy content. Based on the above the briquettes produced in this study are suitable for domestic use. Lastly, the results indicate that the amount of nitrogen, sulphur, hydrogen and oxygen found in this charcoal are acceptable. Environmentally friendly and safe to use for indoor.

The results further indicate that using clay as binder will yields higher calorific values as compared to wheat. Given the abundance of clay in Lesotho, the results exhibit that the production of briquettes will be sustainable and would not affect food production as in the case of wheat.

4.6.2. *Comparison with other studies*

The results of other commercial briquettes available in the market from different sources are depicted in Table 7. From existing literature, it is evident that the charcoal briquettes produced are highly competitive with other existing briquettes. The briquettes produced in this study have an average higher heating value of 25 MJ/Kg while most commercial briquettes have a higher heating value of ranging between 24MJ/Kg and 31.2 MJ/Kg. Briquettes made from waste material tend to have a low higher heating value as compared to briquettes produced in this study and commercial briquettes.

Table 7: Commercial charcoal briquettes and waste material charcoal briquettes

Waste Composed Briquette	HigherHeating Value (MJ/kg)	(Source)
Commercial Charcoal		
Coconut Shell Char	31.2	https://briquettesolution.com/bio-and-fuel-briquette-calorific-value-biomass-sawdust-coal-charcoal/
Oak Char	24.6	https://briquettesolution.com/bio-and-fuel-briquette-calorific-value-biomass-sawdust-coal-charcoal/
Redwood Char	28.35	https://briquettesolution.com/bio-and-fuel-briquette-calorific-value-biomass-sawdust-coal-charcoal/
Casuarina Char	27.26	https://briquettesolution.com/bio-and-fuel-briquette-calorific-value-biomass-sawdust-coal-charcoal/
Eucalyptus Char	26.75	https://briquettesolution.com/bio-and-fuel-briquette-calorific-value-biomass-sawdust-coal-charcoal/
Waste Material Charcoal		
Water hyacinth	16.8	(Carnaje et al., 2018)
Cardboard and Saw dust	16.94	(Lela et al., 2016)
Rice Husk	17.04	(Brand et al., 2017)
Rice Straw	17.98	(Brand et al., 2017)

90%Rice Straw + 10% Rice Husk Ash	17.01	(Brand et al., 2017)
Groundnut shells and bagasse	22.5	(Lubwama and Yiga, 2017)
Waste compost	22.42	(Brand et al., 2017)
Sugar cane leaves (cow dung binder	19.11	(Shuma and Madyira, 2017)
Waste Plastic and Coal	19.27	(Nwabue et al., 2017)
Buffing Dust of Total Solid Wastes	20.17	(Oyelaran et al., 2015b)
Human Waste	25.1	(Ward et al., 2014)
Used Tire	23.02	(Chatziaras et al., 2016)

Furthermore, traditional biomass has a calorific value 12-20 MJ/kg compared to the manufactured briquettes 24-26 MJ/Kg. This implies that the briquettes produced could be used as an alternative for traditional biomass (cow dung, agro-residues, shrubs, wood etc) for household cooking and heating applications because the have a higher energy content.

4.6.3. Limitations of the study

The study reveals the potential for optimisation of production techniques which could improve the results attained. Firstly, the methods used for drying of briquettes could be optimised by using solar crop dryers which have the capacity of driving down the moisture content. In additions, the variation in the results in the moisture content indicates that there is opportunity for achieving low moisture content. Secondly, the carbonisation process still has room for improvement which could lead to lower volatile matter, thus improving the caloric value of briquettes. Lastly, the higher heating value was calculated using an empirical formula in the absence of bomb calorimeter machine.

5. CONCLUSION AND RECCOMENDATIONS

5.1.Conclusion

The overall goal of this research is to develop a combustible energy product made from local (waste) materials which will be used in rural areas for heating and cooking applications. This solid fuel will serve as an alternative to traditional usage of biomass (cow dung, agro-residues, shrubs, wood).Thus, the study developed briquettes using the two species of *Sehalahala (Seriphium plumosum and Felicia filifolia*) and evaluated the performance properties of charcoal briquettes made from the two shrubs. The results indicate that mean percentage value of the four manufactured briquettes for the respective parameters evaluated were found to be as follows: moisture content (6.83 ± 2.72) m %,volatile matter content (30.53 ± 5.93) m %, ash content (3.77 ± 1.10) m %, fixed carbon (58.88 ± 6.51) m %, and higher heating value (25.66 ± 1.28) MJ/kg. In addition, the low nitrogen content and zero sulphur content imply that minimum amounts of the oxides of both sulphur and nitrogen will be released during burning of this charcoal hence burning of this charcoal will not impose negative environmental impacts.

This implies that the new briquettes produced has a higher energy content, less indoor air pollution and burns longer than traditional biomass (cow dung, agro-residues, shrubs, wood, etc) used in rural Lesotho for cooking and laughing applications.

In addition, the results indicated that the clay binder yields higher calorific value compared to the boild wheat flour suspention mix.

5.2.Recommendations

Government of Lesotho should consider the production charcoal briquettes using *Sehalahala* which is harvested during public works programmes. This concept could make the process more sustainable and create jobs for rural economies.

5.3.Area for further research

There is a need to research further on the economic and financial viability of producing charcoal briquettes using the exotic weed *Sehalahala.*

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