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Research Title:

Production and Characterization of Fuel Briquettes Made from Agricultural Residue Blended with Organic Wastes Using a Hydraulic Press Designed and Manufactured Locally

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ABSTRACT

Alternative energy sources have gained attention in order to substitute the dwindling conventional energy sources. In this context, briquetting technology has been applied to utilize loosen organic feedstocks effectively through solid fuel production. The objective of this study was to produce briquettes from agro-industrial and organic wastes in different combination using simple hydraulic press machine and subsequently to study briquettes physical, chemical and mechanical properties. In this research, coffee husk and bagasse as agro-industrial wastes and sawdust, paper residue and Khat as organic wastes were used for briquette making experiment with a binary mixing weight ratio of 0:100, 25:75, 50:50, 75:25 and 100:0 respectively with three selected binders (10 % w/w) namely starch, molasses and gum Arabic. The effect of feedstock combination, variation of binder types and feedstock preheating were studied following standard procedures on briquettes' physical, mechanical and energy content at ~7 MPa compaction pressure and particle size of < 1 mm (except mashed paper).

From the experiment, bulk density of briquettes was ranged from 474 -1107 kg/m^3 at preheating temperature of 140 ^{0}C. The effect of binders was analyzed using bagasse feedstock which had relatively low bulk density during preheating method. Thus, its highest bulk density was found to be 462.7 kg/m^3 for starch binder. Coffee husk feedstock has been selected to study Mechanical strength of briquettes using selected binders and its maximum values was exhibited by starch binder as 80 % shatter resistance index and 9.5 MPa compressive strength next to preheating method at 140 ^{o}C. But, other binders' effect was not that much deviated in the yield of good quality briquettes in terms of density and mechanical strength. Paper briquette alone had the highest value of 99.51 % and 23.10 MPa shatter resistance index and compressive strength respectively regardless of other binders effect. This indicated that paper itself could be a potential binder of other feedstocks. The moisture content, ash content, volatile matter and Fixed carbon of briquettes were ranged from 4.5-9.3 %, 0.45-11.8%, 70.1-83.5 % and 5.79, 18.5% respectively and the calorific values of briquetted fuels ranged from 15.44-18.34 MJ/kg. The significance of this study was meaning full in the production of briquettes with acceptable physical, mechanical and thermal properties by utilizing agro-industrial waste and discarded organic wastes in different combination.

Key words: *Agricultural waste, briquettes, Organic waste, Piston press*

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ACRONYM

ASTM	American Standard for Testing of Materials
FC	Fixed Carbon
HHV	Higher Heating Value
IRI	Impact resistance index
LHV	Lower Heating Value
MC	Moisture Content
MSW	Municipal Solid Waste
VM	Volatile Mater
WE	Water Equivalent

1. INTRODUCTION

1.1. Background

Biomass is the fourth highest primary energy source in the world after oil, coal and gas, contributing 10.6 percent of the total global primary energy supply (Birwatkar, 2014). In most of developing nations wood fuels, agricultural straws, and grasses are the most prominent biomass energy sources (Tumuluru, 2010). The utilization of biomass offers an environmentally friendly route for the production of clean and sustainable fuels for the future (Nyakuma et al., 2014). Among the alternative energy resources, the biomass becomes an important renewable energy resource because it has appealing properties, such as low production cost, low greenhouse gas and low acidic gas emissions (Chou et al, 2009). However, many of the developing countries produce huge quantities of agro residues, they are using it inefficiently causing extensive pollution to the environment (Maninder, 2012).

Likewise, in Ethiopia, approximately 3.3 million tons of excess agricultural byproducts are generated from coffee, cotton, wheat, and barley productions yearly (Assefa, 2022). In the recent review of (Yalew, 2022), the annual potential supply of agricultural wastes including crop residues and dung estimated about 55.4 million tons, out of which more than 60% is used as fuel and approximately 88% the total energy supply is dominated by biofuel. The household sector takes up nearly 90% of the total energy supplies (Gebrekidan, 2015). Besides, utilization of low bulk density, variable moisture content, and particle size of municipal solid waste (MSW) create feeding, handling, storage, and transportation challenges (Jaya, 2021). In order to combat the negative handling aspects of bulk biomass, densification (such as baling, palletization, extrusion, and briquetting) is often required (Sengar, 2012). Commonly, briquetting is known to physically transform loose raw materials generated from agro-processing such as rice husks, bagasse, ground nut shells etcetera and other discarded organic materials like municipal solid waste into high density fuel briquettes through a compacting process **Invalid source specified.**.

If such crop residues are converted into briquettes they can provide huge and reliable source of feedstock for thermochemical conversion (Sengar, 2012). Converting loose biomass source of energy in to solid fuel decreases deforstation, reduce environmental pollution due to neutral carbon emmission, and encourages community to have their own offgrid energy system (Shuma, 2017).

In briquetting technology, the briquettes qulity and shape depend on the raw materials used and type of technologies selected during production,. Furtheremore, rawmaterials characterstics affect quality and burning efficiency of fuel briquettes which should be ensured the consistent supply of raw materials, physical property and cost of briquetting (Asamoah, 2016).

1.2. Justification/ Problem statement

In Ethiopia, especially agricultural residues are considered to be the most important and traditional source of domestic fuel in different rural areas. These biomass residues are byproducts of common agricultural leftovers such as *teff*, *wheat*, *maize*, *sesame*, *cotton stalk*, *coffee husk* and *bagasse* and others. Rural residents use crop residue in direct burning for the purpose of heating and cooking. But using loosen and low density biomasses for fuel is difficult to handle, transport, store, and combust due to different physical factors such as moisture content, irregular shapes and sizes (Akowuah, 2012). Besides, due to urbanization, different combustible organic wastes which can have a potential to be utilized as fuel are generated and dumped to landfills. Those wastes incur cost for sorting, handling, transporting and disposing. Briquetting the discarded organic wastes with agricultural residues and agro-industry wastes in different proportion will eliminate the aforementioned problems and other health related issues while exposing with wastes.

Apart from problems of transportation, storage, and handling, the direct burning of *loosen* biomass in grates or stove is associated with very *low thermal efficiency* in terms unsustain combustion and widespread *air pollution* by generating fly ash. Briquetting of residues and wastes is more suitable to be used as an energy source due to its potential to be briquetted into a hard stable fuel that has a high energy density and provide more *consistent* combustion and improve storage, transportation and waste management system. Therefore, in briquetting of abundant agricultural leftovers with other urban organic wastes, extensive *dependency* on trees for fire wood will be minimized. This study developed hybrid briquettes using selected agro-industry materials and combustible organic wastes in different mixing proportions to study their physical, mechanical and thermal properties.

1.3. Objectives

1.3.1. Main objective

The main objective of this project is to briquette of agro-industrial residues and other discarded organic wastes in different blending proportions for energy purpose using simple hydraulic press briquetting machine designed and manufactured locally.

1.3.2. Specific objectives

- To prepare and characterize proportionally blended feedstocks with binders.
- To designed and manufacture manually operating hydraulic press briquetting machine.
- To study the physical, mechanical and thermal properties of different briquetted samples.

1.4. Significance of the project and beneficiaries

The significance of this study is inevitable in the production of fuel briquettes from low valued agricultural residue and municipal solid wastes with acceptable physical, mechanical and thermal properties of the end products. This could bring substantial socio-economic benefits during collection, transportation, sorting and preparation of feedstocks so as involved segments of the society can earn income through performing the aforementioned activities in the briquette production process. As a researcher point of view, this briquetting production project can contribute to the society in the provision of adequate energy source in the form of fuel briquettes. Furthermore, the project would have environmental significance such as minimization fly ash and particulates during open burning of loosen biomass, minimization of solid waste generation at the source by sorting out combustible materials, and combating climate change by saving cutting down of trees for domestic heating and cooking purpose.

1.5. Expected Outputs

Considering the benefits of using agricultural residues and municipal solid wastes as feedstock for the production of briquettes, it will be understood that the alternative energy source would be an economic and environmental positive impact. Generally, the following main outputs are expected from this research project;

- Introducing simple piston press briquetting machine which enables to briquette bimass energy sources into densified fuel.
- Provision of adequate energy source by means of briquettes made from agricultural residue and municipal wastes which have consistence burning intensity, durable and transportable.
- Improving waste management system by recovering combustible organic wastes for fuel briquette production, there by land fill space requirement for burring will be minimized.

1.6. Limitations

Due to unavailable of calibrated bomb calorie meter, this research characterization work is mainly theoretical based from literature data for calorific value estimation of each uncombined feedstocks to determine the calorific values of blended briquetted samples from their mass based mixing proportion. Emission test of briquettes during burning was difficult to test using conventional open stoves. Because, the exhaust gases were diluted with ambient air as the fuel burns. To get actual values of emission amount, proper test should be conducted by developing well confined and oxygenated chamber with emission exhaust line to accommodate gas analyzer sensor.

2. LITERATURE REVIEW

2.1. Introduction

This section reviewed about basic concepts on biofuel briquetting processes, technologies, feedstock types and natures, possible binder types and their properties, factors affecting briquetting technologies. Furthermore, it discussed about the importance of raw materials selection and pretreatments prior to briquetting process. The review also assessed the availability and opportunities of municipal wastes for fuel purpose through briquetting process including sorting, collection, treatment, storage and densifying.

2.2. Biomaterial Briquetting Technology

Briquetting technology is the process of densification of biomass to produce homogeneous, uniformly sized solid pieces of high bulk density which can be conveniently used as a fuel (Maninder, 2012) which may be carried out by pyrolysis densification using a binder (Nagarajan, 2021), (Deepak, 2021), (Bing, 2021), direct densification of biomass using binders (Elyas, 2021), (Kpalo, 2020), (Ajimotokan, 2019) and binder-less briquetting (Clara, 2019), (David, 2019). For the primary objective to be achieved, common main activities involve drying and chopping of raw materials, crushing, binder preparation, mixing, extrusion/pressing and quality assessment of the fuel briquettes (Patrick, 2021), (Raju, 2021).

According to Mani et al., biomass densification process passes through three stages. In the first stage, particles are closely packed by rearrangement due the energy dissipated which causes inter-particle and particle-to-wall friction. In the second stage, the biomass particles are forced against each other and undergo plastic and elastic deformation by which particles become bonded through the van der Waals and electrostatic forces as a result of inter-particle contact. The third stage is the reduction in bulk volume results in the density of the material reaching the true density of the biomass ingredients and at this stage the deformed and broken particles can no longer change their position due to a decreased number of cavities (Mani, 2003)

In general, biomaterial densification processes can be achieved in baling, palletization, extrusion, and briquetting, which are carried out using a bailer, pelletizer, screw press, piston press, or roller press. Palletization and briquetting are the most common densification used for solid fuel applications (Tumuluru, 2010)

2.2.1. Piston press briquetting

There are two types of piston press namely the die and punch technology and the other one is hydraulic press. In the die and punch technology, the standard size of the briquette produced is 60 mm, diameter. The power required by a machine of capacity 700 kg/hr is 25 kW. The Hydraulic piston presses are commonly used as briquetting machines. Hydraulic press can possibly be considered when looking for a small briquetting machine, which makes briquettes less dense and are sometimes soft and friable (Maninder, 2012). Sometimes this technology is referred as ram and die technology, the biomass is punched into a die with very high pressure either mechanically by a reciprocating ram powered by a massive flywheel, or by a hydraulically driven piston as shown in Figure 3.1., resulting a compressed mass known as briquette. Relatively the piston press device has long life of wearing parts and low power consumption (Longjian, 2009).

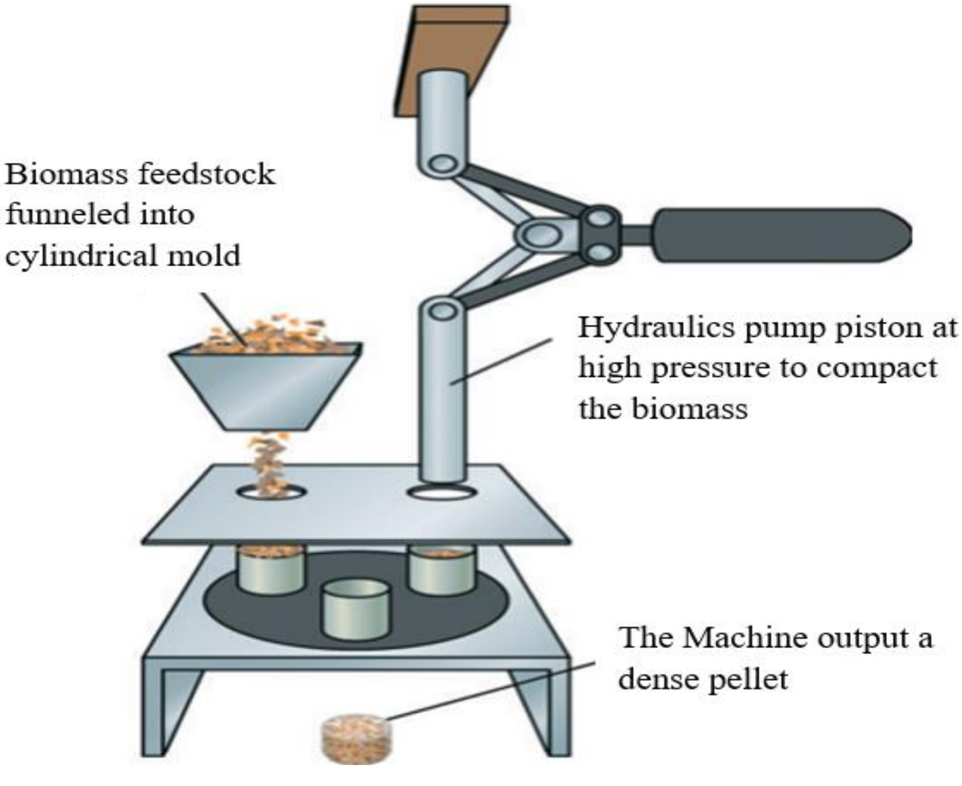


Figure 2.1 Briquettes production process from a typical hydraulic press (*Tumuluru, 2010)*

2.2.2. Screw press briquetting

In the screw process, material is fed continuously into a screw which forces the material into a cylindrical die; this die is often heated to raise the temperature the point where lignin flow occurred. Pressure builds up smoothly along the screw rather than discontinuously under the impact of piston (Kers, 2000). The screw press performance and the briquette mechanical property depends on three major factors; those are screw and die geometry, barrel and screw geometry, power requirements, machine production factors (component production soundness, surface finishing, technical know-how in machining, appropriate material selection etc.) and feedstock properties (Bello, 2020). In a mathematical modeling predicted by (Orisaleye et al., 2020) the yield strength of the compacted material is highly dependent on die entry angle through the die and also on the friction coefficient at the interface between the die and the compacted material. Therefore, increase in the friction coefficient, yield strength, die angle and inlet diameter resulted in increase in the die entry pressure. Increase in friction coefficient and briquetting die length also resulted in increase in the die pressure (Orisaleye, 2020).

After all, the briquette quality and production process of a screw press are superior to piston press technology with production capacity in the range of 75-250 kg/h (Oladeji, 2015). These briquettes can be produced with a density of 1200Kg/m^3 from loose biomass of bulk density 100 to 200 Kg/m^3 and the briquette obtained from screw press can be carbonized (Ajit, 2017). However, comparing wear of parts in a piston press, like a ram and die, to wear observed in a screw press shows that the screw press parts require more maintenance. The compaction ratio of screw presses ranges from 2.5:1 to 6:1 or even more.

In this process, the biomass is extruded continuously by one or more screws through a taper die which is heated externally for smooth extrusion if the heat generated within the system is not sufficient for the material to reach a pseudo-plastic state. Here also, due to the application of high pressures, the temperature rises fluidizing the lignin present in the biomass which acts as a binder. The outer surface of the briquettes obtained through this process is carbonized and has a hole in the center which promotes better combustion. Standard size of the briquette is 60 mm diameter (Maninder, 2012). The schematic representation of screw press is indicated in Figure 2.2 with different zones for processing of biomass feedstocks.

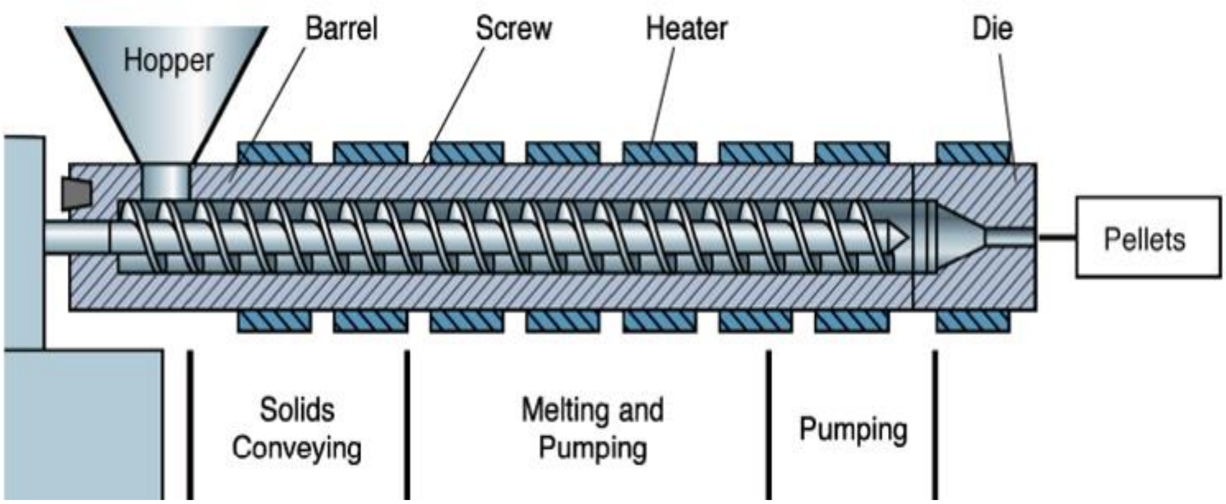


Figure 2.2 Schematic diagram of screw biomass particle extruder (Tumuluru, 2011)

2.2.3. Roll press densification

Roll pressing is a simple and cost effective way of agglomeration of particulate solids. It can be used for both dry and moist materials with various particle size distributions. If it is necessary, some additives might be added to improve properties of a product (Hubert, 2001). Roller presses consist of two rollers of the same diameter, rotating horizontally in opposite directions on parallel axes. Ground biomass is forced through the gap between the two rollers after which densified products in the form of pockets are formed. Because the rotation of the rollers is in opposite directions, the biomass is drawn in one side and the densified product is discharged out the opposite side (Yehia, 2007). In this regard by using smooth rolls, the machine output can be a sheet having a specific thickness based on the gap provided between the rollers. The sheet produced is used to produce the agglomerates, as shown in Figure 2.3, and the fines are again recycled back to the feeder. (Jaya., 2010)

To get good quality compacted product, the use of a screw feeder which feeds materials consistently is very important. The throughput of the press is driven only by the screw feeder, no matter of the roller speeds as long as compacted material is produced. During the process, controlling the rollers gap is a good way to obtain compact of the same quality when throughput is varied (Guigon, 2003).

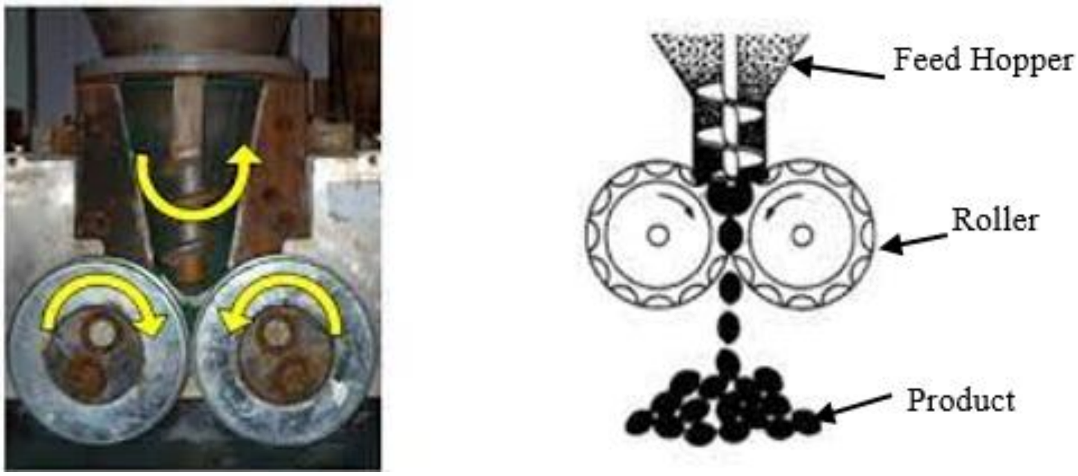
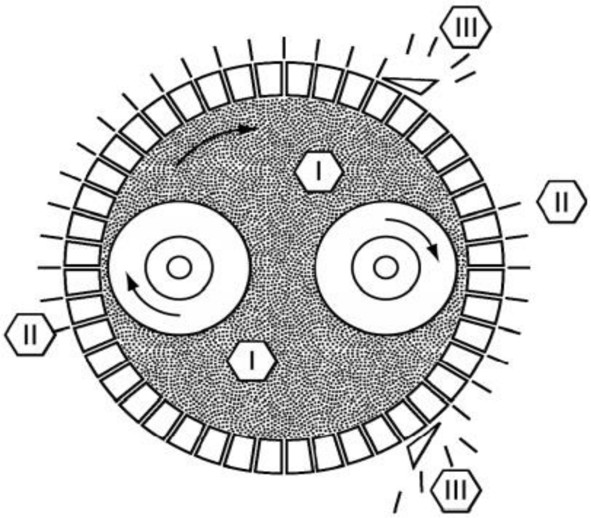


Figure 2.3 Roller press densifier (ecoursesonline.iasri.res.in)

2.2.4. Pelletizing

Pelletizing is closely related to briquetting except that it uses smaller dies so that the smaller products are called pellets. The pelletizer has a number of dies arranged as holes bored on a thick steel disk or ring and the material is forced into the dies by means of two or three rollers as shown in Figure 2.4. The two main types of pellet presses are: flat/disk and ring types. Other types of pelletizing machines include the Punch press and the Cog-Wheel pelletizer. The main application of pellet machines is to produce animal feed from various types of agricultural wastes.



I: Unpelleted materials

II: Pellets extruded through die plate

III: Pellet knives

Figure 2.4 Working process of die for pellet production

Different commercial pelletizers are available with production capacities ranging from 200 kg/hr to 8 ton/hr, indicating that the pelletizer capacity is not restricted by the density of the raw material (as in the case of piston or screw presses). And their respective power consumption of the pellet mills ranges from 15–40 kWh/ton (Grover, 1996). Prior to palletization process in the case of biomaterial densification, biomass should be first ground and was stored in an airtight container under room condition for subsequent use. Then the pellets were formed by compression machine which had a control on the load, holding time and temperature controller of the dies. (Noorfidza, 2016)

2.2.5. Low Pressure Briquetting

There are different types of manual presses used for briquetting biomass feed stocks. They are specifically designed for the purpose or adapted from existing implements used for other purposes. Manual clay brick making presses are a good example. They are used both for raw biomass feedstock or charcoal. The main advantages of low-pressure briquetting are low capital costs, low operating costs and low levels of skill required to operate the technology. Low-pressure techniques are particularly suitable for briquetting green plant waste such as coir or bagasse (sugar-cane residue). The wet material is shaped under low pressure in simple block presses or extrusion presses. The resulting briquette has a higher density than the original material but still requires drying before it can be used. The dried briquette has little mechanical strength and crumbles easily. The use of a binder is imperative (Maninder, 2012)

2.3. Binders used in biomass briquetting

Densification can be done by applying heat and pressure to maintain desired shape, strength and size of briquettes. But, it may incur cost of briquetting production associated with energy. Using natural binders as a binding component in the biomass feedstock such as lignin, protein, and starch have an inherent function in the densification process. Additionally, solid bridge between biomass particles will be created by applying certain pressure and temperature, these solid bridges develop through sintering the molecules from one particle to another at the contact points of particles. (Elyas, 2021)

The selection of binder is very important by considering its binding property and affordability. Simultaneously, the binder should not contain any undesirable toxic compounds and elements. There are various types of binder, both inorganic (cement, bentonite, clay, etc.) and organic (starch, pitch, plastics, etc.). Bentonite, or colloidal clay, is commonly used as a binder in feed pelleting and is made up of aluminum silicate composed of montmorillonite. Proteins are natural binders that are activated through interactions with other biomass compositions, such as lipids and starches, and the heat produced in the dies. Some agricultural biomass, like alfalfa, has high protein content and can be used as a binder to improve the durability of pellets made from lower lignin content biomass materials (Guojie, 2018).

There are three categories of binders, namely, organic, inorganic and heavy petroleum products binders. The binding force that acts between the individual particles in densified products is categorized into five groups. They are solid bridge, attraction forces between solid particles, mechanical interlocking bonds, adhesion and cohesion forces, interfacial forces, and capillary pressure (Davies, 2013). Commonly used, organic binders are sub-grouped into biomass binder (e.g., cassava paste, wastepaper pulp, molasses, cow dung, and starch). Briquettes made with inorganic binders (such as clay, lime, cement, plaster, and sodium silicate) have higher compressive strength, compaction ratio, and hydrophobic nature compared to those made with an organic binder. However, such briquettes display an increase in ash content, burn out temperature, and reduced calorific value (Sunday, 2020).

Binders can be added during mixing of the feedstock or after carbonization of the feedstock before densification. Some biomass material will not agglomerate except with the addition of binder especially if a low-pressure compaction technique is employed (Akowuah, 2012)**.** High-pressure densification utilizes the natural binding components such as starch, protein, lignin, and pectin, which are squeezed out of the particles of the biomass materials, to facilitate inter-particle bonding. (Sunday, 2020).

2.3.1. Starch binders

Starch is commonly used in briquetting process as binder. In the research conducted by (Aransiola et al., 2019) high quality and storable briquettes were produced from the blend of carbonized corncobs and cassava starch, corn starch and gelatin. The research showed that the relaxed density and compressive strength of the briquettes produced are adequate; besides, the length of time or service life of the stored briquettes proved acceptable stability after some months of storage (Aransiola, 2019). In addition, during hydrochar pellet production, starch pellets exhibited better mechanical strength when starch binder content is 20% at 3.07 Mpa pressure. During examination of using scanning electron microscope, starch and protein combined closely with hydrochar, but pellets with starch as the binder (20%) exhibited the highest equilibrium moisture content. But, regarding combustion performance, low ignition temperature (T_i) was observed for all binder based pellets (Zhexian, 2020).

2.3.2. Molasses binders

Molasses is a byproduct of sugar refinery which exhibited binding property of particles. In the experiment conducted by (Wang et al., 2019) molasses addition from 10% to 20%, mass density and energy density of the pellets significantly increased to a range of 947.1–1301.9 kg/m^3 and 23.55–33.40 GJ/m^3, but HHV of pellets was decreased. The "sold bridge" formation from molasses by recrystallization of sugar enhanced the tensile strength of the pellets. In addition, the molasses binder also delayed the moisture uptake rate and slightly increased the EMC content which depended more on the HTC temperature. From the experiment, the combustion analysis showed that the molasses binder decreased the ignition temperature (17–42 °C), and the maximum mass lose rate decreased about 0.6–0.8%/°C, indicating that molasses pellets was combusted in a moderate process. The results suggested that molasses binder assisted palletization of hydrochar from food waste had potentials for the preparation as solid biofuel (Tengfei, 2019).

2.3.3. Inorganic binders

Inorganic binders have many excellent advantages, such as strong adhesion, low-cost and good hydrophilicity. Clay, lime, plaster, cement and sodium silicate are common types of inorganic briquette binders. Inorganic binder can be divided into three types as industrial briquette binder, civilian briquette binder and environmental protection briquette binder. (Guojie, 2018). But, the use of such binders including bentonite, calcium hydroxide, sodium silicate, and clay cause ash problems in the combustion process, reduce the calorific value, and also result in NO_x and SO_x emission. (Elyas, 2021)

2.3.4. Cow dung

Cow dung is a combustible organic material which can beaded to other biomass materials to make hard and stable briquettes. Ailin Song et al. investigated the effect of the additives on combustion performance of cow dung briquette (CDB) which was prepared using the cold-press briquetting technology by mixing of coal and cow dung as raw materials, composite of potassium nitrate, manganese dioxide and citric acid as combustion promoter, mixture of calm gastrin and molybdenum as smoking suppressor, sodium humate and red clay as binder and acidified calcium oxide as desulphurizer. When the mass ratio of cow dung to coal is 1:3-4, the mass content of binder, combustion promoter, smoke suppressor and desulphurizer are 17.0%, 6.0%, 4.5% and 6.5%, respectively, the calorific value of CDB was 19.1 MJ/kg, ash content is 29.5%, volatile matter is 13.0% and desulphurization rate can be reached to 70.02%. (Ailin, 20119) In another study, the possibilities of using briquettes made from biochar and cow-dung at various proportions for energy-intensive processes was investigated. Out of 4 samples, the one made with cow dung and biochar derived from mango peel showed the highest calorific value and carbon sequestration of around 7300.56 Kcal/kg and 31.8 mg/kg respectively (Samarpan, 2021).

2.4. Variables that affect Briquette Properties

Quality briquette production process is highly dependent on different factors which influences the physical, mechanical and combustion characteristics of the finished product. The major affecting factors are machine factors, feedstock material factors and machine operating conditions (Bello, 2021). Specifically, the conversion of biomaterials into densified pellets or briquettes is influenced by different physical properties feedstocks such as moisture content, particle size distribution, bulk density, particle density. Furthermore, operating parameters such as size of the die, operating temperature and power requirement are also among the critical influencing factors in briquetting production process. Controlling the aforementioned variables in the briquetting process reduces the energy to be applied and enhances the briquette quality in terms of durability, density, and calorific value. (Mani, 2003). Hereafter, the main briquetting process variables such as temperature, pressure, retention time, and die geometry and shape, nature of feedstock and composition of biomass feedstock will be discussed in details.

2.4.1. Process Variables

Process variables are those factors which are non-material specific, that is to say that they are a set of conditions imposed on biomass materials by the mechanical densification equipment. The common process variables employed in briquetting production process are temperature, pressure and holding time.

2.4.1.1. Temperature

Application of temperature in briquetting machines affect briquettes end quality during overall briquette production process. Temperature of the briquetting machine promotes the release of biomass components such as lignin, cellulose, and hemicellulose where the lignin act as binder (Sunday, 2020). Briquette quality attributes like durability and bulk density of densified biomass are significantly influenced by temperature due to the presence of lignin. Researchers reported that lignin has low melting point (~140 ^{0}C) and thermosetting properties that would help for active binding thereby the briquette quality in terms of strength is increased. Most of the time, for different feedstocks, optimum temperatures during the densification of non-carbonized briquettes ranged between 100 °C to 250 °C. Control of temperature during briquette production enhances production efficiency and improves the durability and strength of the final briquette (Bernice Asamoah, 2016).

Sunday et al., 2020 in their study of briquetting wheat straw, found that the degree of compaction and dimensional stability went up as the temperature was increased from 60 to 140°C. They also found that briquette expansion decreased when the die temperature was between 90 and 140°C. They further observed that briquettes were surface-charred and slightly discolored at temperatures above 110°C due to chemical degradation. Provision of excess die temperature will decrease the friction between feedstock and die wall enabling densification at lower pressure to produce low-quality briquette, whereas, low die temperature requires higher pressure application and power consumption which also leads to lower production rate, but provides higher-quality briquettes (Sunday, 2020).

2.4.1.2. Pressure

Biomass can be densified under a high compaction pressure or a low compaction pressure. Generally, the feedstock type, moisture content, and particle size and shape determine the amount of pressure to be applied. Densification under low compaction pressure requires a binding agent to enable inter-particle bonding (Sunday, 2020). The compressive strength of briquettes increased with the increase in applied pressure. The pressure applied in briquetting process attribute to achieve the compactness briquette that enhances the inter-molecular bonding property of the briquette particles, hence improves the strength property (Ajimotokan, 2019).

Researchers revealed that application of high pressures and temperatures during densification process may develop solid bridges by a diffusion of molecules from one particle to another at the points of contact, which increases density. Pressure plays an important role on the quality of briquette made from agricultural biomass during handling, transportation and storage. The reviewed work of (Tumuluru, 2010), concludes that increasing the pressure on biomass feedstock initially increased the density sharply, and further increased the pressure brought slight density increment. Sengar et al. 2012 studied briquettes briquette production from Corncob showed that as the compaction pressure increased from 2.10-6.60 MPa, the density also increased with constant particle size of 2.40 mm (Sengar, 2012).

2.4.1.3. Holding time

Holding time in briquetting process has great effects on the density and durability of the products. Generally, longer time for briquetting produces products with higher density. However, in order to guarantee the productivity, the time for briquetting should be as short as possible (Wang, 2018). The quality of briquette is influenced by the retention or hold times of the materials in the die. Final relaxed density of briquetted fuel and the relaxation behavior following removal from the die depend on many factors related to die geometry, the magnitude and mode of compression, the type and properties of the biomass material, and storage conditions Many studies on high-pressure compaction of biomass materials indicate that upon removal of the material from the die, the density of the product decreases with time to a final relaxed density. At the highest pressure (138 MPa), the effect of holding time was negligible. For most feed materials, the rate of expansion is highest just after the removal of pressure and decreases with time until the particle attains constant volume (Tumuluru, 2010).

2.4.2. Nature of feedstock

2.4.2.1. Moisture content

Moisture content of biomass feedstock is an important parameter that determines the overall quality of biomass briquette. During briquetting, moisture content of biomass facilitates starch gelatinization, protein denaturation, and fiber solubilization during the processes of densification. Steam-treated biomass is superior, as the additional heat modifies physiochemical properties (gelatinization of starch, denaturation of protein) to such an extent that binding between the particles is significantly enhanced, resulting in improved densification qualit (Tumuluru, 2011)**.** However, moisture acts as both lubricant and binding agent, beyond the optimum level of moisture content, the briquetted material would not be compacted, regardless of the pressure level (Davies, 2013). In this context Moisture content should be as low as possible, generally in the range of 10-15%. When the moisture content is more than 15%, the briquettes quality become very weak and less compacted. Besides, high moisture content will pose problems in grinding and excessive energy is required for drying (Oladeji, 2015).

2.4.2.2. Particle sizes

Particle size distribution is the initial important factor of any given biomass raw material with respect to densification processes (Martinez, 2019). Particle size and shape are of great importance for the densification of biomass materials. The briquetting energy consumption increased with the increasing of particle size for homogeneous materials, but the rate of increase slowed down gradually. For chopped materials, mixing different sized materials reduced the energy consumption, but it was still higher than that of milled materials. Adding in small sizes of milled or chopped materials reduced the briquetting energy consumption. The energy consumption during briquetting process is proportional to particle size. Thus, briquetting energy consumption increased as particle sizes became larger in homogeneous materials but energy consumption could be minimized by mixing different sizes of chopped materials with milled or chopped materials (Wang, 2018). Finer grind of feedstock material (<2 mm) gives a larger surface area for bonding, which results in the production of briquette with higher density, strength, and durability. It is noted that mixing various particle sizes improves the packing dynamics and also contributes to strength and stability of briquettes (Sunday, 2020). But, particle size variation had little impact at high compacting pressure and temperature (Okot, 2019).

2.4.2.3. Biomass composition

Biomass materials possess macro and micro molecules such as cellulose, hemicellulose, lignin fats, resins, and ash (Sunday, 2020) and (Myasnikova, 2019). Total organic content of plant biomass around 12% of capillary moisture, is represented by carbon (45-50%), oxygen (40-45%), hydrogen (4.5-6.0%), nitrogen (0.3-3.5%) and a small amount of sulfur (up to 0.05%) (Myasnikova, 2019). Among the major components, cellulose is linear polymer and complex carbohydrate (or polysaccharide) with a high molecular weight and a maximum of 10,000 monomeric units of D-glucose, linked by β-1,4-glycosidic bonds. Cellulose is an abundant source of carbon in biomass. This carbon source in the biomass enables combustion of briquettes and higher carbon content is commonly related to a higher calorific value (Sunday, 2020). Cellulose $(C_6H_8O_4)_n$ is insoluble in water and forms the base structure of the biomass martials whereas, hemicellulose with general formula of $(C_5H_8O_4)_n$ is insoluble in alkalis (Nagarajan, 2021). The lignocellulosic fibers including cellulose, hemicellulose, and lignin are different in their physical and chemical structure, they can play a different role in terms of the effective bond type and the bonding ratio formation, as a binder (Afra, 2021)**.** The other component of biomass is starch which undergoes to be gelatinized at high temperature and influences the binding properties of biomass feedstocks. Proteins in biomass cell denutured during the densification proces, leading to the formation of new bonds and structures with other available proteins, lipids, and starches, helping to improve the binding capacity. Fat content in biomass acts as a lubricant during pillarization, increasing throughput, and reducing pelleting pressure. However, higher fat content can hinder binding. Lignin, contained in plant cell wall, denotes a complex amorphous aromatic polymer with a three-dimensional network, composed of phenylpropane units linked together (Tumuluru, 2010). The high temperature developed during the high-pressure densification process assists the inherent lignin, which is the binder in the biomass, to bind the biomass and form a densified fuel called briquettes (Panwar, 2011)

In the feed material, lignin serves as an in-situ binder enabling the binding process at high temperatures when it softens making it possible to produce more durable briquettes. Lignin is technically and economically effective which acts as a gluing agent of the cellulose crystalline and hemicelluloses component for mechanical strength (Myasnikova, 2019).

2.5. Biomaterials sources for Fuel Briquetting

Biomaterial/biomass can be referred as all organic matter which is originated from plants as well as animals and their derivatives. Typical solid biomaterial sources are wood, wood chips, agricultural residues, plant, algae, and organic fraction of municipal solid waste. (Angulo, 2011). Generally, biomaterials for briquetting production can be categorized as agricultural residue, forest residue and municipal wastes.

2.5.1. Agricultural Residue

Millions of tons of agricultural leftovers are generated annually which are handled inefficiently and caused air pollution during burning in loosen form. (Maninder, 2012). Among many agricultural processing byproducts, rice husk, corn stover, cotton stalk, groundnut husk, etc. are the prominent source of heating and cooking in developing nations (Akowuah, 2012**).** Crop residues takes over more than half of the world’s agricultural phytomass. Residual biomass, from agriculture or forestry, can be converted into synthesis gas (syngas) to generate electrical or thermal energy another useful chemicals (Lozano, 2018). Effective utilization of abundantly available agro residues helps energy conservation efforts and increase farmers’ incomes (Dinesha, 2019). *Nagarajan and Prakash* investigated the preparation and characterization of solid fuel briquettes, which were made from bagasse, corncob and rice husk in combination with different mixing ratios (Nagarajan, 2021). *Falemara et al.,2018* studied the physical, mechanical and combustion properties of briquettes produced from agricultural wastes specifically groundnut shells and corn cobs and wood residues (Anogeissus leiocarpus), and mixture of the particles at 15%, 20%, and 25% starch levels (binder). The briquettes produced were analyzed for density, volatile matter, ash content, fixed carbon, and specific heat of combustion. Their result showed that the density ranged from 0.44 g/cm^3 to 0.53 g/cm^3, while briquettes produced from groundnut shells had the highest (0.53 g/cm^3) significant mean density. Mean volatile matter and ash content of the briquettes ranged from 24.35% to 34.95% and 3.37% to 4.91%. (Falemara B. C., 2018)

2.5.2. Forest residue

Forest residues mainly logging residues consisted of branches, leaves, lops, tops, damaged or unwanted stem wood, etc. are often left in the forests for various reasons (Mishra, 1996). In the study conducted by *Ullah et.al.*,2021, briquettes were prepared from dried and milled forest waste including tree leaves and branches to be used as energy sources using screw extruder. From their experiment, the briquettes physical properties regarding quality and thermal properties were analyzed at moisture content of <15%, mold temperatures of (225, 250, 275, 300 °C) and biomass sizes (2, 4, 6 mm). The results showed that at the maximum moisture content of 12% density, durability, calorific and ash content of briquettes were 1092 kgm^{-3}, ≥95% and 4339 kcal/kg and 7.23%, respectively (Ullah, 2021). Roman et al., 2021, studied the mechanical and energetic properties of briquettes made form pine forest residues. The size reduced materials of forest residues were compacted by the principal stresses using a specially designed compacting tube, with additional equipment directly mounted on the testing machine. The compaction process was carried out using the presented material and through continuous monitoring of the process parameters. During the study, it was estimated that the moisture content of the compacted material should be equal from 10 to 15%. The calculated average value of the unit energy consumption during the briquetting process (WB) was equal to 0.14 MJ·kg−1 (Roman, 2021).

2.5.3. Municipal wastes

Both wastewater as sewage and solid waste collection and treatment practice in developing nation is still a challenge. But, in developed nations municipal solid waste and sewage are collected, reused, recycled, and energy recovered before disposal. (Coelho, 2019). Source of waste raw materials can be collected from households, institutions and business centers (Njenga, 2009). Different factors such as cultures, consumption habit and economic status contributed to variations in the generation and composition of municipal waste which can also affects waste management and recovery (Han, 2018)**.** For the energy consumption purpose in the case of briquette making process waste combustible materials need to be separated to avoid the inert and hazardous materials and the sorted materials are prepared accordingly for briquette production (Consonni, 2005). Preparation process of combustible materials for briquetting purpose involves either grinding or chopping and mixing with binders or heat treatment (if needed) in order to overcome difficulties of storage, transportation, feeding, and handling resulted from low bulk density, variable moisture content, particle size, and shape (Tumuluru, 2021)**.**

2.6. Potential Feedstocks in Ethiopia for Briquette production

Ethiopia is rich in woody biomass, crop residue and animal dung resources which generates about 141.8 million metric tons of biomass per year. But, at the present time the annual biomass exploitation potential for different purpose is about 71.9 million metric tons (Benti, 2021). When it comes to bio-energy utilization concept, the total availability biomass for energy consumption is estimated to be 750 PJ per year (46.5% forest residue, 34% crops residue, 18.8% livestock waste, and 0.05% MSW) (Gabisa, 2018). The total availability of crop residues from agricultural practices has been estimated to be 22.4 million tons per year of which 10.3 million are used as fuel. The potential supply of dung is 33.0 million tons per year of which 22.8 million tons per year is used as fuel (Susanne, 2013).

On the other hand, Ethiopia is one of the sub-Saharan countries facing rapid urbanization consequently producing a huge amount of wastes in the major cities such as Addis Ababa, Mekelle and BahirDar. Most of the generated wastes end up in landfills without any economic value (Gebreslassie, 2020). According to the existing management practices of MSW in the capital city of Addis Ababa, it is estimated that the solid waste generated rate is about 0.45 kg per capita per day with average estimated bulk density of 330 kg/m^3, and a total of approximately 6019 m^3 solid waste is generated in the city. The estimated physical composition solid waste generated is; vegetables 4.2%, paper 2.5%, rubber/plastics 2.9%, wood 2.3%, bone 1.1%, textiles 2.4%, metals 0.9%, glass 0.5%, combustibles leaves 15.1%, none combustible stones 2.5%, and all fines (sand, ash, and dust) 65% (Gelan, 2021). In general, in Addis Ababa The generation of plastics bags and bottles is high (36%), followed by food wastes (28%) and paper and cardboard (21%), bottle (6%) and tins/can (9%) (Kifle, 2012).

For instance, the mean weight waste generation by sample households in Bahirdar city was 0.22kg per capita per day (Wegedie, 2018). In Adama city solid waste generation rate is 0.42 kg/day/person in 2020 which is beyond the national average level of 0.33kg/day/person. In total, about 69,536 metric tons of waste is generated in the city annually. Therefore, a sustainable transition of the current SWM practices are surely needed to overcome the environmental, economic, and social challenges caused by ineffective and inefficient waste management in the city (Assefa, 2017).

From the literature review very limited research work has been reported about producing briquettes by the method of blending agricultural biomass with municipal solid wastes. It is hypothesized that blending agricultural biomass in current solid waste based pellets or briquettes might give direction in the development of new feedstock. The purpose of this work was to investigate the potential feedstock recovery from solid waste in blending with agricultural residues in the presence of binders. The more combustible feedstock may increase the low heating values materials in co-combustion process through blending. This briquetting method would have a dual benefits of waste management and energy recovery. Effect of blending ratio, binders type used, and raw materials combination on briquettes physical, mechanical and thermal were studied.

3. EXPRIMENTAL METHODS

3.1. Introduction

This section presented details about equipment used, experimental and design procedures. Experimental procedures were structured orderly to address specific objectives namely feedstock collection and preparation, binder collection and preparation, feedstock's energy content determination and proximate analysis, design and assembly of hydraulic briquetting machine and briquettes characterization.

3.2. Equipment Lists

The main equipment and materials used for this experiment were multi-purpose grinder (APOLYMIX, PX-MFC 90 D), sieves set up (Armfield, CEN-MKII-A), polyethylene plastic bags, electronic analytical balance (model: FA1104, readability: 0.0001 g), ceramic crucibles, heating oven (Model: Biobase-101-0, temperature range: 50-300^{o}C), furnace (Model: SX-2.5-12 Box-resistance), spatula, desiccator, piston press customized machine (proprietor type), universal testing machine (Model: WP 310), bomb calorimeter (STANDARD DD/01) and multi-gas analyzer (*infralyt smart*).

3.3. Procedures

3.3.1. Feedstocks collection and Samples Preparation

Coffee husk and bagasse wastes were collected from nearby agro-processing factory, whereas sawdust, paper residue and Khat as organic wastes were collected from furniture workshops, paper factory, and waste bins respectively from Adama, Ethiopia. Waste potato, molasses, and gum Arabic were also collected to prepare binders. After collection, coffee husk, bagasse, sawdust and Khat samples were immediately sun dried to prevent biological degradation and spoilage due to initial moisture they contain. The dried feedstocks were ground into pieces and allowed to pass through 1 mm mesh in order to have uniform particle sizes. All ground and sieved feedstocks were stored in airtight plastic bags until subsequent experiments. Feedstocks for the briquetting experiment were prepared by mixing agro-industrial residues and municipal organic wastes (Table 3.1) with a mixing ratio of 0:100, 25:75, 50:50, 75:25 and 100:0 %w/w respectively so as to study the combination effect of briquetted feedstocks' energy yield, mechanical properties and combustion efficiency. The mixing proportion was selected in such a way to see combination effect when the amount to be blended varied uniformly by 25% as per the preliminary experiment conducted so far.

3.3.2. Binders collection and Preparation

Starch, molasses and gum Arabica binders were selected and prepared. The selection criteria were based on availability and accessibility of the materials nearby the research area. The binder added for each feedstock was 10 %w/w of the main feedstock. Each binder preparation method was done as follow.

a) Starch: starch could be obtained from chemical distributors as extracted form or from starch containing plats, crops and industrial residue. As binding ratio increase in briquetting process it may incur additional cost. In this context, waste potato was used to show the possibility of extraction of starch for briquetting purpose. Waste potato was collected, crushed, ground and washed several times. The starch containing residue in the wash water was allowed to settle to the bottom and it was dried after the water being decanted. The dried starch then stored in air tight plastic bag for subsequent experiment. During briquetting sample preparation, 10 % w/w starch was weighed and gelatinized as shown in Figure 3.1. The amount of water needed to cook and mix the starch was determined to be 30 %w/w of the sample. It was then heated to 65°C for 10 minutes, at which point it started to thicken and ready to be mixed with the sample.

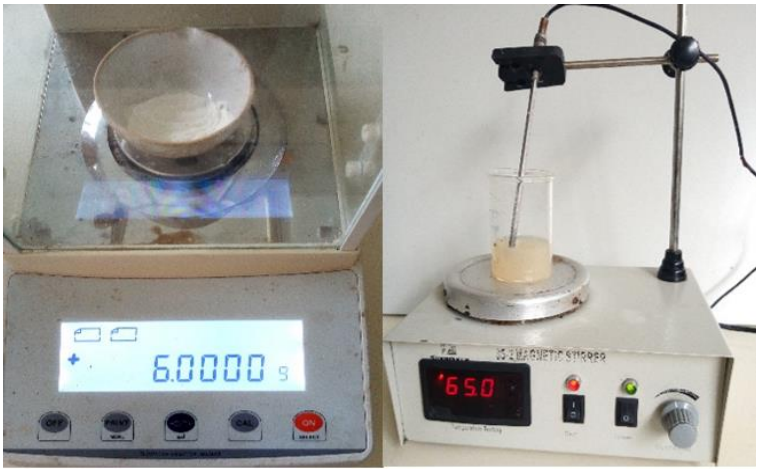


Figure 3.1 Preparation of starch binders

b) Molasses: Molasses was obtained from Wonji sugar factory, Wonji, Ethiopia. The molasses used for briquetting was 10 %w/w of the main feedstock. For the total amount of 60 g feedstock powder, 6 g of molasses was weighed in 500 ml beaker and heated to 60 °C to reduce the viscosity as shown in Figure 3.2. Then, 60 g of main feed stock was added into the beaker and mixed with the molasses very well.

Figure 3.2 Preparation of molasses as a binder

c) *Gum Arabica:* 10 wt.% of the sample of Gum Arabic powder as a binder was measured and transferred into a beaker containing 30 ml of water at 60 °C. Then, the content was allowed to be stirred constantly using magnetic stirrer for 45 minutes. The thicken and well mixed Gum Arabic binder was finally applied in feedstock particle binding during subsequent briquetting process.

Figure 3.3 Preparation of *Gum Arabic* as a binder

Table 3.1 Feedstock blending proportion with binders

S/N	Proportionalities (P) label	Selected agricultural residues	Selected organic wastes	Ratio % w/w	Binders %w/w
1	P1	Bagasse	----	100	10%of P1
2	P2	Coffee husk	----	100	10%of P2
3	P3	----	Khat waste	100	10%of P3
4	P4	----	Sawdust	100	10%of P4
5	P5	----	Paper waste	100	10%of P5
6	P6	Coffee husk	Khat	25:75	10%of P6
7	P7	Coffee husk	Khat	50:50	10%of P7
8	P8	Coffee husk	Khat	75:25	10%of P8
9	P9	Coffee husk	Sawdust	25:75	10%of P9
10	P10	Coffee husk	Sawdust	50:50	10%of P10
11	P11	Coffee husk	Sawdust	75:25	10%of P11
12	P12	Coffee husk	Paper	25:75	10%of P12
13	P13	Coffee husk	Paper	50:50	10%of P13
14	P14	Coffee husk	Paper	75:25	10%of P14
15	P15	Bagasse	Khat	25:75	10%of P15
16	P16	Bagasse	Khat	50:50	10%of P16
17	P17	Bagasse	Khat	75:25	10%of P17
18	P18	Bagasse	Sawdust	25:75	10%of P18
19	P19	Bagasse	Sawdust	50:50	10%of P19
20	P20	Bagasse	Sawdust	75:25	10%of P20
21	P21	Bagasse	Paper	25:75	10%of P21
22	P22	Bagasse	Paper	50:50	10%of P22
23	P23	Bagasse	Paper	75:25	10%of P23

3.3.3. Proximity Analysis and Energy Content of Feedstocks

Feedstocks' physical and chemical property analyses were carried out for determination of moisture content, volatile matter, fixed carbon, ash content and calorific value. Individual feedstocks and their binary combinations with the specified proportion were taken for the property analysis by adapting standard procedures.

3.3.3.1. Moisture content

Moisture content of a sample was measured by an oven dry method in accordance with ASTM D2444-16 standard as it was adapted by I*ittabut*.2015, One gram of each dried powdered sample was taken in silica crucibles and kept in an oven (Model: Biobase-101-0) at temperature of 105°C for 24 hours. Then the crucibles were taken out of the oven and immediately cooled in a desiccator. After it reached to room temperature samples were weighed. This procedure was repeated until constant weight was obtained. The moisture content test was replicated three times for each of the sample following the same procedure. The loss in weight is expressed as moisture content in the sample. The moisture content of sample was calculated by using following formula (Ittabut, 2015).

$$\text{MC}\ (\%\text{w/w}) = \frac{W_2 - W_3}{W_2 - W_1} \qquad 3.1$$

Where, W_1 = weight of crucible (g),

W_2 = weight of crucible + sample (g),

W_3 = weight of crucible + the sample after draying (g)

3.3.3.2. Volatile content

One gram of each dried powdered sample was taken in a ceramic crucible. The crucible was covered with silica lid. Then the ceramic crucible was kept in a furnace (Model: SX-2.5-12 Box-resistance) for 7 minute at the temperature of 925°C ± 20°C. The ceramic crucible was then taken out from the furnace and allowed to cool in air. The percentage of volatile matter of the sample was determined by using (ASTM D3175-18) standards. Volatile content determination of each sample was replicated three times. Volatile content of the sample was determined by using the following Equation 3.2 (Kebede, 2022)

$$\text{VM}\ (\%) = \frac{A - B}{A} * 100 \qquad 3.2$$

Where, A = weight of sample after oven drying (g),

B = weight of sample (g) after weight loss at the temperature of 925°C ± 20°C and 7 minute in a furnace

3.3.3.3. Ash content

Ash content of individual feedstock was determined by weighing one grams of finely ground, dried samples into a pre-ignited and previously weighed ceramic crucible, placed in a furnace (Model: SX-2.5-12 Box-resistance) and ignited for 2 hours at 750 ^{0}C. Then, the crucible was taken out, cooled in desiccators and weighed. The method followed to determine ash content was (ASTM, 1993) standard. Ash content analysis for each sample was triplicated by following the same procedures.

$$\text{Ash content (\%)} = \frac{Ash\ weight\ (g)}{oven\ dryed\ sample\ (g)} * 100 \qquad 3.2$$

3.3.3.4. Fixed carbon

Fixed carbon is the solid combustible residue that remains after a sample is heated at 925 ± 20 degrees Celsius for a period of 7 minutes and the volatile matter is expelled. The percentage of fixed carbon (PFC) was computed by subtracting the sum of Percentage of Volatile Matter (PVM), Percentage of Ash Content (PAC) and Percentage of Moisture Content (PMC) from 100 %. (Onukak, 2017)

$$\text{Fixed Carbon} = 100\% - (\text{PVM} + \text{PAC} + \text{PMC}) \qquad 3.3$$

3.3.3.5. Calorific value

The energy content of the biomass was measured using a digital oxygen bomb calorimeter (Model: STANDARD DD/01). Operational principle of the calorimeter was based on converting the heat released from the complete combustion of a sample fuel in an oxygen environment inside a bomb. One (1) g of samples were weighed by crushing parts of briquettes. Then, the crushed samples were again pelletized to be properly used in the metal crucible placed inside the bomb vessel in order to limit the speed of combustion. The bomb vessel containing the sample was enclosed tightly and filled with oxygen at 30 atm. The bomb was then immersed inside a vessel containing 2 litters of distilled water which were in direct thermal contact, forming the measuring system of the calorimeter. The bomb calorimeter and the water containing vessel were placed in a thermally insulated jacket. The sample in crucible was ignited by using electrical circuits which heats the ignition wire instantly from which burning cotton thread falls into the fuel sample below causing the sample to ignite. The heat produced after combustion of the sample was recorded in terms of temperature rise of water in vessel and finally it was converted into MJ/kg.

Considering that the outer vessel is adiabatic, the combustion process leads to increase the temperature of the water surrounding the bomb in ΔT. If it is known the energy equivalent (total heat capacity) of the calorimeter C, the amount heat q_{syst} due to the combustion of the fuel and the ignition wire, is given by Equation 3.5: (Gravalos, 2016).

$$q_{Syst} = \mathrm{C}\Delta\mathrm{T} \Rightarrow \mathrm{m}_{fs}\mathrm{H}_{fs} + \mathrm{m}_{ct}\mathrm{H}_{ct} \qquad 3.4$$

Where, m_{fs} is the mass of the fuel sample [g], m_{ct} is the mass of the cotton thread [g], H_{fs} is the calorific value of the fuel sample [$J \cdot g^{-1}$], H_{ct} is the calorific value of the cotton thread [$J \cdot g^{-1}$]. The heat capacity of the calorimeter C can be determined by the calibration of the instrument by measuring the calorific value of benzoic acid (C_6H_5COOH). The combustion reaction of the benzoic acid at 25˚C is defined as:

$$C_6H_5COOH\ (s) + 7.5O_2\ (g) \rightarrow 7CO_2\ (g) + 3H_2O\ (l) \qquad 3.5$$

The heat capacity is calculated according to Equation (3.7)

$$\mathrm{C} = \frac{\mathrm{m}_{ba}\mathrm{H}_{ba} + \mathrm{m}_{ct}\mathrm{H}_{ct}}{\Delta\mathrm{T}} \qquad 3.6$$

where m_{ba} is the mass of the benzoic acid [g], m_{ct} is the mass of the cotton thread [g], H_{ba} is the calorific value of the benzoic acid [$J \cdot g^{-1}$], H_{ct} is the calorific value of the cotton thread [$J \cdot g^{-1}$], and ΔT_c is the observed change in temperature during calibration experiment [˚C]. Having identified the C, the calorific value of the fuel sample can be calculated according to the Equation 3.8:

$$\mathrm{H}_{fs} = \frac{\mathrm{C}\Delta\mathrm{T}_{fs} - \mathrm{m}_{ct}\mathrm{H}_{ct}}{\mathrm{H}_{fs}} \qquad 3.7$$

where ΔT_{fs} is the observed change in temperature during combustion of the fuel sample [˚C].

Figure 3.4 Measuring Samples Calorific Value

3.3.4. Designing and assembling of hydraulic briquetting machine

3.3.4.1. Materials of construction

The material used for the construction of main parts of manual hydraulic press was the mild steel. Because, mild steel has a reasonable strength and hardness; it is ductile and easier to be welded and machined, and it is relatively cheaper than stainless steel. Besides, 12-ton load capacity hydraulic jack was used and assembled with the pre-designed structure. The detail components of hydraulic press machine were presented in Table 3.2.

Table 3.2 Components of hydraulic press

S/No.	Name of parts	Materials of Construction
1	Upper plate	Mild Steel
2	Spring	Mild Steel
3	Jack	Mild Steel
4	Moveable plate	Mild Steel
5	Columns	Mild Steel
6	Moving frame support pins	Mild Steel
7	Base (support frame)	Mild Steel
8	Mold Cylinder	Mild Steel
9	Punch	Mild Steel
10	Bottom frame Supports	Mild Steel

3.3.4.2. Design of Hydraulic Press Frame structure

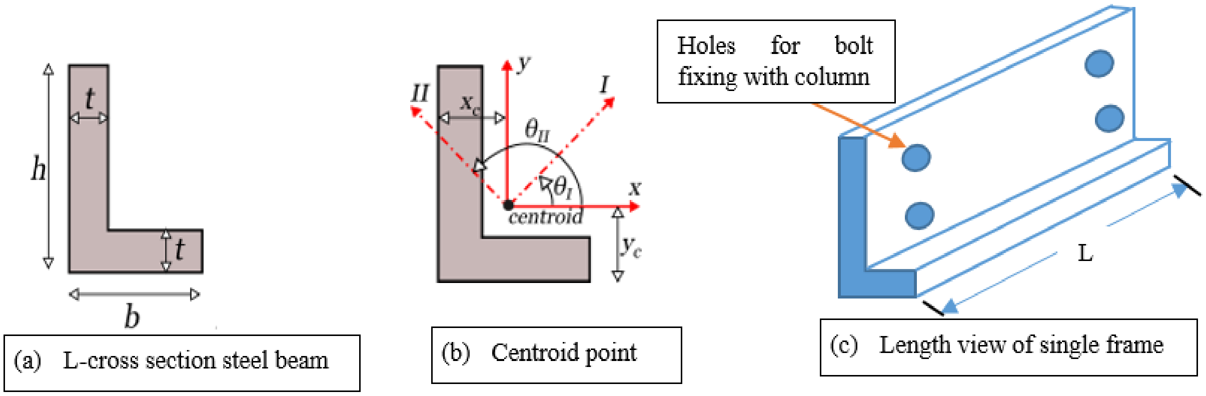
I. ***Maximum working pressure:*** Maximum working Pressure of hydraulic press machine was determined using Equation 3.9 (Osarenmwinda, 2012);

$$\mathrm{P_{Max}} = \frac{\mathrm{F_{Applied}}}{\mathrm{A_{Ram\ cross\ section}}} = \frac{\mathrm{F_{Applied}}}{\pi(r)^2} \qquad 3.8$$

The top platen consists of two standard L-Section positioned horizontally and bolted to the ends of the top of the vertical beams (one in front and one at the back). The center of the top platens was crossed with a 100 X 100 mm steel plate of 10 mm thickness that serves as a resting place for the pulled out ram of the hydraulic jack. This plate, however, was subjected to compressive stress since it is located between the hydraulic jack and the top platen. The stress induced in the plate is calculated as shown below:

$$\sigma_t = \frac{F_{Max}}{(A)} \qquad 3.9$$

where: F = applied load, σ_t = compressive stress of the material (mild steel).



(a) L-cross section steel beam

(b) Centroid point

(c) Length view of single frame

Figure 3.5 Upper frame cross section and structure

II. Determination of working plate thickness: This is necessary in order to select the appropriate thickness that would be able to bear the applied load. The bottom plate can be assumed to be clamped at the four corners and the center is subjected to concentrated loading from the base of the hydraulic jack. The plate thickness 't_p' for top cross frame and the working plate was computed using eqn.3.11 (Sumaila, 2011).

$$t_p = \sqrt{\frac{6M}{(\sigma_{all} b)}} \qquad 3.10$$

where: M = maximum bending moment, b = width of platens and σ_{all} = allowable tensile stress for the platens material.

$$M_{max} = \frac{L*W}{4} \qquad 3.11$$

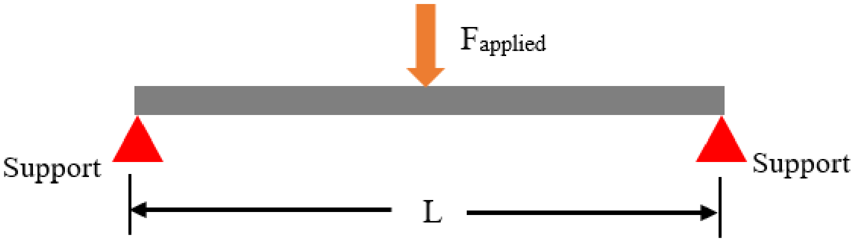


Figure 3.6 Simple supported metal platen metal bending moment diagram

III. **Design of base plat supports diameter:** The diameter of the working plate supports diameter was computed from eqn. (3.13):

$$d_s = \sqrt{\frac{8F}{3\pi\tau_{all}}} \qquad 3.12$$

where: F = applied load and τ_{all} = allowable shear stress for the pin material

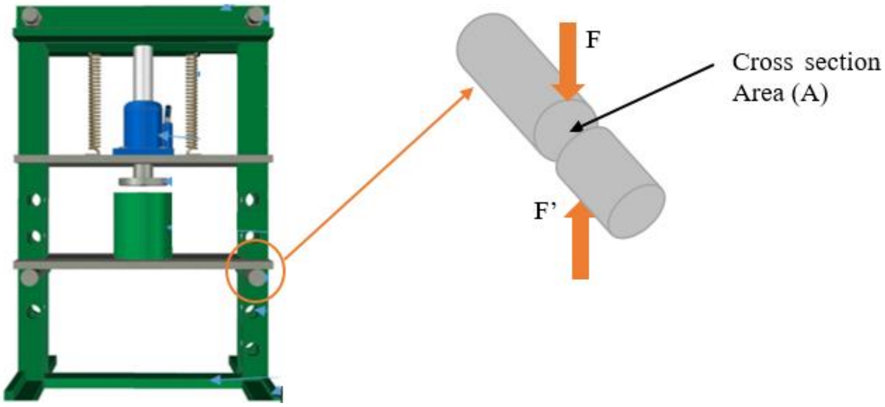
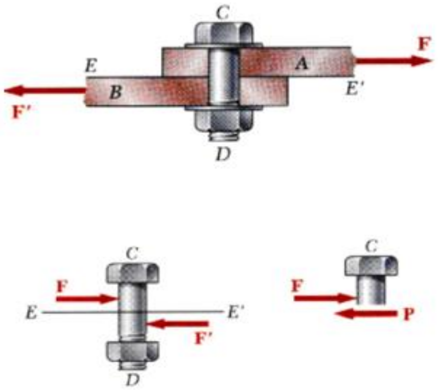


Figure 3.7 Base Plate support Pin diagram

IV. **Design of bolts/nuts:** The top cross support beams of the hydraulic cylinder were secured by means of bolts to the vertical frame. The major diameters of the bolts were computed from equation 3.14. Br 72

$$d_b = \sqrt{\frac{4F}{3n\tau_{all}}} \qquad 3.13$$

where: F = applied load, n = number of bolts and τ_{all} = allowable shear stress for the bolts material



E= Equilibrium line

A= plate A

B= Plate B

D= Diameter of bolt

F = Force due to plate A

F'= Force due to plate **B**

Figure 3.8 Bolt and Nut diagram when subjected to two opposite plate forces

V. **Design of ram retract Springs:** two parallel compression springs having spring constants of 9 N/mm arranged between the upper and hydraulic jack support platens symmetrically relative to the hydraulic jack position. The amount of springs force hindering the applied load was determined using Hook's law in equation 3.15.

$$F = -KX \qquad 3.14$$

Where; k is spring constant (N/m) and X is deformation length (m).

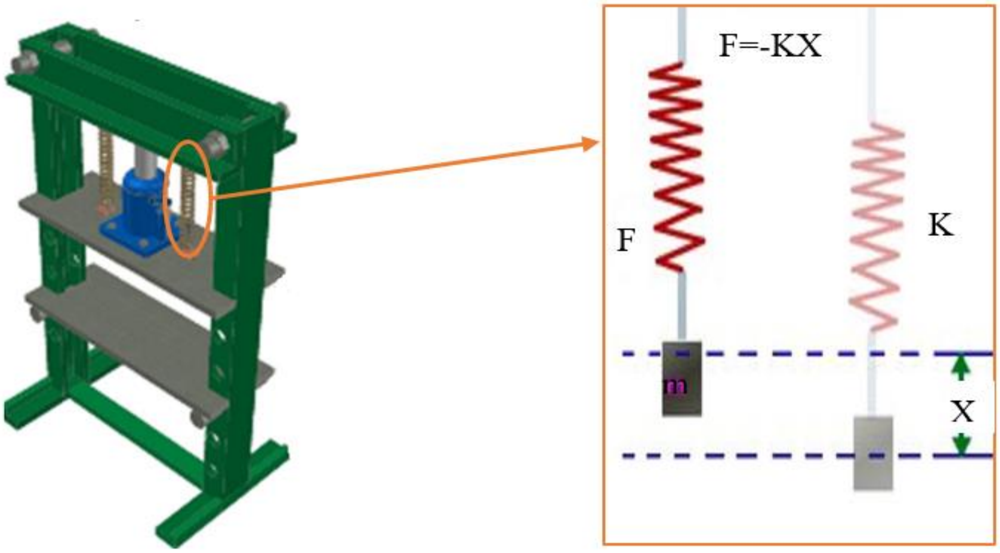
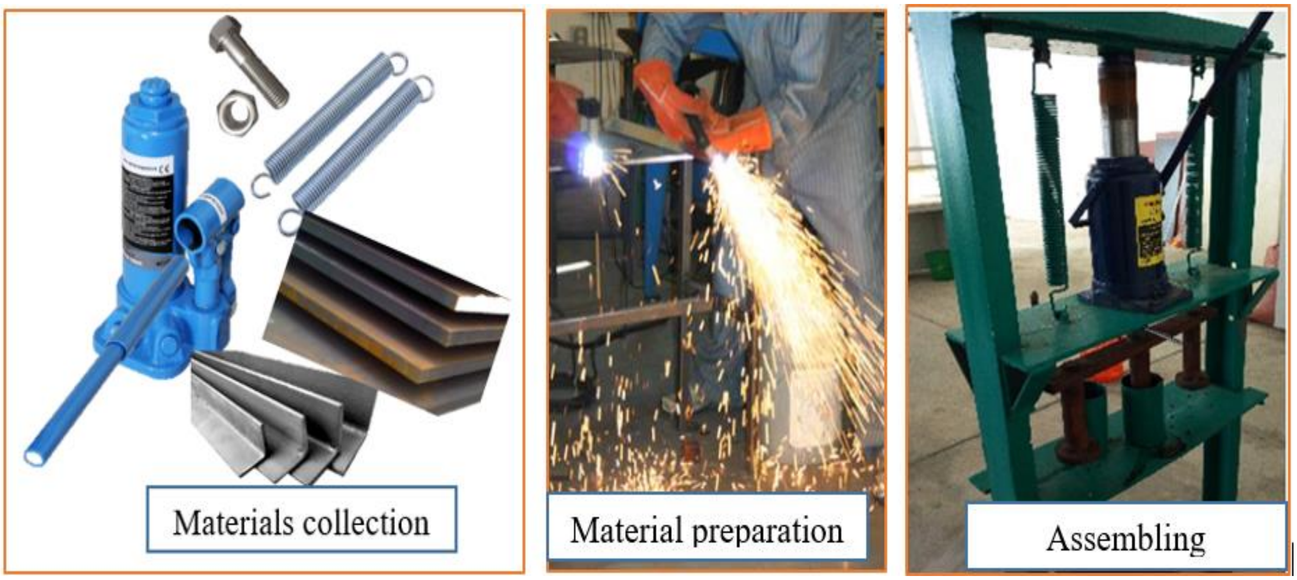


Figure 3.9 Ram retracting springs diagram

3.3.4.3. Assembling of Hydraulic Press Machine

The various processes followed in the assembling of this hydraulic press machine include measurement, marking out, cutting, drilling, welding, fastening, grinding and painting. The assembling process was executed by the basis of pre designed separate components. Figure 3.5 showed the steps followed and the activities done during hydraulic press machine assembling process.



Materials collection

Material preparation

Assembling

Figure 3.10 Assembling process of Piston press Machine

3.3.5. Briquette Production Process

The briquettes were formed by using previously fabricated hydraulic press machine. Cylindrical mold with an inner diameter of 60 mm, a height of 80 mm was used to create a densified product. The mold was filled with the defined amount of samples (60 g) and densified under constant operating conditions (temperature of 21-25°C, dwelling time of 5 minutes and constant pressure of ~7 MPa. The produced briquettes' initial density was measured immediately after ejection from the mold. The resultant briquettes (Figure 3.10) were placed on a dry surface and left to air dry in well ventilated room for 30 days before testing mechanical properties, since after 30 days the sample weight remained constant whenever it was measured frequently.

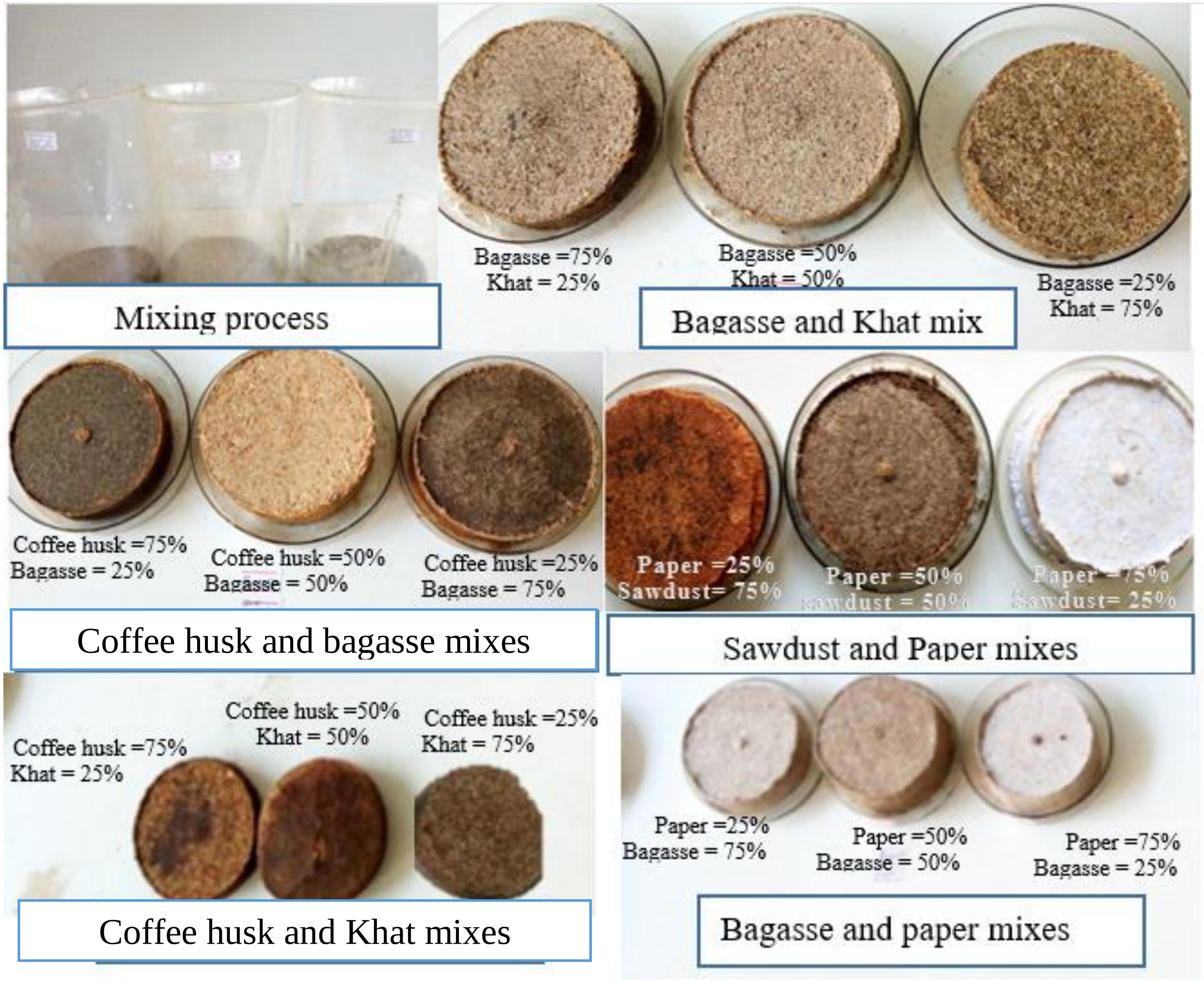


Figure 3.11 Briquette preparation process and air dried mixed briquette samples

In other experiment, in order to investigate the preheating temperature effect, oven heating method @ 140 ^{o}C was used. Feedstocks were initially transferred into the mold and the mold metal was taken in to an oven at which 140 ^{o}C operating temperature was set since at this point lignin considered as an internal binding agent starts melting fully as reported in the literature herewith. After the temperature become stable at the aforementioned set point (4-6 minutes), the mold along with the sample was immediately placed under hydraulic press for densifying. Then the temperature effect was investigated on briquettes physical and mechanical properties.

3.3.6. Briquette Characterization

Briquetted samples were studied to determine their compressible strength, heating value, moisture content, bulk density, and flue gas amount. The analysis adapted the ASTM standard procedures for each subject matter.

3.3.6.1. Bulk density Test

Bulk density of biomass briquettes can be measured geometrically as it was explained by *Bhagwanrao et al., 2014,* for briquettes which are already cylindrical in shape, whose volume was known by the formula i.e.(π/4) × (diameter of cylinder) × height. In this context briquettes bulk density was measured just after briquetting process. A fixed diameter of 73 mm and weight of 60 g cylindrical briquette sample height was measured. The height of individual samples indirectly determines the compactness of the briquette just after molding. Finally, the density of briquette was calculated using Equation 3.16 (Bhagwanrao, 2014).

$$\rho = \frac{\mathrm{m}}{\mathrm{v}} \tag{3.15}$$

But volume of cylindrical shape is expressed as,

$$\mathrm{v} = \pi \mathrm{r}^2 \mathrm{h} \tag{3.16}$$

then, density of briquette would be;

$$\rho = \frac{\mathrm{m}}{(\pi \mathrm{r}^2 \mathrm{h})} \tag{3.17}$$

Where; ρ = density of briquette sample

m = mass of briquette sample

r = radius of briquette sample

h = height of briquette sample

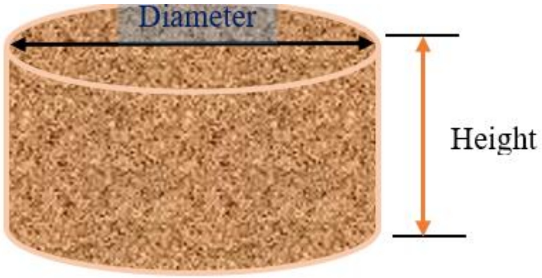


Figure 3.12 Geometrical bulk density determination

3.3.6.2. Impact Resistance Test

The briquettes' impact resistance was tested by adapting the ASTM D440 -86 drop shatter method. The briquettes were dropped twice from about 1.80 m height onto a concrete floor. The test was conducted after 30 days of briquettes samples formation. The fraction of briquette retained was used as index of briquette breakability. The percentage weight loss of briquettes was expressed as a percentage of the initial mass of material remaining on the solid base, while the shatter resistance was obtained by subtracting the percentage weight loss from 100. The IRI was calculated using the following formula (Henning, 2018);

$$\%\ \text{weight loss} = \frac{\text{weight before shattering} - \text{weiht of shattering}}{\text{weight before shatter}} * 100 \qquad 3.18$$

$$\text{shatter resistance} = 100 - \text{Percentage weight loss} \qquad 3.19$$

3.3.6.3. Compression strength test

The compressive strength of a briquette was measured by the maximum load it can bear before cracking or breaking in response to gradually applied force between two plates of compression testing machine. Compression strength test of each briquette sample was carried out using Hydraulic Universal Material Tester, (Model: WP 310) (Figure 3.12) with a load cell capacity of 50 kN and a cross-head speed was 1.5 mm/min in accordance with ASTM D2166-85 at Mechanical Engineering department, Adama Science and Technology University (ASTU). In this case, the compression strength estimation helps to know the total weight a briquette can withstand during bulk storage. After all, compression strength was determined by placing a single briquette at a time on a tensile strength testing machine and manually lowering a plate onto the briquette until it cracked. The fracture load can be compared to that of other briquettes with different dimensions and it was calculated using the following equation (Henning, 2018).

$$Compression\ strength\ (kPa) = \frac{Fracture\ load\ (N)}{Area\ of\ fracture\ (m^2)} \qquad \text{Equation 3.20}$$

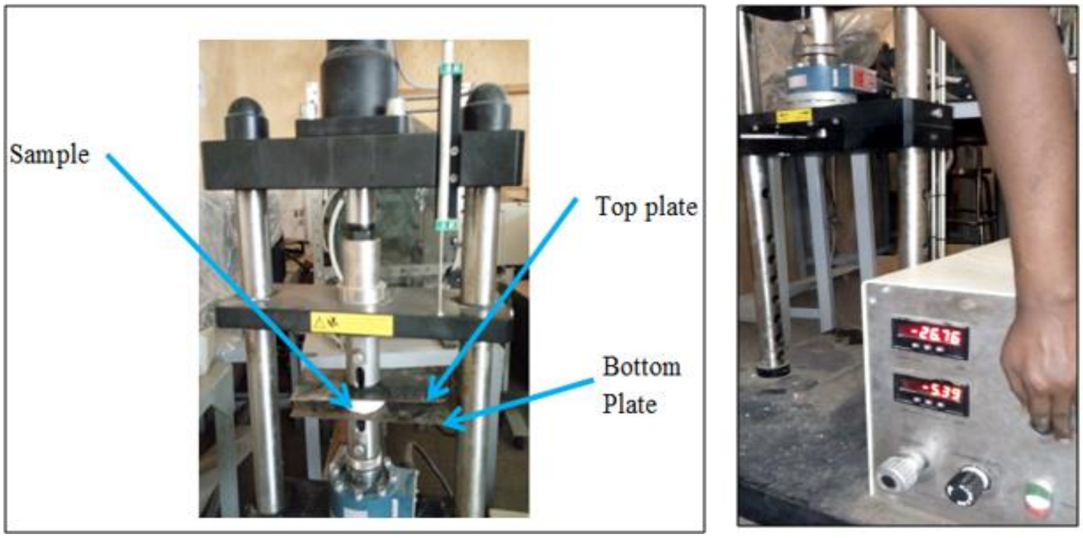


Figure 3.13 Samples compression strength test

4. RESULTS

4.1. Hydraulic machine specification and design calculations

For the simple hydraulic piston press of 12-ton ram press capacity, the applied force was calculated to be 117,720 N. Thus, from Equation 3.9, maximum working Pressure produced by the jack ram was calculated as 55 N/mm^2. The minimum cross sectional area of the top plate frame due to the upward force of 117,720 N, was determined to be 15,000 mm^2 from eqn. (3.10) and the bending stress was calculated as 7.848 N/mm^2. This value of stress provides for a safe design given that the material used can withstand up to 420 MPa.

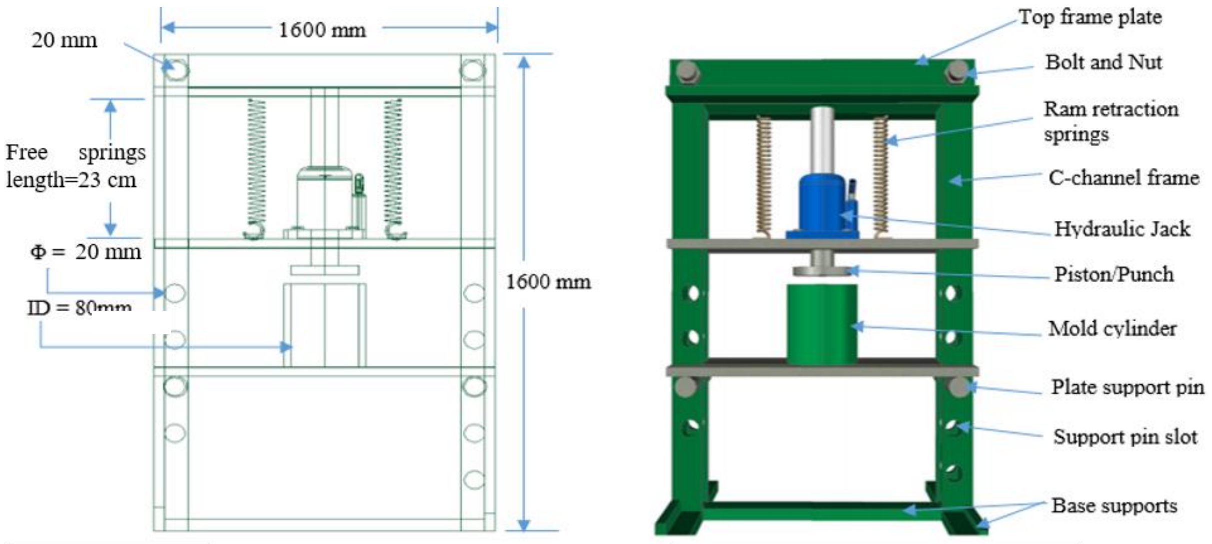
The minimum thickness of the working plate, t_p was computed to be 30 mm using Equation 3.11 and 3.12 for platens width (b) of 250 mm, L= 500 mm with allowable tensile stress for the platens material of 300 N/mm^2. The diameters of the moving frame supports were computed as 20 mm from Equation (3.13) with 248 N/mm^2 allowable shear stress for the pin material. The top cross support beam of the hydraulic cylinder was secured by means of 2 bolts to the vertical frame. The major diameters of the bolts were computed as 10.1mm from Equation (14) for 2 bolts (n), 248 N/mm^2 with allowable shear stress for the bolts material and it was taken as 20 mm bolt diameter to be more secure. The ram retracting springs having spring constants of 9 N/mm arranged between the upper frame and lower platen. The amount of springs' force hindering the ram was calculated to be 555 N at 62 mm spring elongation. C-channel column cross section, minimum cross section area was determined to be 588.6 mm^2 in response to 12-ton maximum load with mild steel tensile strength of **400** N/mm^2 and safety factor of 2.5. Therefore, 2x(80 mm, 40 mm and 6 mm thickness C- channel cross section was selected.

For the columns, the design consideration includes two (2) c-channel (80 mm X 40 mm), thickness 6mm vertical support beams each of length 1600 mm. All two (2) beams have Five (5) evenly spaced holes each of 11 mm radius. The holes accommodate the pin that support the lower worjing platen (or vertical moveable component). The stress induced in the two horizontal beams is purely axial stress but is negligible since the same applied force tends to extend and compress the shafts. The moveable plate ends were grooved and fitted with C-type column frames to slide freely during operation.

Table 4.1 Specification for components of hydraulic press machine

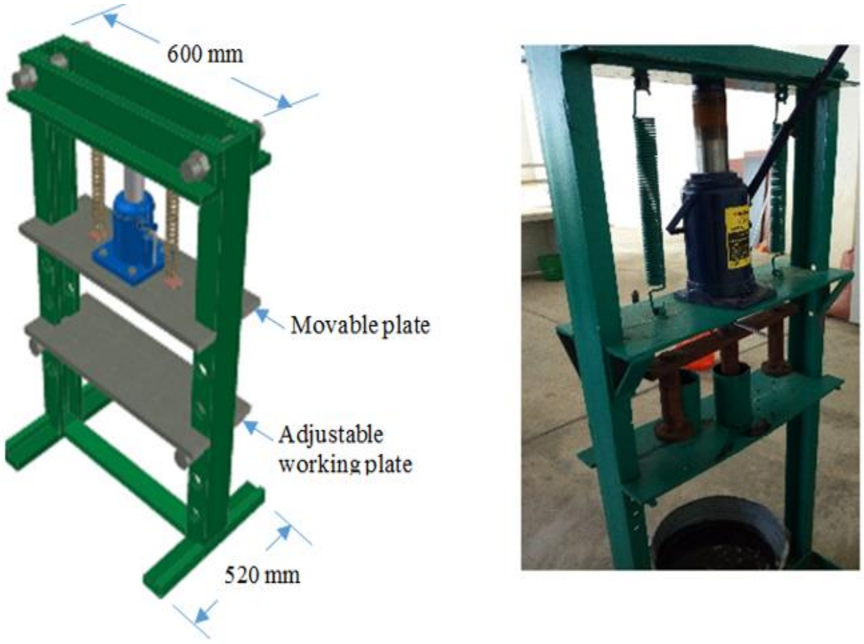
S/No.	Name of part	Materials of Construction	Specification
1	Upper frame	Mild Steel	• Type: L-shape cross section beam • Length: 500 mm • Short leg (flange) width =4.45 • Height of the L'' section =4.45 • Quantity: 2 welded together by plate
2	Spring	Mild Steel	• Type: Elastic • Quantity: two (2) • Free length: 240 mm
3	Jack	Mild Steel	• Capacity: 12 ton • Height: 300 mm • Ram diameter: 52mm
4	working plate	Mild Steel	• Length: 500 mm • Width: 250 mm • Thickness: 30mm
5	Columns	Mild Steel	• Type: C type cross section (80 mm X 40 mm), thickness 6mm • Height: 1600 mm
6	Working frame support pins	Mild Steel	• Type: round rode • Diameter: 20 mm • Length: 250 mm
8	Mold Cylinder	Mild Steel	• Height: 140 mm • Diameter: 75 mm • Thickness: 4mm
9	Punch	Mild Steel	• Height: 240 mm • Diameter: 36 mm • Punch tip plate • Flange Diameter: 73mm
10	Bottom frame Supports	Mild Steel	• Type: Angle (45mm X 45mm) • Quantity: 4 • Length: 2X520 mm (welded with columns perpendicular to plates) • 2X600 mm (welded with columns Parallel to plates)

To maintain stability of moveable plate and retract the pulled out ram after operation, dual ram return tension springs having a spring con stant of 9 N/mm were arranged between top cross fixed frame and movable plate**.** Then a 12-ton load capacity hydraulic jack was held rigidly together with a 10 mm thick movable mild steel plate by means of bolts and nuts. The frame base support was arranged by welding 2 X 520 mm angle bars with columns perpendicular to plates and 2 X 600 mm same angle bars with columns parallel to plates. The overall structure of fabricated Hydraulic press machine was indicated in Figure 4.1 with 2D and 3D AutoCAD sketches.



(a) AutoCAD 2D

(b) AutoCAD 3D sketch (Front view)



(c) AutoCAD 3D (SW Isometric) sketch

(d) Fabricated real hydraulic press machine

Figure 4.1 AutoCAD designed and assembled Hydraulic briquetting machine

4.2. Bulk Density Test

As it was observed from Figure 4.2, the maximum bulk density was found to be 1107 kg/m^3 for P8 (Coffee husk: Khat waste; 75:25) while the lowest bulk density was 498 kg/m^3 for P-20 (bagasse: sawdust; 75:25 combination) at constant particle size of < 1mm, molding temperature of 140 ^{0}C. Among the briquettes, P3, P7, P9, P10, P15 and P18 had highest bulk density ranging from 906-1070 kg/m^3 next to P8 briquette sample.

The result of the study in Fig. 4.2 showed that higher densities were observed for briquettes which contained mainly higher portion of saw dust and *khat* in the sample combination. This was relatively due to higher percentage of lignin available in saw dust and *khat* sample. The results comply with the report of (Karunanithy, 2012) that moisture and lignin contents had strong positive influence, whereas extractives had negative influence on bulk density of the briquettes. The other reason may be due to fine particle size of sawdust and Khat when it was sieved and selected below 1 mm mesh. After grinding ultra-fine particles were produced particularly for saw dust and Khat feedstocks, since particle size was selected to be constant (< 1 mm) for all samples. Therefore, generally sufficiently small particles regardless of energy requirement are required to get a random distribution for embedding into the larger particles during briquetting process (Oladeji, 2015). The above bulk densities average result showed comparable bulk densities of the samples obtained by (Mitchual, 2013) for the same particle size <1 mm) of different organic materials which values were ranged from 453-764 kg/m^3 , at compacting pressure <10 MPa).

Although fine particles are important for higher bulk density briquette production, too fine particles affect briquette durability since they are broken down and generated from the densified product during transportation and storage. Hence, from thermal treatment process, most of the briquettes had highest shatter resistance index and compression strength relative to binder alone briquettes. But paper and paper containing briquettes had the highest value of shatter resistance index and compressive strength. Paper had 99.51 % and 23.10 MPa of shatter resistance index and compressive strength respectively. Briquettes/pellets processed under suboptimal conditions such as at lower temperature, lower moisture content, and with less desirable chemical compositions, or with insufficient die size and roller speed are less durable and can result in more fines in the final product (Tumuluru, 2010).

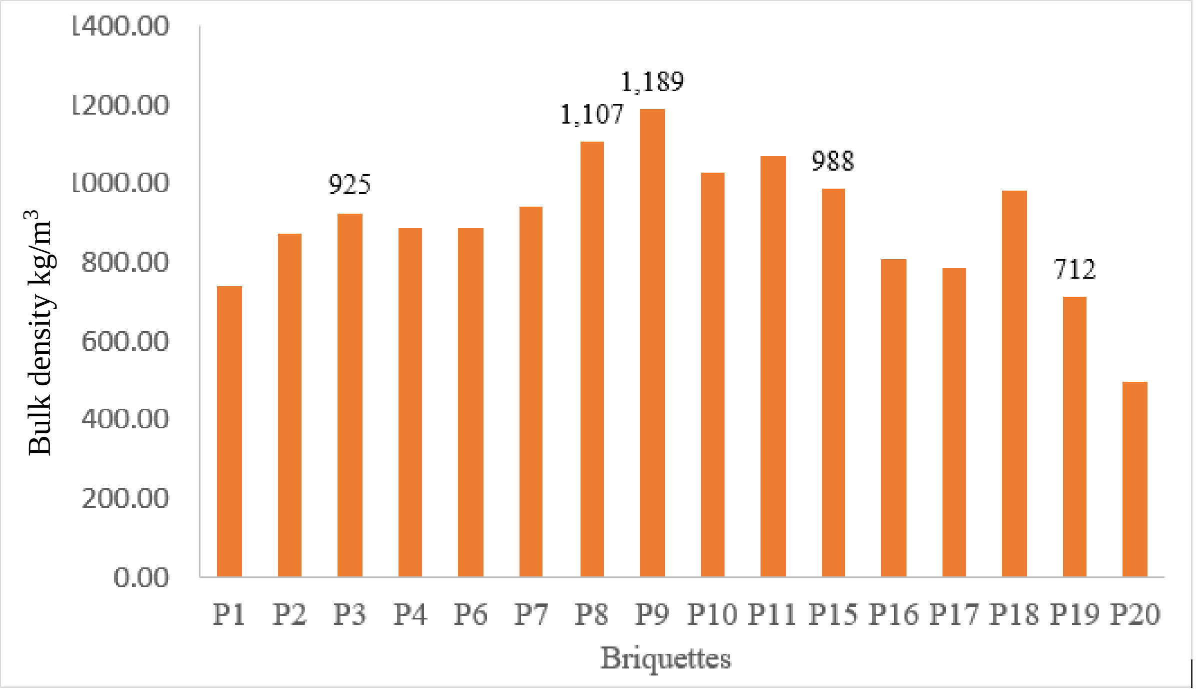


Figure 4.2 Briquettes' Bulk Density Test @ 140 ^{o}C preheating temperature

In this experiment lignin had dominant effect in binding of feedstock particles since at high temperature lignin starts softening and melting thereby more durable and compacted briquettes can be produced (Myasnikova, 2019). In relation to this (*Setter et al., 2020)* showed that the addition of 50% lignin in finely ground bagasse feedstocks reduced the longitudinal expansion briquette sample by approximately 49%, compared to briquettes produced without lignin when the temperature reached around 140 °C during briquetting process, the lignin polymer softens and acts as a bonding agent between the particles. In addition to lignin's effect on bulk density, the addition of 50% lignin increases the compressive strength by 369.70%. The addition of 10% lignin was sufficient to increase the mean diametric compressive strength of sugarcane bagasse briquettes by 84.85%. The addition of 25% lignin provided a 166.67% increase in the mechanical strength of the briquettes (Setter, 2020). *Nalladurai Kaliyan and R. Vance Morey* studied that measured temperatures of roll-press briquettes and pellets made from corn stover and switchgrass ranged from 51 to 81 ^{o}C, which is well within the range of glass transition temperatures of corn (i.e., 50–113 ^{o}C) and the briquettes were mechanically stable. They conclude that activating (softening) the natural binders using moisture and temperature in the range of glass transition is important to make durable particle–particle bonding (Kaliyan, 2010).

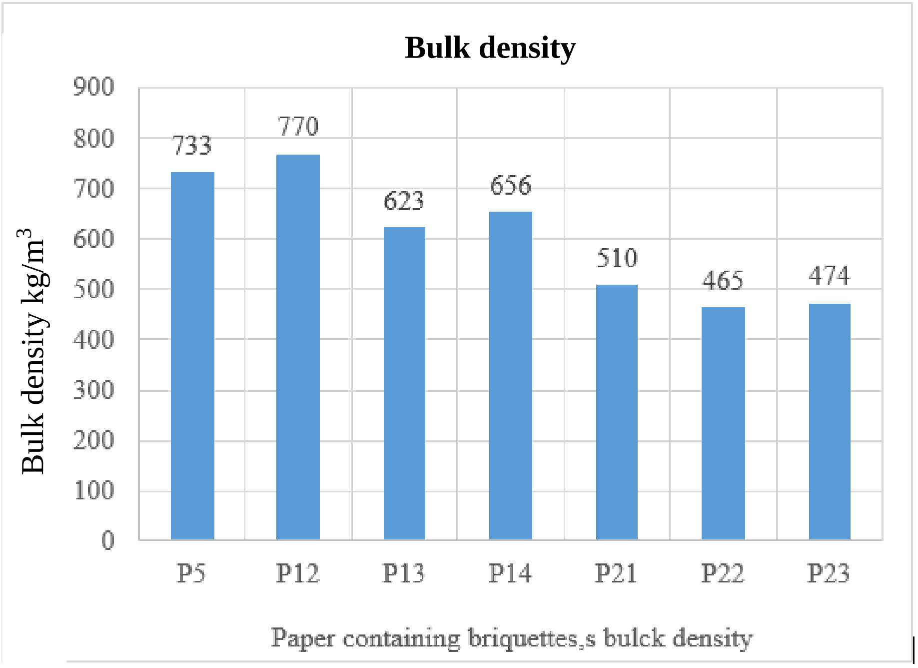


Figure 4.3 Paper Containing Briquettes' Bulk Density

The results obtained regarding paper admixture briquettes were comparable with the research work of Odusote et al., (2016), who produced and characterized briquettes made from Waste Paper and Sawdust. Test results showed that compressive strength of 100% paper briquette had a compressive strength of about 5.215 MPa (Odusote, 2016).

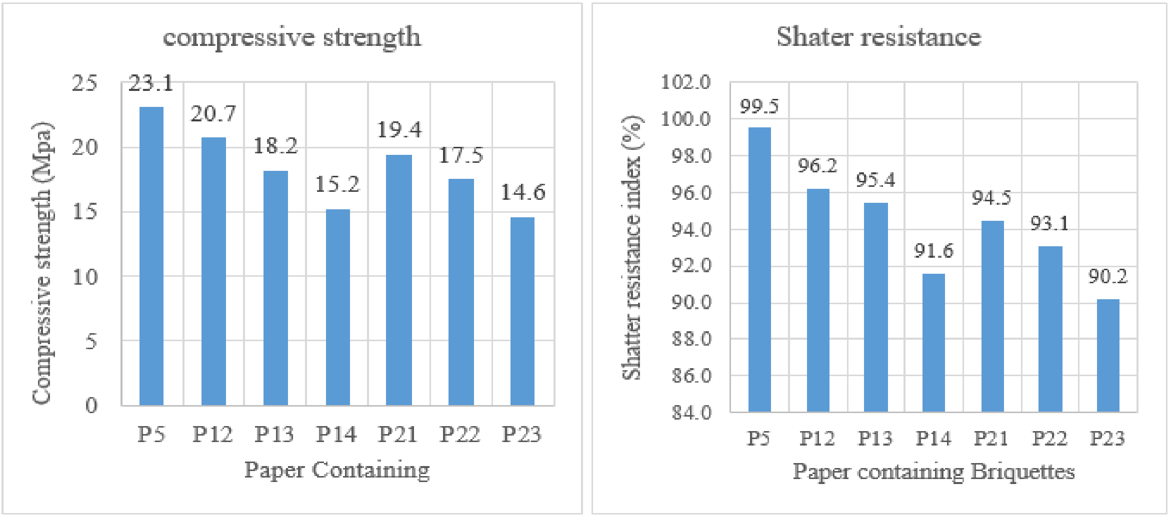


Figure 4.4 Paper containing briquettes' durability test

4.3. The effect of binder types on briquette's properties

4.3.1. Binders effect on briquettes bulk density

The effect of binders (10 %w/w) on bulk density was studied by selecting relatively low density yield bagasse containing briquettes from thermally treated briquettes as indicated in Figure 4.2. Hence, the effect of starch, molasses and Gum Arabic binders were applied to examine their effect on briquettes strength at constant pressing pressure of ~7 MPa, room temperature (22 ^{0}C) and particle size of < 1 mm. Bulk density of bagasse was found to be high (462.7 kg/m^3) using starch binder as shown in Figure 4.3, whereas gum Arabica had 452.3 kg/m^3 which was not that much far from the maximum limit. But paper and paper containing briquettes had the special briquetting process and should be seen differently due to paper binding effect during pulping and mashing with other dry feedstocks. It had highest value of shatter resistance index and compressive strength as shown in Figure 4.4. Paper had 99.51 % and 23.10 MPa of shatter resistance index and compressive strength respectively. According to the study of *Oyelaran et al.*, (2015) the effect of waste paper ratio in groundnut shell was examined. As per the study an increase in the ratio of the paper waste resulted in increase of durability. For up to 20% of paper waste in the admixture the durability is above 90%. Therefore, a stable biomass briquette can be made of waste paper and up to 20% groundnut shell admixture without addition of binder (Oyelaran, 2015). The statement reported by these researchers comply with the result of this research regarding to paper containing briquettes.

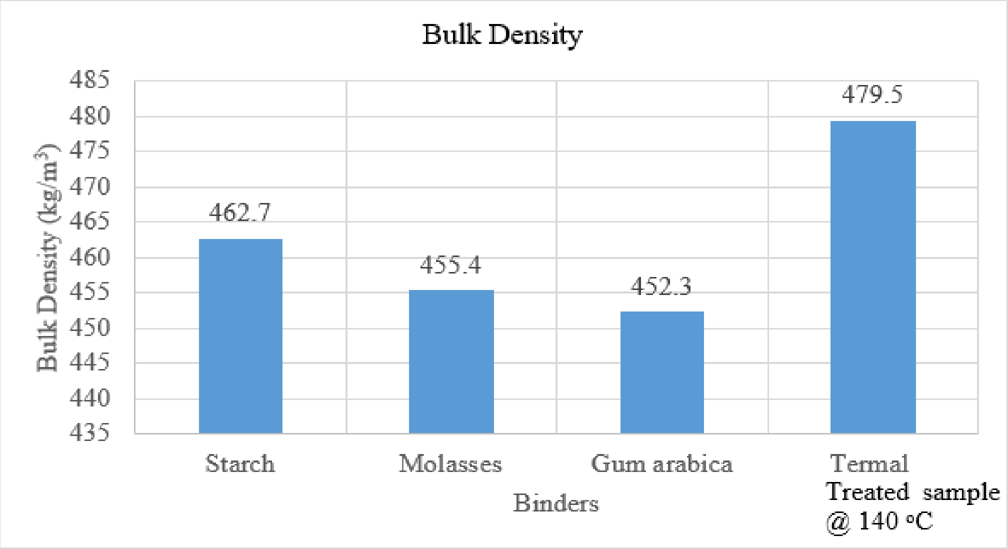


Figure 4.5 Binders effect on bagasse briquettes' bulk density

The bulk density of samples in figure 4.5 were comparable with the work of (Wakchaure, 2007) with 10% w/w molasses binder concentration. Hence, maximum bulk density observed for wheat straw and tree leaves briquettes were 638.7 kg/m^3 and wheat straw briquettes 287.69 kg/m^3. *Chirchir et al.,* investigated on molasses and cow dung bidders effect on physical properties of rice husk-bagasse-charcoal dust composite briquettes. As per their examination, density increased with increase in amount binders used. The mean density of briquette at 10% amount of molasses binder was 630 kg/m^3. However, the feedstock type and nature varies slightly, the result obtained using bagasse as a binder is comparable with the result of bulk density of coffee husk in Figure 4.5 (Chirchir, 2013). In the study of *Muazu et al. (2015),* 10% starch binder had better binding effect resulted an 867 kg/m^3 of briquettes made from corncob and rice husk admixture. The result seems more far from the results obtained in this research work, but the briquetting pressure applied was 31 MPa which was 4 time we used (Muazu, 2015). The other study conducted by Sotannde et al., (2010) investigated both starch and gum Arabic effect on the physical and combustion properties of sawdust briquettes. The result showed that briquettes bonded with starch gave closest result of density and durability of 0.546 g/cm3 and 95.93% respectively, while briquette bonded with gum Arabic had a density of 0.425 g/cm3 and durability rating of 94.85% (Sotannde, 2010).

4.3.2. Binders effect on briquettes durability

The binders effect on mechanical properties of the briquette was determined by taking 100% coffee husk feedstock at constant amount of 10 %w/w binders, ~7MPa pressing pressure, < 1 mm particle size and 3 minutes of holding time. The result showed that the binding effect of starch was relatively good (Figure 4.6) in response to the briquette compression strength and durability test.

The shatter resistance of coffee husk briquette with 10 % w/w starch binder was the highest value of 90%. This implies that briquettes produced using starch binder is more durable during transferring, handling and storage. High durability might be possible with larger particle size due to mechanical interlocking of relatively long fibers. But, in the case of preheating process at 140 ^{0}C, lignin was the only natural binder within the coffee husk cell which exhibited the highest binding effect as shown in Figure 4.6. Starch also exhibited better binding effect in the study of *Muazu et al.,* that shatter resistance index corncob and rice husk admixture with 10 % starch binder was about 90% (Muazu, 2015).

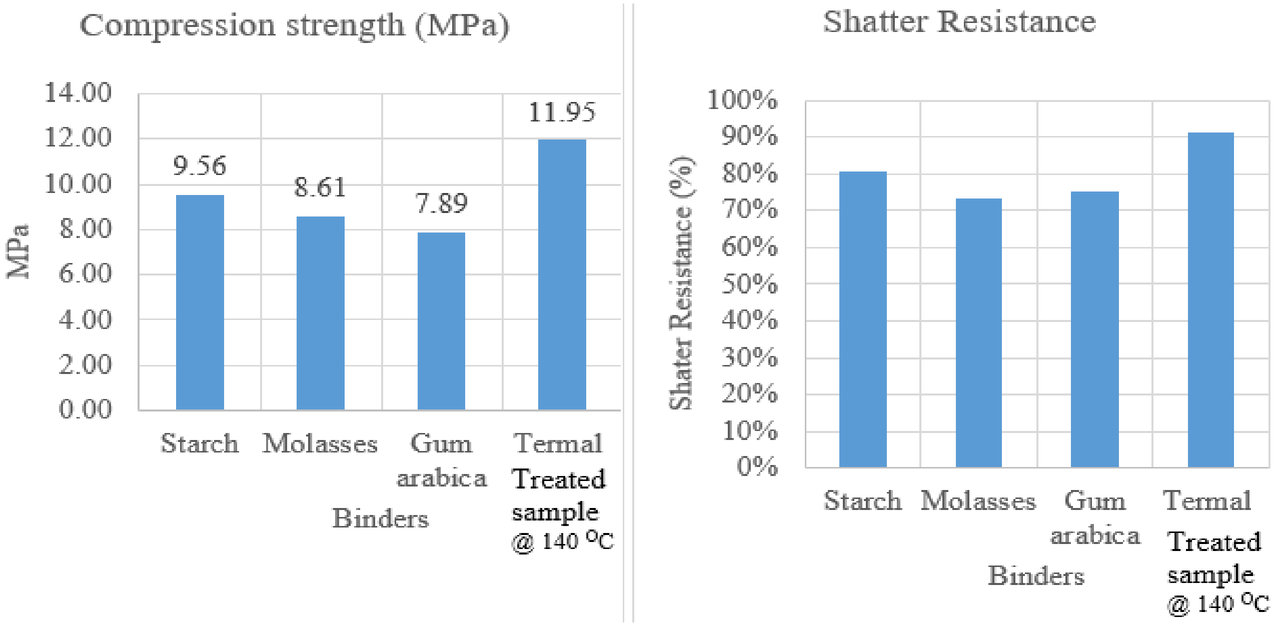


Figure 4.6 Effect of binder types on durability of coffee husk briquettes

4.4. Samples proximate analysis result

Proximate analysis of samples was conducted following ASTM's standard procedures with 10% wt/wt starch binder mixture. Almost, after briquetting the proximate result of feedstocks and its briquetted products are unchanged.

4.4.1. Moisture content

Paper briquette had the lowest moisture content of 4.5 % in dry basis as shown in Table 4.2. The highest moisture content observed was 9.3 % for coffee husk briquette. The effect of low moisture content of paper reduced the moisture content of briquettes containing paper in its binary combination of different proportion. In contrast, briquettes constituted of coffee husk in different proportion exhibited rise in moisture content. The highest moisture content in coffee husk may be due to the fact of the presence of relatively excess amount of lipid and fats and low amount of cellulosic materials as it was reported in the review work of (Tumuluru, 2010)**.** The remaining briquettes moisture content laid between 4.5 % and 9.3 %. *Demirabas* reported that straw and waste paper briquettes moisture content was found 13-22% and the researchers conclude that the moisture content up to the specified figure could achieve stability on briquettes' durability

(Demirbaş, 1998). But, too much excess moisture affects particle compaction and causes briquette spoilage and deterioration (Zhang, 2016). In contrast, low amount of water content presented in briquette samples may generate fine particles which would be difficult during transportation and storage. Moisture contents in the range of 5-10 % are usually optimal for woody raw material (Ungureanu, 2018). Hence, as it is shown in Table 4.2 almost in average main feedstocks and their blends moisture content fulfilled the standard ranges as indicated by many researches.

Table 4.2 Proximate result of briquetted biomasses

S/N	Samples Code	agricultural residues	Organic wastes	Ratio wt. %	Starch binder	MC wt. %	VM wt. %	Ash wt. %	FC wt. %
1	P1	Bagasse	----	100	10%of P1	6.7	83.5	2.42	7.38
2	P2	Coffee husk	----	100	10%of P2	9.3	83.1	1.81	5.79
3	P3	----	khat	100	10%of P3	8.1	70.1	3.41	18.39
4	P4	----	Sawdust	100	10%of P4	7.6	81.5	0.45	10.45
5	P5	----	Paper	100	10%of P5	4.5	74.5	11.8	9.2
6	P6	Coffee husk	Khat	25:75	10%of P6	8.5	73.4	2.42	15.68
7	P7	Coffee husk	Khat	50:50	10%of P7	8.2	75.6	2.51	13.69
8	P8	Coffee husk	Khat	75:25	10%of P8	8.9	78.2	2.11	10.79
9	P9	Coffee husk	Sawdust	25:75	10%of P9	6.9	82.2	1.12	9.78
10	P10	Coffee husk	Sawdust	50:50	10%of P10	8.3	82.6	1.05	8.05
11	P11	Coffee husk	Sawdust	75:25	10%of P11	8.7	82.9	0.91	7.49
12	P12	Coffee husk	Paper	25:75	10%of P12	5.4	76.2	8.52	9.88
13	P13	Coffee husk	Paper	50:50	10%of P13	6.2	79.1	6.34	8.36
14	P14	Coffee husk	Paper	75:25	10%of P14	7.3	81.3	3.24	8.16
15	P15	Bagasse	Khat	25:75	10%of P15	7.7	74.2	2.8	15.3
16	P16	Bagasse	Khat	50:50	10%of P16	7.4	76.4	3.1	13.1
17	P17	Bagasse	Khat	75:25	10%of P17	6.9	79.2	3.32	10.58
18	P18	Bagasse	Sawdust	25:75	10%of P18	6.9	81.8	1.2	10.1
19	P19	Bagasse	Sawdust	50:50	10%of P19	7.5	82.4	1.4	8.7
20	P20	Bagasse	Sawdust	75:25	10%of P20	7	83.1	2.3	7.6
21	P21	Bagasse	Paper	25:75	10%of P21	5.1	75.9	9.3	9.7
22	P22	Bagasse	Paper	50:50	10%of P22	6.2	78.4	7.8	7.6
23	P23	Bagasse	Paper	75:25	10%of P23	6.6	80.8	4.4	8.2

MC = sample’s moisture content, VM= sample’s volatile matter, FC= sample’s fixed carbon

4.4.2. Ash content

The ash content of briquettes with 10 %w/w starch binder as shown in Table 4.2 was found to be in the range of 0.45 % to 11.8 %. The minimum ash content value of 0.45 % was recorded for saw dust briquette and the maximum was 11.8 % for paper briquette. Determination of ash content is significant in its burning rate and ignition time. Higher ash content in a fuel usually leads to higher dust emissions, air pollution, and affects the combustion volume and efficiency of combustion. Excess amount of ash residue causes problem of blocking air from entering into the cooking stove, thereby hindering the burning rate of briquettes unless the stove is often shaken to clean the ash during cooking. The average ash content of agro-waste materials in general is 6.5 % (Ujjinappa, 2018) which is comparable with the average value of the current study. Hence, the briquettes produced by this research can be used as a fuel without threat of ash residue in the cooking stove.

4.4.3. Volatile matter

The volatile matter of briquettes had the lowest and highest values of 70.1 % and 83.5 % respectively. The highest value of 83.5 % volatile mater recorded for bagasse briquette as shown in Table 4.2 whereas, the lowest amount of 70.1 % was recorded for Khat briquette. This implies that lower volatile matter is an indication that ignition may not be easy, but once ignited briquettes will burn consistently, while high volatile content results in high combustibility at low ash content (Falemara, 2018).

Blending of higher volatile materials such as sawdust, bagasse and coffee husk with lower volatile materials (Khat and paper) resulted in the production of optimum quality briquette. In contrast, the higher the volatile matter of briquettes, the higher the amount of emissions during burning. This implies that low volatile matter is required for good quality briquette (Falemara, 2018). Approximately, all biomasses have a volatile content of around 70-86% of the weight of the dry biomass, compared with coal, which contains only about 35% volatile matter. Consequently, the fractional heat contribution of the volatile matter is more for biomass, which makes biomass a more reactive fuel than coal, giving a much faster combustion rate during the devolatisation phase (Tamilvanan, 2013). Hence, the briquettes produced by this research fulfilled the required volatile content to be used as a fuel.

4.4.4. Fixed Carbon (FC)

Fixed carbon for coffee husk briquette was found to be the lowest percentage of 5.79, whereas the highest value of FC was recorded as 18.5% for Khat briquette as shown in Table 4.2. The high ash content of fuel briquette implied that the combustion remnant of such fuel was high but with a low heating value (Ajimotokan, 2019). Higher ash content in a fuel usually leads to higher dust emissions, air pollution, and affects the combustion volume and efficiency of combustion (Falemara, 2018). It is known that coal has the higher value of fixed carbon than biomass feedstocks. *Tamilvanan (2013)* has reported that coal has fixed carbon amount of 28.9 % by weight (Tamilvanan, 2013). He specifically revealed that blended bagasse and paper briquette has avarage fixed carbon content of 9.63 % by weight in dry basis which was too close to 9.3 % bagasse to paper at 25:50 blende ratio of this research as shown in Table 4.2. as per the report of Rorisa et al. (2019) fixed carbon content (FCC) of Khat waste branch of raw material waste was 20.9% which was closely comply with the FCC of Khat reported in this research (Rorisa, 2019).

4.5. Briquettes calorific value

The calorific value of briquettes determine the amount of heat energy produced in joule per kilogram after complete combustion process. Hence, after measurement, the calorific values of briquetted fuels were determined, but due to uncalibrated bomb calorimeter, the values were slightly deviated from the reported values in different literatures. Therefore, literature values of single components were taken to estimate the blended briquettes based on their mass composition. Therefore, from the literature characterization of calorific values in Table 4.3, sample briquettes' calorific values were ranged from 15.44-18.34 MJ/kg. Out of the briquettes, coffee husk and saw dust combination had relatively maximum calorific values ranged from 17.64-18.31 MJ/kg. The least calorific value of 15.44 MJ/kg was recorded for Khat briquette. Khat and other feedstocks' admixture exhibited relatively low calorific value due to low khats' calorific value effect. The other least calorific value recorded was for paper and paper containing briquettes relative to the aforementioned briquette samples. Table 4.2 illustrates that paper had the highest ash content among the briquettes which has a potential to reduce the calorific value. Although, it was relatively the lowest value, it is still close to the other briquettes' calorific values. Furthermore, the least calorific value in Khat (15.44 MJ/kg) reported by *Rorisa et al.* (2019) is due to relatively high ash content as shown in table 4.2 and the high amount of lignin component in Khat sample (Rorisa, 2019). Another studies conducted by *Mhilu et al. (2014)* for coffee husks, exhibited a calorific value of 18.34 MJ/kg (Mhilu, 2014). Similarly, *Brunerová et al. (2020)* and Lela et al. (2015) investigated the calorific values bagasse and saw dust as 17.06 MJ/kg and 17.41 respectively (Lela, 2015) and (Brunerová A. H., 2020). Both research works output for the specified feedstock were presented in Table 4.3. The addition of 10% binders didn't affect the calorific value of a sample, since among 10% binders' energy content was insignificant.

Table 4.3 Briquettes Calorific Value

S/N	sample	Calorific Value (MJ/kg)	Calorific literature value and combination values	Starch binder amount	S/N	Sample	Calorific Value (kJ/kg)	Calorific literature value and combination Values	Starch binder amount
1	P1	17.06	(Brunerová A. H., 2020)	10% of P1	13	P13	17.33	Combination values as per mixing ratio	10%of P13
2	P2	18.34	(Mhilu, 2014).	10% of P2	14	P14	17.84		10%of P14
3	P3	15.44	(Rorisa, 2019)	10% of P3	15	P15	15.85		10%of P15
4	P4	17.41	Lela, 2015)	10% of P4	16	P16	16.25		10%of P16
5	P5	16.32	(Tamilvanan, 2013)	10%of P5	17	P17	16.66		10%of P17
6	P6	16.17	Combination values as per mixing ratio	10%of P6	18	P18	17.32		10%of P18
7	P7	16.89		10%of P7	19	P19	17.24		10%of P19
8	P8	17.62		10%of P8	20	P20	17.15		10%of P20
9	P9	17.64		10%of P9	21	P21	16.51		10%of P21
10	P10	17.88		10%of P10	22	P22	16.69		10%of P22
11	P11	18.31		10%of P11	23	P23	16.88		10%of P23
12	P12	16.83		10%of P12					

5. CONCLUSIONS AND RECOMMENDATION

5.1. Conclusions

This study investigated the physical, thermal and mechanical properties of briquettes made from the admixtures of organic wastes (paper, Khat & sawdust) and agro-industrial wastes (coffee husk and bagasse) at different blending ratio with 10 %w/w of binders. After a preliminary design, 12-ton maximum working load hydraulic press briquetting machine was developed for feedstock briquetting purpose. The variations of three selected binders namely starch, molasses and gum Arabic were prepared and applied in briquetting making process with the aforementioned feedstock admixtures to study their binding effect on briquettes property. Besides, feedstocks were treated thermally at 140 ^{o}C to investigate the internal binding ability of intracellular lignin component. From the study, it could be concluded that (1) bulk densities of briquettes were promising for handling, transportation and storage as the results confirmed in figure 4.6 for instance shatter resistance indexes were greater than 80% for coffee husk briquette using different binders. Furthermore, briquettes durability was improved by using thermal heated sample during briquetting processes. All binders had relatively good binding effect, but starch binder exhibited more attribution in bulk density and shatter resistance index. (2) The proximate analysis results for moisture content, ash content, volatile matter and fixed carbon of admixture briquettes were investigated following standard procedures and results in Table 4.2 indicated that briquettes made from different combinations of feedstocks could be used as a source of fuel. This can be illustrated that the cumulative effects of proximate values indirectly affect the calorific values of briquetted samples. In this context, briquettes calorific values were an indication of products having considerable energy content as shown in Table 4.3. Generally, different briquettes were produced with the expected output of the overall objective that could be achieved by maintaining complying physical, mechanical and thermal properties.

5.2. Recommendations

Production of briquette from agro-industry waste and discarded organic waste was a more efficient way of utilizing the energy resources due to the higher heating values generated. I, the principal investigator would like to recommend researchers and end users the following tips;

- Different discarded waste materials which have a potential to be used as energy source should be sorted out and densified by blending with other organic materials.
- Since from experiment feedstock thermal treatment enhanced the mechanical property of the briquettes, special thermal heater low pressure briquetting mold should be designed.
- In this research work cylindrical mold was used to produce briquettes, thus, in order to increase oxygen, transfer during burning special hole making molds should be designed and installed thereby combustion efficiency could be achieved.
- Experimental characterization of blended mixtures should be tested using well calibrated bomb calorimeter.
- Emission test of briquettes during burning should be tested using well confined, oxygenated chamber with emission exhaust line to accommodate gas analyzer sensor.

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