CHAPTER ONE

1. INTRODUCTION

1.1 Background to the Study

Following the world's increase in demographics, there is increasing demand for domestic and industrial energy use. The desired energy resource is expected to be safe and contribute minor percentage to environmental hazard when compared to the obtainable energy technologies. This is to ensure energy source can meet the numerous demand sustainably. Many nations have been sourcing the indigenous alternative energy resource that is renewable and sustainable. The safest and environmental sustainable energy resources is renewable energy and include biomass, solar, hydro, wind etc.

Biomass is considered one of the most available energy source and is applicable in numerous energy conversion systems. Biomass energy refer to energy generated from the use of materials resulting from existing organisms or newly reproduced living organisms of plant and animal origin (Sugathapala and Chandak, 2013). It is known to be the third most utilized energy resources in the world while coal and oil are the first and second respectively (Tumuluru *et al.*, 2010a). It would have been the largest but as the result of oil boom in the nineteenth century, it made nations to divert to fuel produced from decay of plant and animal origins as their major source of energy. Though the use of fossil fuel has dominated since the last fifty years, biomass still provides about 14% of the world's yearly energy that is utilized world over (Purohit *et al.*, 2006; Werther *et al.*, 2000; Zeng *et al.*, 2007). Biomass resources used for energy source comprise of residues from agriculture, harvests from forests crop residues, starchy crops, compost manure, remains from agro-industrial and food processes, public solid wastes and other organic resources (Caputo *et al.*, 2005).

Biomass wastes are remains or waste that can be replenished, made of biological material and can be used without conversion as a fuel, or converted to other form of fuel or energy product. The most prominent of these wastes are wood waste, rice husk, agricultural straws, grasses, groundnut shells etc. In Nigeria, 9-150 million tons (MT) of these crop residues are produced annually (Agoro and Ogie, 2012; Simonyan and Fasina, 2013). The reprocessing of agricultural residues materials into valuable products is not often practiced in developing countries such as Nigeria. This has given rise to environmental difficulties such as contamination, caused by indiscriminate dumping of refuse on the streets and in the drainage systems and water ways, causing blockages of water ways on rainy days. This practice has also led to the outbreak of epidemics (Yahaya and Ibrahim, 2012).From these bulky magnitudes of agricultural residues generated in Nigeria, there is immense potential of their use for energy production. Biomass wastes if well managed, offer countless benefits, the greatest significant being that they are renewable and maintainable energy resource. They are able to considerably decrease net carbon emission when compared to fossil fuel.

Energy resource from biomass can be in form of solid (charcoal and firewood), liquid (ethanol and biodiesel) or gas (biogas). The type of conversion process to be applied in converting a given biomass material is subject to the moisture content of the material. Thus, direct burning is usually used for conversion of low moisture content biomass waste materials into useful energy source.

The lowest expensive biomass resources for energy production are the waste products from wood or agro-processing operation. Biomass densification or compaction technologies are among the promising ways of overcoming the limitation of low bulk density in biomass wastes. In making briquette or pellets, mechanical pressure reduces the volume of biomass wastes and converts them to a denser solid product that is of less difficult to handle and store than the raw material. Briquette production increases bulk density of the biomass wastes to about tenfold of its original bulk density. Briquettes can be used as substitute to firewood fuel as demand for firewood fuel especially in the developing countries continue to rise as a result of increasing population. Biomass densification can be performed using hydraulic press, pellet mills, extrusion processes or roller presses.

There are numerous existing briquetting machines for the production of briquettes. Most of them are hydraulic press briquetting machine. This is because this type of briquetting machine is easy to operate and has low cost of production. Assessment of performance of hydraulic press is great impediment in its commercialization. This is because of the variables that accounts to the production process. There is however need to model the performance operation of briquetting process and also optimize the quality of briquettes produced at various input variables. Current studies on hydraulic briquetting press as it relate to the structural design and optimization has not exhaustively determined the production potential of the machine in producing good quality briquettes (Krizan*et al.*, 2010; Matus*et al.*, 2010; Gatmaitan*et al.*, 2012). The major problem associated with producing good quality briquettes is examining how the production process affect the compositional content of the briquettes. However, there are a number of variables that ought to be considered during briquette productions and these factors include the machine parameters, physical properties of the biomass material and composition of biomass wastes. These factors are in synergy and play significant roles in evaluating the performance of a hydraulic press briquetting machine as well as the quality of the briquette it produces. Combination of all these factors affect the binding characteristics of the briquettes and therefore the durability, compressive strength and other important features of the briquettes are also affected. Apparently, performance and briquette quality of many hydraulic press briquetting machines can be assessed if there are mathematical models that can be employed. Thus, it becomes pertinent to develop model for predicting performance of a hydraulic briquetting machine for biomass waste. Since briquette production involve a lot of process input that effluence the quality of briquette produced, optimization technique is ideal for raw material allocation. This however will ensure that good quality briquette is produced. Quality in terms of environmental sustainability when being used as source of energy. This is achievable by constraining those factors that constitute environmental problem while burning. Interestingly, biomass waste differ in their composition and during material preparation for production of briquette, some of these inherent compositions are altered and as a result during burning, they might be produce gases that is injurious to environment. Obviously, a sustainable energy source has to be environmental friendly and possess high heating value.

1.2 Problem Statement

Hydraulic press briquetting machine is one of the adopted briquetting machine because of the numerous advantages it has over other types of briquetting presses. However, not much studies had been done on the machine as it relate to its performance during operation. Also the effect of the production process on quantity of briquettes being produced has not being well known. There are a lot of existing hydraulic press briquetting machines that have been developed by several researchers but these machines cannot be evaluated with specified standards because of unavailability of standard measure to describe their performance and functionality. Usually, major concern has been to study various properties of biomass materials for briquette production (Shekhar, 2010; Bhoumick *et al.*, 2016; Yazdani and Ali, 2016; Onuegbu *et al.*, 2012; Olorunnisola, 2007; Tembe *et al.*, 2014; Raju, *et al.*, 2014) while other research works evaluate the influence of process variables on the briquettes quality and obtained empirical models from such analysis (Tumuluru *et al.*, 2015; Davis and Mohammed, 2013; Amanor, 2014). Some performed a structural analysis on the designed machine using finite element analysis (FEA) but did not study the consequence of the designed model of the structure on the operational characteristics of the machine and briquette quality (Saleh, 1992; Muni and Amarrrnath, 2011; Bapat and Dessai, 2009). Difficulties has been encountered on determining quantity and quality of briquettes produced by hydraulic briquetting machine. Tackling this challenge will create a major head way in the utilization of hydraulic briquetting press for producing good quality biomass briquettes.

Basically, hydraulic press is a mechanical system and its performance can be studied by mathematical models using established scientific principles. Empirical models may be good for a specific machine but definitely not ideal in a generalized application.

This work intends to use Buckingham pi theorem approach that have been applied in various mechanical systems to predict the performance of hydraulic briquetting machine. This approach involve development of mathematical models using dimensional analysis by considering the performance parameters of hydraulic press briquetting machine. This will ensures that much effort is not wasted in design and testing as only variables sensitive to the analysis of the machine are studied. The study will as well optimize the process variables for production of environment friendly briquettes.

1.3 Aim and Objective of the Study

The aim of the work is to model and optimize the performance parameters of hydraulic press briquetting machine for biomass wastes. The specific objectives of the research are to;

1. Characterize some selected biomass materials and also determine the relevant parameters affecting briquette quality during hydraulic press briquetting operation.
2. Develop mathematical models using dimensional analysis (Buckingham π-theorem) for predicting the performance parameters (output capacity, quantity

of damaged briquettes, production efficiency and bulk density) of hydraulic press briquetting machine in producing briquettes.

3. Validate the developed models with a briquetting machine using various biomass materials.

4. Evaluate the significant effects of some process variables on the quality of briquettes.

5. Perform quality optimization of the process variables for production of quality briquette.

1.4 Scope of the Study

The scope of this research work is on development of mathematical models that will be used for predicting the performance of hydraulic press for production of briquettes from biomass waste materials. It also optimized the process variables (particle size, binder ratio and inlet hydraulic pipe configuration). The work equally studied the significance of pressure and particle size on the bulk density and compression ratio for five biomass materials.

This models are only applicable to C-frame hydraulic system. This is because C –frame hydraulic press is commonly used in briquette operations.

1.5 Justification of the study

Management of biomass wastes has been a major concern to developing countries. In Nigeria, dump site of these materials are scattered all over the country constituting environmental hazard to the inhabitants. A hydraulic briquetting machine requires in-depth knowledge of the principles and theories behind its performance parameters during briquetting operation. This study will provide an important and flexible way of determining the performance of hydraulic briquetting machine for biomass waste. Some of the significant and beneficial achievements of the study are:

Biowaste characterization helps to identify the inherent energy potentials of biowastes and determined the most suitable way that can be adopted in their processing.

The predicted models will be used in design and evaluation of hydraulic press briquetting machines hence, productivity, efficiency, quality and required optimized input variables are guaranteed. Efficient indigenous biomass briquetting machine will lead to their indigenous manufacturing and commercialization in various regions of massive waste generation. This could encourage production of briquettes from biowaste materials thereby ensuring effective waste utilization in those regions and also mitigate the problem of energy generation in some parts.

Knowledge obtained from this work will also encourage the establishment of research centers whose mandate would focus on characterization of indigenous waste and opting processing methods for management practice.

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CHAPTER TWO

2. LITERATURE REVIEW

2.1 Concept of Densification

One of the main problems associated with the utilization of biomass waste as source of fuel is its low density which gives rise to high transportation and storage costs and limits utilization of the biomass wastes. This makes the residues beneficial only to areas close to the production site. Compaction which is also known as densification is used to improve characteristics of materials, especially low density biomass, for transport and use as energy source. Briquetting is the compression of low dense biomass material. It is a method used in minimizing the large quantity of the biological material by mechanically compressing the material for easy handling, transportation and storage. Low bulk volume has been one of the largest obstacles facing biomass utilization for energy production. Densification of biomass has been used as a way to minimize this problem by increasing the density of the final product thus improving possibilities for commercialization. By the use of various machines in compressing the materials, the density of the raw material can be increased 70-100 percent of its original density. Due to the higher homogeneity of the densificates from biomass to produce pellets and briquettes, it has been found that the densificates are in general more suitable than when the original raw material of the solid fuel is utilized (Ortiz *et al.*, 2006; UNEP, 2013).

Densification process is divided into two processes. Firstly, compression of the raw biomass materials under pressure to lessen its volume and secondly, the agglomeration of the materials so that the product can continue in its compacted state. When the loose biomaterials are compacted with small to intermediary pressure, (0.2-5MPa), then the inter particle spaces between particles is decreased but high pressure (≥100MPa) collapses the cell walls of the biomass material while its cellulose constituent attains the physical or dry density of the material (Sugathapala and Chandak, 2013). Biomass densification operates to relate the magnitude of the applied force exerted on the material to its physical characteristics. It solves the problem of low density in solid biomass waste and the application of mechanical force to form briquettes, there is savings in transportation and management costs as the result of transporting larger quantity of the briquettes and storing them for a longer time interval. There is also likely to be high heating values over the raw material because of high dense material that is produced. Performance of the machine and operating condition of the machine will determine the optimal density of the briquette. According to Sugathapala and Chandak (2013), it is yet to be established the theory by which compacted biomass material reaches self-bounding but, it is known that at the application of high pressure, morphological configurations such as pectin, lignin and other low molecular substances are removed from the plant cells and act as binding agents for the particle. These binding agents act as internal glue during densification.

During briquette formation, there are two activities that are involved during compression. They are; the way the particles behave when they are under compression and secondly, the inter particles relationship when forming briquettes under substantial mechanical strength. Most often, the second activity is of paramount importance and a fundamental problem to be tackled. There are also two forces that contribute to briquette formation during densification namely; inherent force on the material and force applied to the material otherwise known as mechanical force (Tabil, 1996). The inherent forces are cohesion force that bond the particles of the biomass material together, whereas applied forces are the mechanical forces needed to compress all the particles together. There are stages that a compaction process has to pass through. All the stages involve volume reduction of the compaction particles.

In stage one, there is rearrangement of the particles at low pressures which involves collapsing the uneven filling arrangement known as “arches” or “bridges”. This leads to close packing of the materials during compaction. Because there is friction within the particles at this stage, energy is lost and the physical properties of the loose material are maintained. The second stage involves deformation due to elasticity and plasticity of the materials. This occurs at more force is added to the material. This action causes the particle to fill the void spaces thereby increasing the contact area between particles created in stage one. In the final stage, the compressed density of the particles reaches the specific compactness of the material and the local dissolution of the materials occur if the melting points of the constituents are reached.

These three stages occur simultaneously during compaction process thus as the density increases, the apparent density of the briquette reaches that of the theoretical density of particles and the deformed or shattered particles are no not able to alter position because of the few remaining cavities.

2.2 Factors Affecting Biomass Waste Compaction Process

Regulating densification system require some influential variables. These variables are important in obtaining the required density, stability and superiority. The quality of briquettes can be manipulated by controlling the process variables such as change of formulation, and the use of additives. These variables include process variables, feedstock variable and biomass composition variables. Extensive study was done on densification of biomass and the findings expressed the contributions of these variable in determining the quality of briquette (Shaw, 2008).

2.2.1 Process variables

Process variables are those factors that are set and carried out on biomass materials by the briquetting machine. Process variables include temperature, pressure, retention time and die geometry.

Temperature:

Temperature was found to density of briquettes. This was established in Mani *et al.* (2003) that found out that increasing the temperature of compressing operation will entail the use of less load. This however, would use lesser power for densification thus produce briquette of desired density. This confirms Hall and Hall research as reviewed by Tumuluru, *et al.*, (2010a) who found out increasing temperature in wafer die would reduce the pressure at any given moisture content. In like manner heat addition at increased moisture content at a particular pressure would produce a specific wafer density adding heat, increased the moisture content at which a certain pressure was able to produce a specific wafer density.

Sokhansanj *et al.* (2005) obtained similar report stating that as the temperature is increased, the material tends to resist against the load applied. On investigating briquetting of wheat straw, Tumuluru *et al.* (2010a) reviewed Smith's work on compaction process and found that for a given pressure, at a temperature range of 60-140°C, there is great degree of compaction and stability of the briquettes of briquettes produced. The report also stated that the time required for the briquettes to expand was less when the die temperature is between 90 and 140°C. The report however observed that for wheat straw briquettes, there were external charred at the surface and slight discolored at temperatures above 110°C. This is due to chemical degradation as the walls of the briquettes are building up. In a study that evaluated the densification potentials of corn stover and switch grass using temperature as key parameter, it was observed that there is transition from hard to a soft, rubbery material (glass transition temperature), Kaliyan and Morey (2006) also studied compaction activities of corn stover and switchgrass. They recorded average glass transition temperature at 10, 15, and 20% moisture content (wb) as 75°C. The summary of the findings indicates that increasing moisture content generally reduced the glass transition temperature to the end point of 100°C. Consequently, 75^{o}C and 100°C were chosen as optimum processing temperatures for briquettes. At 150°C it was also revealed that there was moisture migration resulting in a lower durability than the 100°C briquettes. The toughness of the briquettes produced at 100^{o}C was found to be higher than those produced at 75°C.

Pressure:

Pressure is another variable that distinguish briquette quality significantly. Yaman *et al.* (2000) recommended selection of compacting pressure at an optimal value but to obtain the optimal value is has been the major bottleneck as materials differ in their behaviors during pressure application. Supposedly, briquetting pressure increases the mechanical strength of the briquettes as a result of the plastic deformation. However, above an optimum briquetting pressure, fractures may occur in the briquette. This is due to an unexpected expansion on the briquettes. Once the maximum pressure is attained, further in pressure will amount to no significant increase in cohesion of briquette (Ndiema *et al.,* 2002). A report by Li and Liu (2000) on pressure application rate show that compressing oak sawdust at 10.3% moisture content and applying pressure at rates from 0.24 to 5.0MPa/s has significant effect on the dry density. In the study of compression of biomass waste materials like waste paper, it was observed that increasing the pressure from 300 to 800 MPa at about 7% moisture content (wb), increased the density of the material from 0.182 to 0.325g/ml. For material at 18% moisture content (wb) at the same pressures, the briquettes densities were reported to increase up to 0.278 and 0.836g/ml respectively. A contradicting report by Svatek *et al.* (2009) on effect of pressure on final briquette quality shows that compacting pressure has minor influence in analyzing effect of compaction on briquette quality.

Hold (resident) time:

Hold time in briquette operation is the total number of time (sec) the compressing die is left on the briquette after operation. The resident time of biomass material in the die influences the quality of the briquettes. Li and Liu (2000) found that the resident time for oak sawdust had more effect at lower pressures than at higher pressures. At 138 MPa, the influence of resident time became unnoticeable. Its influence on expansion rate is also very small such that times greater than 40 seconds had a trivial effect on density. Al-Widyan *et al.* (2002) discovered that hold (resident) times between 5 and 20 seconds don't have a significant effect on olive cake briquette toughness and steadiness.

Die geometry:

Die geometry refers to the dimensions of the die that affect briquetting operation of a given amount of the material. These geometry are shape, size and configuration of the briquetting die. These configurations determine the energy required for compression, etc. In a review by Tumuluru *et al.* (2010a) and Shaw (2008), they found out that for a given quantity of biomass material, increasing the surface area of briquetting die geometry can increase the density of the briquettes at a given pressure. It was also observed that height of briquettes produced with smaller chambers using a constant mass of material will be higher thus there will be a resultant smaller percentage of expansion.

2.2.2 Biomass waste variables

Biomass waste variables are those variables that affect the compositional and properties of the biomass material.

Moisture content:

Moisture acts as binder in briquetting process. This action of moisture is achieved by reinforcing and stimulating bonding via van der Waal's forces by increasing the contact surface area of the particles (Mani *et al.*, 2003). Moisture present in the biomass accelerates starch gelatinization, protein denaturation, and fiber solubilization processes during briquetting. As a general rule, higher moisture content entails lower the density of the briquettes. Demirbaş *et al.,* (2004) investigated the effect of moisture on briquette quality and found that increasing the amount of moisture content of material from 7-15% of pulping residues and spruce wood sawdust resulted in stronger briquettes. Mani *et al.,* (2006) also reported in the study on corn stover that low moisture content (5-10%) resulted in denser, more stable and more durable briquettes than at a high moisture contents (15%). Li and Liu (2000) however recommend that the optimum moisture content for production of briquettes from compression of wood in a punch-and-die assembly was approximately 8% (wb). Following a study of the compaction of tree bark, sawmill waste, wood shavings, alfalfa hay, fresh alfalfa, and grass, Moshenin and Zaske report as reviewed by Tumuluru *et al.*, (2010a) and Shaw (2008) showed that materials that have lower moisture content and fewer long fibers provided better established wafers, due to restricted expansion. Protoplasm released during the compression, acted as a binder agent and provided fresh alfalfa (19% moisture) with the highest durability. Li and Liu (2000) also found that when the moisture content is too low (4%), there is tendency that the briquettes produced from it will tend to absorb moisture from the atmosphere and expand which will be make the briquettes unsuitable for storage. In other words, the briquette would be fragile in few day of production. In a similar work by Theerarattananoon *et al.,* (2011) on four agricultural residues showed that moisture content of briquettes have effect on their physical properties. They stated that optimum moisture content of 9% -14% is suitable for durability of the briquettes. In some briquetting operation, water is added in form of steam and in this case, the water in a better form as the additional heat to the water will modify the physio chemical properties of the material thereby enhancing the binding agent between the particles. Those physical and chemical properties include the starch gelatinization and denaturing of proteins. The resultant is formation of high quality briquette (Thomas *et al.*, 1997). From this, it is obvious that the optimum moisture content for densification is different for different types and species of materials which makes the set individual biomass waste process conditions also different. However, processing of briquettes at moisture content range of 8%-15% will not have much effect on the durability of the briquette (Theerarattananoon *et al.*, 2011 and Arzola *et al.*, 2012).

Particle size, shape, and distribution:

Generally, the briquette quality is inversely proportional to the particle size. Mani *et al.* (2003) alluded to the idea that particle size distribution has an effect on pellet quality. According to Payne's report as reviewed by Shaw (2008), a proportion of fine to medium particles is required though pellet quality and the efficiency of commercial pelleters will suffer if coarse material is not present. The effect of particle size distribution was listed as an important material property for forage wafer making when comparing leaf to stem ratios, as a higher leaf content has been reported to produce a superior densified product; this may also be due to increased protein content in the leaf. Arzola *et al.* (2012) reported that average particle size had the most influence on pellet density.

2.3 Biomass Wastes

Agriculture is an important part of the economy of most developing countries and large quantities of biomass wastes are generated each year from these agricultural activities amounting to about 140 billion tons (Koopman and Koppegan, 2006). Biomass wastes otherwise known as organic materials are produced as by-product during harvesting and processing of agricultural crops. Biomass waste has always been a major source of energy for mankind. According to REN21 (2012). In 2010, biomass waste accounted for about 12.2% of global primary energy consumption which constituted 73.1% of the world's renewable energy. It is also the third largest source of energy after oil and coal (Tumuluru *et al.*, 2010a). In developing countries, it plays even a more significant role in providing domestic cooking energy and small, medium and commercial scale industries energy. In Nigeria, biomass accounted for 85% of the total domestic energy consumption in 2006 as shown in Fig. 2.1 (IEA, 2012). The quantity and quality of these wastes generated each year is sufficient for sustainable energy generation in any country and so feedstock material for energy production vary depending on the type available in a given country. These residues are heterogeneous in nature with variation in bulk density, moisture content, particle size and distribution depending on the mode of handling. There are different sources of biomass residues. They are classified as wood and wood processing residues, perennial plantation residues, agricultural residue, animal waste and municipal solid waste (Sugathapala and Chandak, 2013).

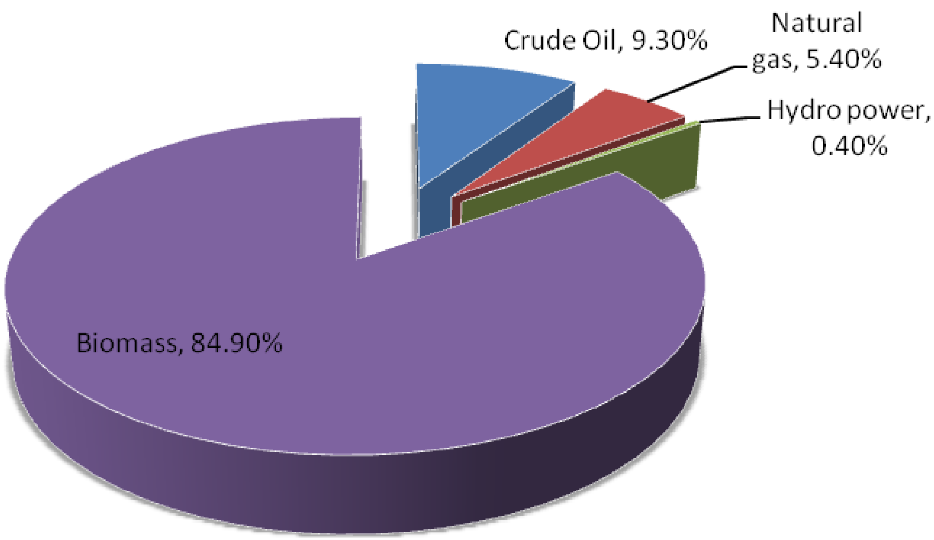

Fig.2.1.Domestic energy consumption in Nigeria in 2006
Source: IEA (2012)

Wood and wood processing residues

Wood is the main source of energy for household and industries. It is estimated that about 55% of global wood harvest is burnt as fuel and the remaining 45% is used as industrial raw material (Parikka, 2004). A considerable amount of the part used as industrial material also ends up as primary or secondary process residues suitable for energy production. Wood residues include stem, branches, etc. and wood processing residues include saw dust, charcoal, etc.

Perennial plantation residues

Perennial plants such as coconut tree, rubber tree, oil palm tree, cocoa tree etc. generate considerable amount of wood residues from pruning and replanting activities. For example, coconut trees generate residues in the form of wood, fronds, husk and shells and it is estimated that at a productivity of 720 nuts/ha/yr., the residue generated from fronts, husk and shell alone amounts to 5 ton/ha/yr. (AbdulSalam *et al.*, 2005). In the case of oil palms, tree trunks and fronds become available during replanting generating about 80 ton/ha on 25 yr cycle and during processing, 6 ton/ha of fiber, shell and empty bunches (Sugathapala and Chandak, 2013).

Agricultural residue

Agricultural residue refers to all organic material that are produced as the by-product from agricultural activities. They constitute the major part of the total annual production of biomass residue and are very important source of energy (Sugathapala and Chandak, 2013). In the developing countries, large amount of agricultural residues are wasted through open dumping or burning in the field and hence, they are sometimes referred to as "waste". Agricultural residues are generated either at the time of harvest or produces along with the finished product during processing. Residues produced during agricultural activities include rice straw and husk, sugar cane top, bagasse, cocoa pod, maize cob/husk, etc.

Animal waste

Livestock represent an important industry in many countries and as such there are a lot of wastes generated from these animals which the farmers dispose of either by direct use as fertilizers or in some instance by land filling. Such animal waste like poultry droppings, cow dung, etc. is commonly available in commercial farming system. Most time the major challenges faced by the owners of these farms are the waste disposal system to adopt. Modern technology decompose-these animal wastes in an anaerobic environment to generate methane gas which is a superior gaseous fuel produced in biogas digesters.

Municipal solid waste

There are organic wastes that are generated by sectors such as residential, industrial, and commercial and institutions. Economic development and urbanization have led to increase in the quantity and complex composition of municipal solid waste (MSW) in cities of developing countries leading to serious concerns over the proper waste management in the local communities (UNEP, 2013). The organic wastes generated include; food and vegetable at market places, papers etc.

2.3.1 Characteristics of biomass wastes

Biomass comprises of cellulose, hemicellulose, lignin, lipid, protein, simple sugar, starches, water, hydro carbons (HCs), ash and other compounds. Their composition varies depending on the species, type of plant tissue etc. To characterize a given biomass material, properties such as particle size and shape, elemental composition (ultimate analysis), moisture content, proximate analysis, heating value, bulk density, specific gravity, thermal conductivity etc. are conducted. The proximate analysis evaluate solid biomass material according to their moisture content, volatile matter, fixed carbon and ash content while the ultimate analysis shows the composition of the material based on the ash and chemical elements such as carbon, hydrogen, nitrogen, sulfur and oxygen.

According to UNEP (2013), carbon, hydrogen and sulphur contained in a given biomass material contribute positively toward the heating value while oxygen and nitrogen lowers these properties. In agricultural biomass, these properties vary according to their species, stage of growth, growing condition etc.

2.3.2 Agricultural residue generation in Nigeria

Report on the increase in agricultural production (Fig. 2.2) and increase in the amount of major crops grown yearly (Table 2.1) in Nigeria indicate certainly that there is increase in the amount of agricultural residues produced annually but estimation of the amount of residues generated during agricultural activities is usually hampered by lack of data on crop production.

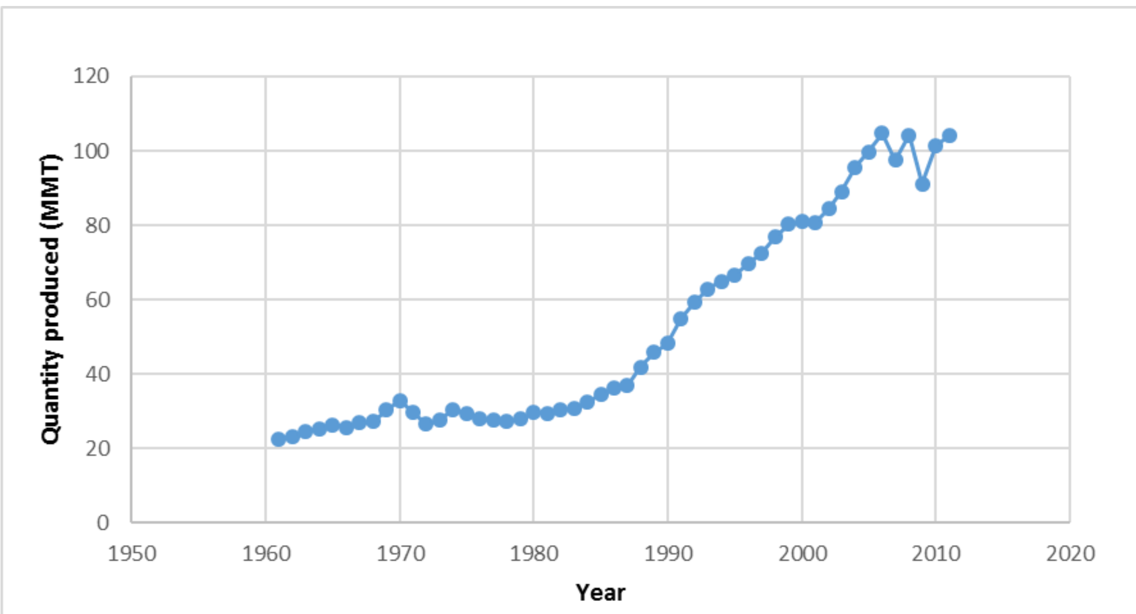

Fig 2.2 Agricultural production in Nigeria
Source: CBN (2013)

Hence, a variety of methodological approaches has been used to estimate crop residue production on national, regional or global scale (Bentsen *et al.*, 2013).

Most studies apply specific constant multipliers to crop production statistics in other to calculate the residue generation (Smeet *et al.*, 2007). This means that residue generation is assumed to be proportional to the total production of crop in a given region. The calculation theory by Bentsen *et al.* (2013) gives the residue production (RP) (kg/yr.) for each given crop as shown in eqn. 2.1.

$$RP = A \times RY \qquad 2.1$$

Where;

A= harvested area (ha) &RY= crop residue yield (kg/ha.yr)

Crop residue yield is calculated from the residue to product ratio (RPR) and the values are given for some crops in Table 2.1.Research has shown that RPR is not constant but depends on yield (Y) (kg/ha.yr) which has an exponential relationship with RPR (Scarlat *et al.*, 2010). The equation is given in eqn. 2.2.

$$RPR = ae^{b \times Y} \qquad 2.2$$

Residue yield (RY) (kg/ha.yr) for a given crop is calculated from the yield as given in eqn. 2.3.

$$RY = Y \times e^{bY} \qquad 2.3$$

Where;

Y = Yield (kg/ha.yr) &a and b = constants

From eqn. 2.3, it indicates that for constant a>0 and b<0, increase in Y will result in decrease in RY and after a certain point, eqn. 2.3 converges asymptotically toward zero. This is not what is obtainable in actual crop production. Therefore, RPR is estimated using harvest indices (HI) for each crop as given in eqn. 2.4 (Bentsen, 2013).

$$RPR = \frac{1-HI}{HI} \qquad 2.4$$

Using eqn. 2.4, the annual quantities of residues generated from crops in Nigeria (Fig. 2.3, 2.4 and 2.5) were estimated. Quantity of residue generated between 2004 and 2006 show there is increase in residue generated in Nigeria and this confirms that there is increase in agricultural production (Fig. 2.2). Crops with highest residue yield include maize, cassava, groundnut and millet.

Table 2.1: Residue to Product Ratio of Waste Agricultural Biomass Materials

Crop	**RPR value**
Wheat Residue	0.9-1.6
Cotton hulls	0.26
Cotton stalks	3.0-5.5
Rice Straw	0.8-2.5
Rice husks	0.17-0.22
Groundnut shells	0.25-0.55
Coffee residues	0.3-1.8
Barley residue	1.4-2.0
Coconut shells	1.9
Millet/Sorghum stalks	1.5-3.7
Palm empty fiber bunch	0.39
Maize Stalks	0.9-4.0
Sugarcane bagasse	0.05-0.2
Sugarcane barbojo	0.09-0.28
Palm fibers	0.2-1.1
Palm shells	0.2-1.0

Source: Yevich and Logan (2013)

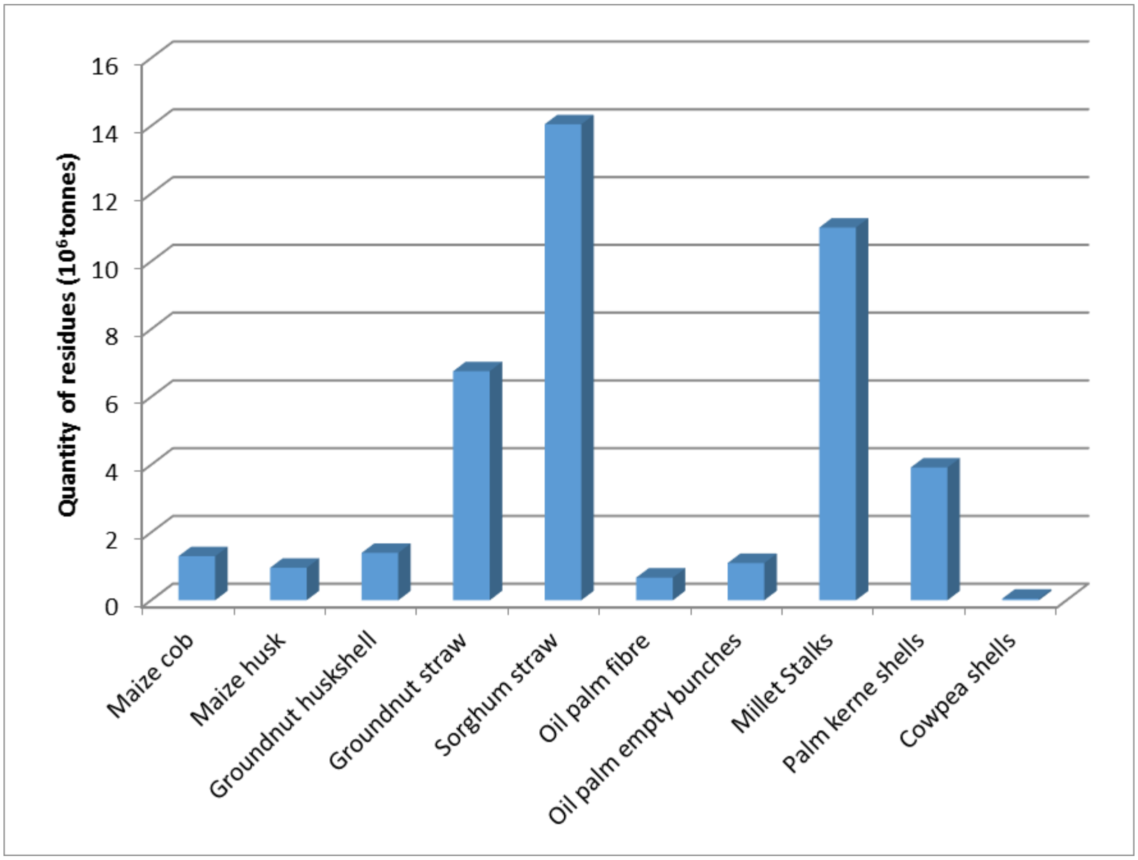

Fig 2.3 Feedstock residues produced in 2004
Source: NASS (2012)

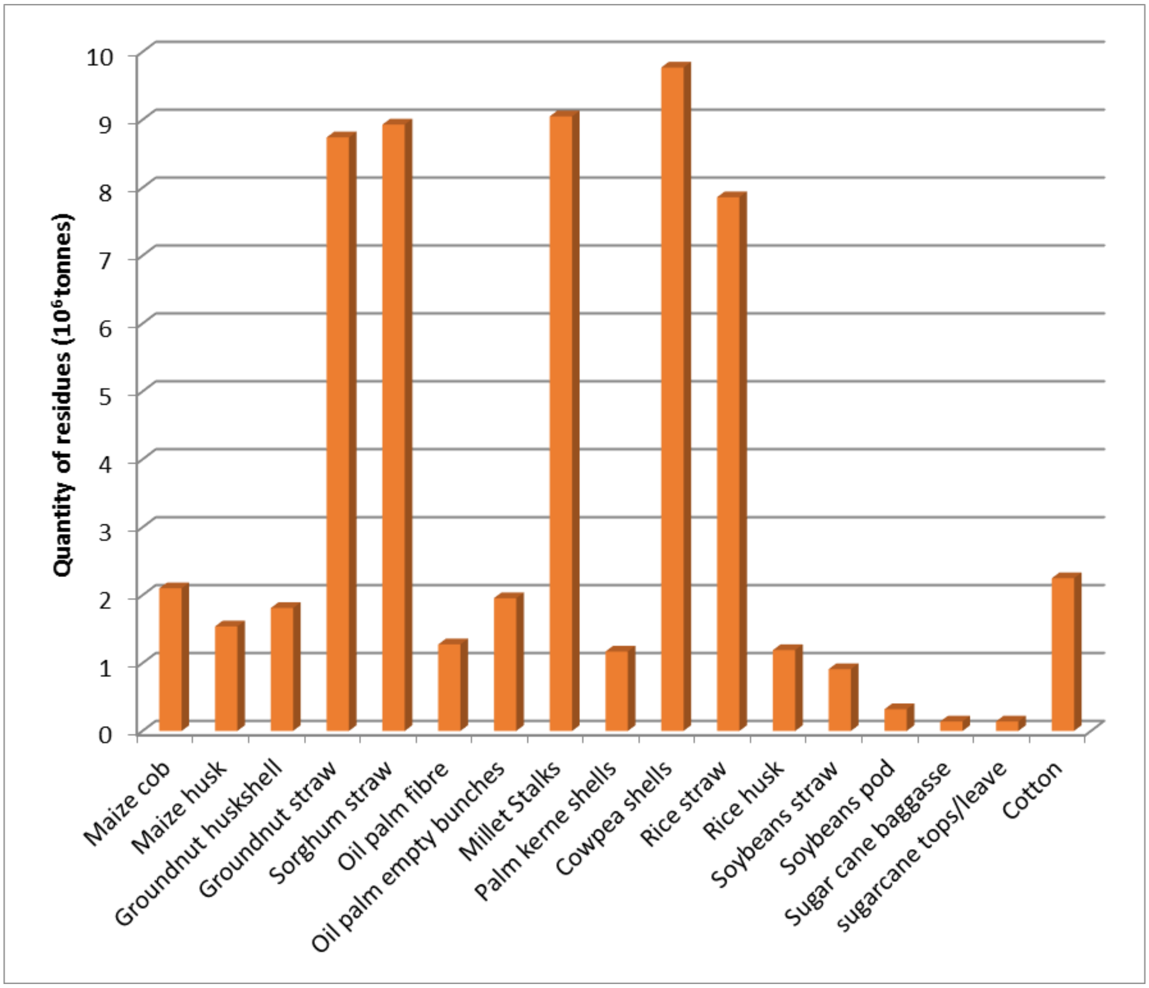

Fig 2.4:Feedstock residues produced in 2006
Source: NASS (2012)

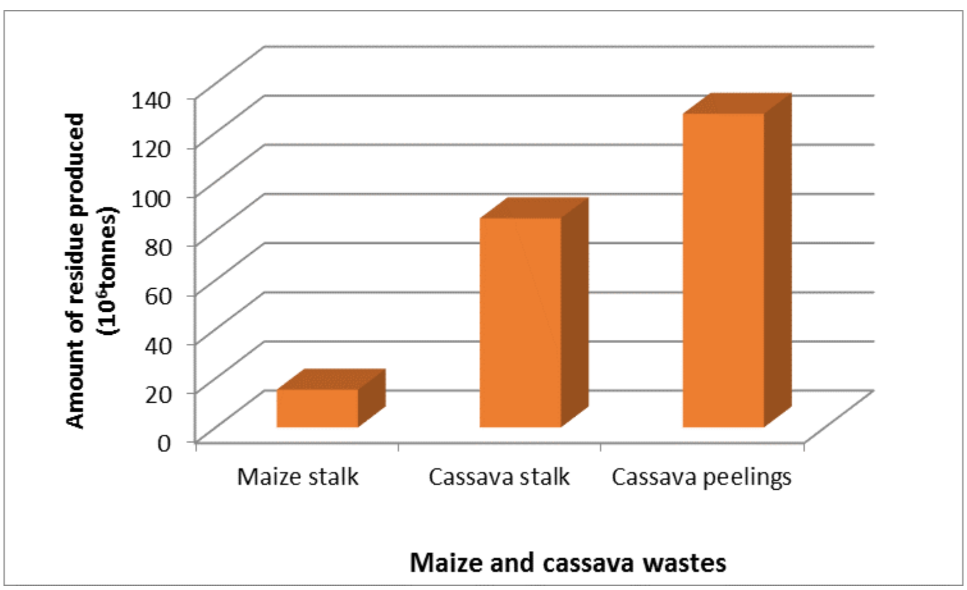

Fig 2.5:Maize and cassava residues produced in 2006
Source: NASS (2012)

2.3.3 Management of biomass waste in Nigeria

Burning or dumping in open places is the easiest and least expesive way mainly used to reduce or eliminate biomass wastes produced during agricultural activites in Nigeria. Ratio of these disposal methods adopted in urban and rural areas of Nigeria are compared in Fig. 2.6. The two major methods used in waste management has adverse negative effect on the environment (Sabiiti *et al.*, 2004; Sanchez *et al.*, 1997). According to Ezcurra *et al.*(2001), waste burning releases pollutants such as carbon monoxide, nitrous oxide etc. These pollutants are accopanied by the formation of ozone and nitric acid (Hegg *et al.*, 1987), hence contributing to acid rain (Lacaux *et al.*, 1992) thereby posing risk to human health and the ecological system. Conversion of biomass wastes to usefull resources has the potential to supply significant amounts of energy needs in Nigeria. It can help to revitalise rural economies, increase energy independence and reduce pollution. But there are challenges faced in conversion of these wastes to useful resources. These challenges as listed by Onwualu (2010) are lack of information generation and dissemination, quantification of various wastes, technology development and adaptation, economic feasibility, commercialization of research findings, investment promotion, competitive products and lack of policy. However, this research work tends to look at the technological development aspect of these problems. For any sector to grow, there must be large influx of endogenous and exogenous technology. In Nigeria, the local technologies are low and not many Nigerian research workers are working in this area of waste generation and utilization. In addition, because technologies developed abroad are adapted and sometimes replicated, it result to local entrepreneurs not been exposed to the type of technologies required for producing value added products. Omer (2010) and Oladeji (2011) highlighted possible optimum technical and economical utilization of biomass energy and advocated for exploitation of its various technologies. Oladeji (2011) in his study on agricultural and forestry in Nigeria, suggested ways of utilizing them for economic advancement of the country. He stated that the importance of agricultural residues cannot be overemphasized and since they are readily available and offer much potential for renewable energy sources in form of biomass. He also stated that, the energy generated through biomass wastes is friendly to both human and ecology. In his study, he identified various ways agricultural and forestry wastes are convertible to biomass energy products. He highlighted the benefits to be derived from the use of agricultural and forestry residues as energy source in Nigeria. He suggested that all the techniques of conversion identified could form an agricultural complex utilizing briquettes as a renewable energy source; using anaerobic digestion (biogas) to produce energy and fertilizer; composting for soil conditioner; pyrolysis to produce medium grade fuels and chemical preservatives and production of animal fodder through the process of pelletizing. Just like a number of developed countries derive a significant amount of their energy from biomass, developing countries should develop technologies for biomass waste processing. It is reported that countries such as Sweden, Finland, USA, Austria utilizes their biomass waste to generate 16%, 18%, 4%, and 13% respectively of their total energy output (Hall, 1997).

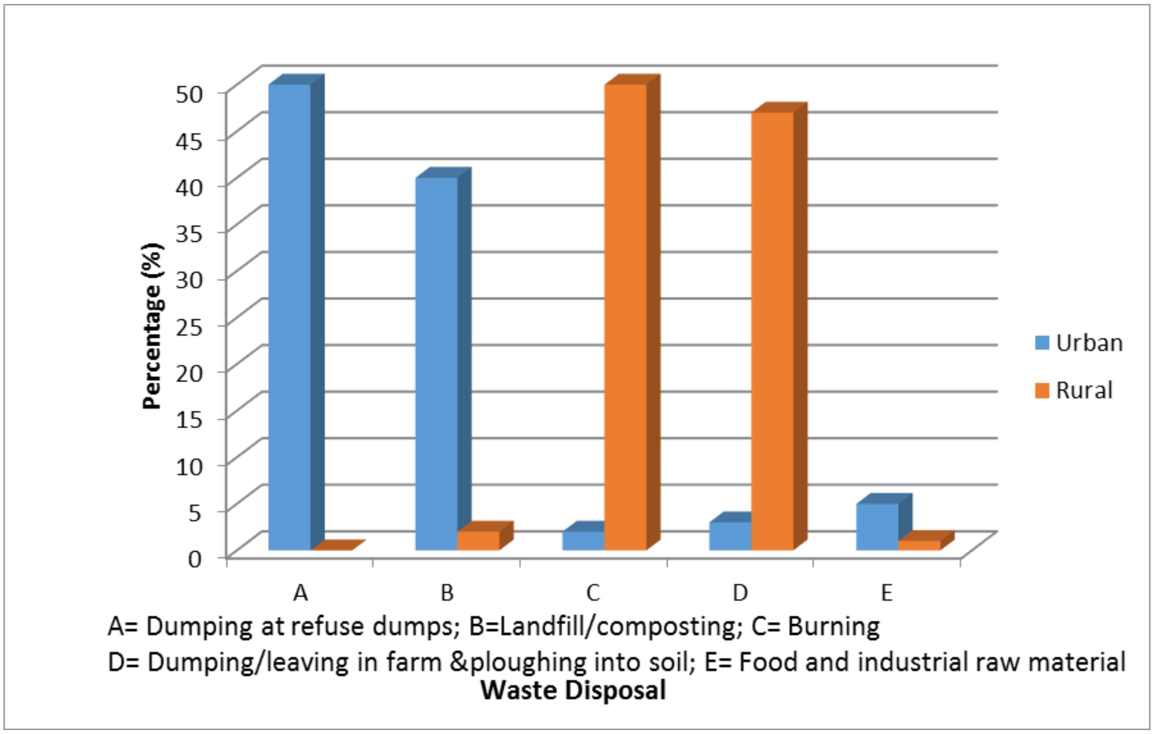

Fig. 2.6 Methods of agricultural residues disposal in Nigeria (%)
Source: Onwualu (2010)

2.3.4 Production of briquettes from biomass wastes

One of the main problems associated with the utilization of biomass waste is its low density which gives rise to high transport and storage costs and this limits utilization of the biomass wastes. Briquetting means densification of loose biomass or other materials and it involves the process of reducing the bulk volume of the feedstock material by mechanical means for easy handling, transportation and storage. It has been used as a way to minimize such problem of low density thus improving possibilities for its commercialization. Through various densification technologies, raw biomass is compressed to densities in the order of 7–10 times its original bulk density. Also due to the higher homogeneity of the biomass waste briquettes, it has been found that the briquettes are more suitable in energy value when compared to the original raw material (Ortiz *et al.*, 2006; UNEP, 2013).In addition to the above benefits, biomass densification can also aid in the following advantages if appropriately processed;

a. It reduce cost and improve ease of storage of biomaterials
b. It improve transportation efficiency
c. It decrease losses of biomass through the prevention of product deterioration,
d. It also increase ease of handling if utilized as a biomass pellet fuel,
e. It increase potential combustion efficiency
f. It offers the ability to standardize feeding mechanisms for gasifier and other biomass based systems.

2.4 Machines for Briquette Densification

According to FAO (1990), briquetting are categorized into five main types namely; piston presses, screw presses, roller press, pelletizing, manual presses and low pressure briquetting. Piston press and screw press are the most commonly used machines for producing briquettes.

Screw press

In a screw press or screw extruder, the rotating screw takes the material from the feed port, through the barrel, and compacts it against a die which assists the build-up of a pressure gradient along the screw (Fig. 2.7). The extruder features three distinct zones: feed, transport, and extrusion zones. The important forces that influence the compaction of the feed material play their role mostly in the compression zone near to the extrusion die. The frictional forces between feed material and barrel/screw, the internal friction in the material and external heating device (of the extrusion zone) cause an increase in temperature (up to 300°C), which softens the feed material. Lignin from the biomass is set free and acts as gliding and binding agent. The speed of densification, the energy consumption of the press and the quality of the briquettes produced depend on: flowability and cohesion of the feed material, particle size and distribution, surface forces and adhesiveness. Screw presses produce high quality briquettes with a homogenous structure and good combustibility, and they require only little maintenance. The main disadvantage is that the wear of the screw leads to elevated spare part costs.

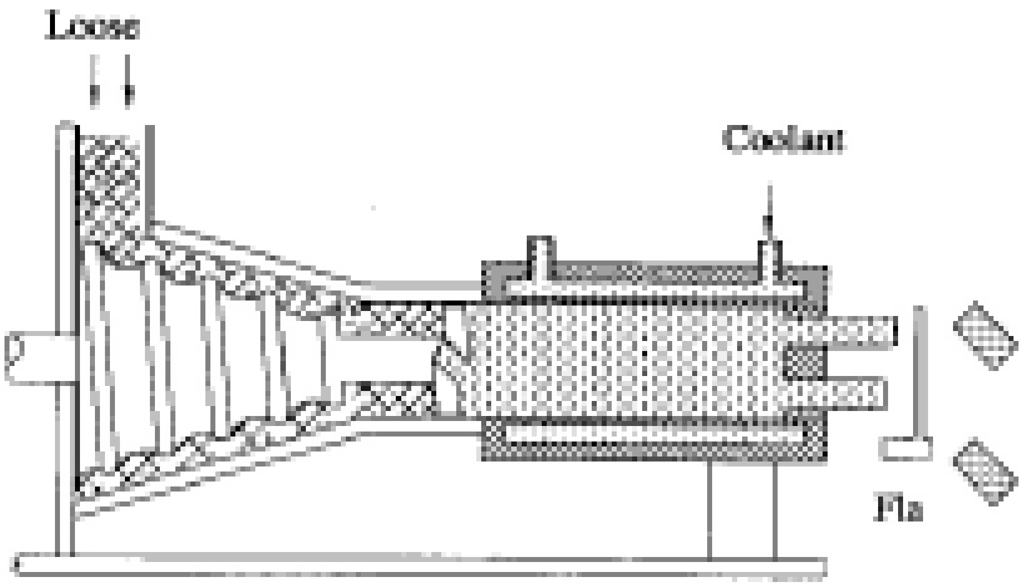

Fig. 2.7: Schematic diagram of a conical screw press

Source: UNEP (2013)

Piston press

The piston press is one of the main high press technologies used for briquetting. The piston press acts in a discontinuous mode with material being feed into a cylinder which is compresses by a piston into a slightly tapering die (Grover and Mishra, 1996). The compressed material is heated by frictional force as it is pushed through the die. The lignin contained in all woody cellulose materials begins to flow and act as a natural glue to bind the compressed material. When the material emerges from the die, the lignin solidifies and holds it together forming cylindrical briquettes. Basically, there are two types of piston press. They are the mechanical (Fig. 2.8), or hydraulically piston press.

In hydraulic piston press, the force generation, transmission and amplification are achieved using fluid under pressure (Parmar *et al.*, 2014). The liquid system exhibits the characteristics of a solid in the sense that it provides a very positive and rigid medium of power transmission and amplification (Sharma, 2005).

Mechanical press machines are usually larger than hydraulic press machines. They produce high and dense briquettes from most materials. They are driven by electric motor geared down through a belt coupling. Internal combustion engine or steam engine can also be used for the direct drive system of mechanical press machine.

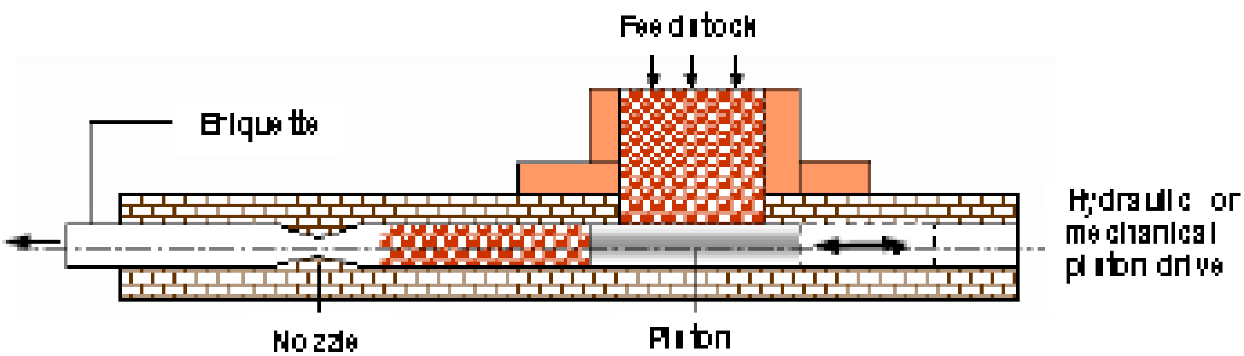

Fig 2.8:Schematic diagram of piston press
Source: UNEP (2013)

Hydraulic press machine was selected for this research work because of the advantages it has over other briquetting machines (Mahajan and Tuljapure, 2016). These benefits include;

1. Full power stroke
2. Built-in overload protection
3. Much lower original cost and operating costs
4. Larger capacities at lower cost
5. More control flexibility
6. Greater versatility
7. Quiet operation
8. More compact
9. Safety

2.4.1 Theoretical framework on development of briquetting machine

Design of hydraulic piston press briquetting machine requires a good sense of the working principle of a hydraulic system. The basic working principle of a hydraulic system is that power is transferred by feeding hydraulic fluid from a closed vessel with variable displacement to another closed vessel. It works on the principle of Pascal's law which states that the pressure in an enclosed fluid is uniform in all the directions. The main advantages of hydraulic piston press over other types of presses is that it provide a more positive response to changes in input pressure. The force and pressure can accurately be controlled and the entire magnitude of the force available during working stroke of the ram travel (Sumaila and Ibhadobe, 2011). To design a hydraulic press for briquette production, the push force developed in the system and the corresponding density of the compressed biomass waste is of great importance to the developer. These push force (F_2) and pull force (F_1) as shown in Fig. 2.9 are calculated using eqn. 2.5 and 2.6 respectively as used by (Gatmaitan*et al.*, 2012). The pressure generated in the hydraulic system is function of the hydraulic components like the pump, motor etc.

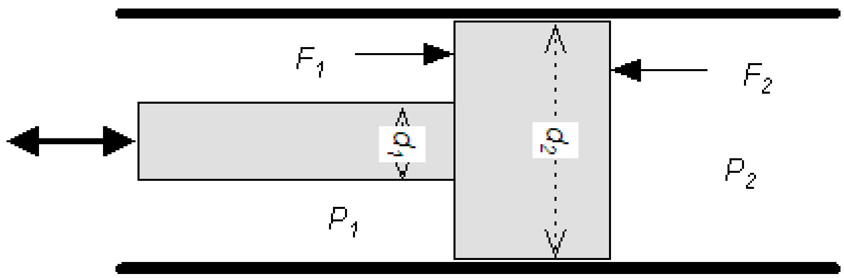

Fig. 2.9: Action of force inside hydraulic cylinder

Source: www.engineering toolbox.com

$$F_2 = P_2 x \left(\frac{\pi d_2^2}{4}\right) \qquad 2.5$$

$$F_1 = P_1 x \frac{\pi(d_2^2 - d_1^2)}{4} \qquad 2.6$$

Where:

P_2 = pressure that causes the compression

P_1 = pressure for extraction of rod

d_2 = diameter of the cylinder

d_1 = diameter of the rod

Volume of oil necessary for the piston stroke (V) is calculated from the effective piston area and the required piston stroke as given in eqn. (2.7) while the pump flow rate (Q) is calculated using eqn. (2.8) (Industrial Hydraulic Services Inc., 2007).

$$V = L \times \left(\frac{\pi d_2^2}{4}\right) \qquad 2.7$$

$$Q = \frac{V}{t_H} \qquad 2.8$$

Where:

V = volume of oil (m^3)

L = stroke length (m)

Q = pump flow rate (m^3/sec)

t_H = stroke time (sec)

Piston speed (v) is the distance travelled by the piston rod at a given stroke time. This is calculated using eqn. 2.9.

$$v = \frac{L}{t_H} \qquad 2.9$$

The specific energy requirement for biomass densification depends on the system used and process variables. Most densification processes involve both compression and pushing work and the energy required for pushing work is often greater than that for compression. The work done during densification is given for both processes in eqn. 2.10 and 2.11 (Tumuluru*et al.*, 2010a).

$$w = A\int_0^X P\,dx \qquad 2.10$$

w = work done on the system (J)

P= applied force (bar)

x= briquette thickness (m)

A= cross sectional area of the die and piston (m^2)

In the compression apparatus, the density at each point is calculated as

$$Density = \frac{m}{xA} \quad 2.11$$

Where;

m= sample mass

During densification using compression technologies, about 37- 40 % of the input energy is used to compress the material while the rest of the energy is used to overcome friction during compression (Tumuluru *et al.*, 2010a). Energies required for densification are temperature dependent such that at a higher temperature, lower amount of energy is required.

2.4.2 Evaluating performance of hydraulic press briquetting machine

To evaluate performance of a hydraulic press briquetting machine as previously discussed, machine design variables and biomass waste variables play key roles.

Firstly, performance of a hydraulic press depends largely on the behavior of its structure during briquetting (Parthiban *et al.*, 2014). This structural analysis involve analyzing the structural components of the machine in order to predict its responses and behaviors by using physical laws and mathematical equations and the main objective of analysis is to determine internal forces, stresses and deformations of structures under various load effects (Bapat and Desai, 2009). To evaluate structural analysis of hydraulic press machine, the frame is the major component and structural design of frame is dependent on the pressing force which determines machine rigidity, dimension of dies and influences dimension of the machine. By optimizing the frame structure, the design variables that can be used to develop better optimized reduced weight, and cost effective components that meet the intended design, functionality and reliability are obtained. Another machine variable that affect performance of briquetting machine is pressure (Tumuluru *et al.,* 2010a; Sengar *et al.*, 2012; Madhava, 2012). This is usually dependent on the design calculations on hydraulic oil, motor and pump selection. However, the pipe head and diameter also play an important role in defining the pressure developed in the system.

Secondly, when hydraulic press are used in biomass waste briquette production, composition of the biomass waste, its particle size, moisture content also contribute to the determine the briquette bulk density thus performance of the briquetting machine. However, most research works on briquetting technology has focused more on optimization of the biomass variables in isolation to an optimized briquetting machine.

These two factors defines the productivity and longevity of the machine which can be evaluated by compacting pressure at cylinder inlet port, output capacity of the machine, machine efficiency, bulk density of the briquettes and compression ratio.

Compacting pressure at cylinder inlet port

This determines the amount of force that pushes the piston head through the stroke to compact the materials. It is affected by the system characteristics such as discharge capacity of the pump, fluid characteristics, and pipe configurations.

Output capacity

This estimates the quantity of briquette produced within a given period of time. Output capacity is a function of machine and biomass waste variables.

Machine efficiency

This estimates the amount of unbroken briquettes produced during the compaction process when compared with the total number of briquette produced in the operation.

Bulk density of the briquettes

Bulk density is used to estimate the effect of compression process on the biomass waste. Bulk density is a serious determining factor in briquetting since it influences durability, compressive strength, burning rate of the briquettes (Huang, 2015).

Compression ratio

Compression compares the bulk densities of the produced briquettes after and before briquetting.

2.4.3 Mathematical modeling using dimensional analysis

Mathematical model is all about mathematical representation of the construction and performance of physical systems which measure variables and parameters and the relationship that exist between them in other to identify the contribution of each of variables in the mathematical equation. These equations are also used to predict effect of changes on that given system. Mathematical modeling of hydraulic briquetting machine will help in description of the machine and also ensures that all necessary parameters are incorporated in the analysis. It will also ensures that much effort is not wasted in design and testing as it will only permit that parameters sensitive studies on machine are studied.

Development of mathematical models incorporates two ideas namely; the measurement of variables and parameters and the relationship between them. Behavior of the models should be similar to but simpler than the machine. Ideally, a model should be close approximation to the real system and should incorporate most of its salient features necessary for the description of the system (Lawson and Marion, 2008). Selection of a given model method depends on the objective of the designer which are either develop by scientific understanding through quantitative expression of the knowledge of the system or test effect of change on a given system. Sometime, the intention might also be to make decision on strategic issues or understand the working principles and scientific laws governing the system performances. In a situation where improvement in the efficiency and overall engineering performance is desired, models have been used in analyzing the system even before construction which in the real world. There are computer software which have been developed to aid designers in system modeling and optimization.

Modeling method to be adopted in a design is based on the type of outcome to be predicted. Lawson and Marion (2008) distinguished models as deterministic and stochastic. Deterministic models are models that ignore random variation, and so always predict the same outcome from a given starting point but stochastic models are statistical in nature and may predict the distribution of possible outcomes. Deterministic or stochastic model can be empirical or mechanistic depending on the level of understanding on which the model is based. A model which uses a large amount of theoretical information and generally describes what happens at one level in the hierarchy by considering processes at lower levels are called mechanistic models. They take account of the mechanisms through which changes occur. In empirical models, no account is taken of the mechanism by which changes to the system occur. Instead, it is merely noted that changes do occur, and the model tries to account quantitatively for changes associated with different conditions.

2.5 Dimensional analysis and Buckingham pi theorem:

The premise of dimensional analysis is that the form of any physically significant equation must be dimensionally homogenous such that the relationship between the actual physical quantities remains valid irrespective of the magnitudes of the base units. Buckingham's pi theorem derives its name from Buckingham's use of the symbol"π"for the dimensionless variables in his original paper in 1914 (Sonin, 2001). The π-theorem tells us that, because all complete physical equations must be dimensionally homogeneous, a restatement of any such equation in an appropriate dimensionless form will reduce the number of independent quantities in the problem by *k.* Dimensionless analysis (Buckingham's pi theorem) has been used in development of mathematical models for prediction of performance of machines and can be used in predicting the performance of hydraulic briquetting machine for biomass wastes.

2.5.1 Design Assumptions of Buckingham’s pi theorem

The Buckingham’s pi theorem essentially have the following assumptions;

1. Every dependent variable (y) is to be determined in terms of “n” measurable independent variables ($x_{1,}\, x_2,\ldots,x_n$).

   where, $y=f(x_{1,}\, x_2,\ldots,x_n)$

2. The quantities ($y,\ x_{1,}\ x_2,\ldots,x_n$) involve “m” fundamentally dimensions labelled by

   $L_1,\ L_2,\ldots,L_m$. For example in a mechanical problem these are usually the mechanical fundamental dimensions, L_1= mass, L_2 = length and L_3 = time.

3. Let “Z” represent any of ($y,\ x_{1,}\, x_2,\ldots,x_n$). Then the dimension vector of “Z “, denoted by [Z], is a product of powers of the fundamental dimensions, in particular

   $[Z] = L^{\alpha1}L^{\alpha2}L^{\alpha3}$

   for some real numbers, usually rational, ($\alpha1,\ \alpha2,\ldots,\alpha_m$)which are the dimension exponents of “Z”. The dimension vector of Z is the column vector

   $$\propto = \begin{bmatrix} \propto_1 \\ \propto_2 \\ \vdots \\ \propto_m \end{bmatrix}$$

   A quantity Z is said to be dimensionless if and only if [Z] =1, i.e all dimension exponents are zero.

2.5.2 Steps of dimensional analysis and Buckingham's pi theorem:

Step 1: Identification of the dependent parameters and independent variables

The first step requires identification of the dependent parameters (Q_o) which are the parameters that are used to evaluate the performance of briquetting machines. They are termed dependent because once all the quantities that defines the parameters are specified, the value of the dependent parameters are determined uniquely. Also, complete set of independent variables ($Q_1 ... Q_n$) that determine the values of each dependent parameter are identified. A set of independent variables are complete if once the values of the members are specified, no other quantity can affect the value of Q_o. They are independent such that if the value of each member can be adjusted arbitrarily without affecting the value of any other member as stated in eqn. 2.13. Starting with a correct set, $Q_1 ... Q_n$ is as important in dimensional analysis as it is in mathematical physics to start with the correct fundamental equations and boundary conditions. The relationship expressed symbolically in equation (2.12) is the result of the physical laws that govern the phenomenon of hydraulic briquetting machine. It is the premise that its form must be such that, once the values $Q_1 ... Q_n$ are specified, the equality holds regardless of the sizes of the base units in terms of which the quantities are measured.

$$Q_0 = f(Q_1, Q_2, \dots, Q_n) \qquad 2.12$$

Step 2: Dimensional considerations

The second step involve to list the dimensions of the dependent parameter Q_o and the independent variables $Q_1...Q_n$. From the complete set of physically independent variables $Q_1...Q_n$, a complete dimensionally independent subset $Q_1...Q_k$ ($k \leq n$) are selected and the dimension of each of the remaining independent variables Q_{k+1} ...Q_n and the dependent variable Q_o are expressed as a product of powers of $Q_1...Q_k$. As discussed earlier, the dimension of a quantity depends on the type of system of units been used. Since hydraulic briquetting machine is a purely mechanical problem that involve mass (M), length (L) and time (T), all quantities have dimensions of the form given in eqn. 2.13.

$$[Q_i] = M^m L^l T^t \qquad 2.13$$

Where the exponents *m*, *l* and *t* are dimensionless numbers that follow from each quantity's definition.

Having chosen a complete, dimensionally independent unit [M, L, T], express the dimensions of Q_0 and all the independent variables $Q_1...Q_n$ in terms of the dimensions of [M, L, T]. These will have the form shown in eqn. 2.14.

$$[Q_o] = \left[Q_1^{N_{i1}} \, Q_2^{N_{i2}} \, ... Q_n^{N_{ij}}\right] \qquad 2.14$$

The exponents N_{ij} are dimensionless real numbers and can in most cases be found quickly by inspection or a formal algebraic method.

Equating the dimension given by eqn. (2.13) with that of eqn. (2.14), three equations are obtained.

$$M_i = \sum_{i=1}^{j} N_{ij} \, m_j$$

$$l_i = \sum_{i=2}^{j} N_{ij}\, l_j$$

$$t_i = \sum_{i=3}^{j} N_{ij}\, t_j$$

Step 3: Dimensionless variables

The third step is to define the dimensionless forms of the n-k remaining independent variables by dividing each one with the product powers of $Q_{1\ldots}$ Q_k which has the same dimension (eqn. 2.15).

$$\pi_i = \frac{Q_{k+1}}{Q_1^{N(k+1)i} Q_2^{N(k+2)i} \ldots Q_n^{N(k+1)k}} \qquad 2.15$$

where I =1, 2,…,n-k

The dimensionless form of the dependent parameter Q_o is obtained as shown in eqn. 2.16.

$$\pi_o = f(\pi_1, \pi_2, \ldots, \pi_{n-k}) \qquad 2.16$$

Thus,

$$\pi_o = \frac{Q_o}{Q_1^{N_{o1}} Q_2^{N_{o2}} \ldots Q_n^{N_{ok}}}$$

For any set of foundation dimensions one can choose a system of unit for measuring the value of any quantity Z. A change from one system of units to another involves a positive scaling of each fundamental dimension which in turn induces a scaling of each quantity Z.

2.5.3 Limitations of Buckingham's pi theorem:

The π-theorem merely tells the number of dimensionless quantities that affect the value of a particular dimensionless dependent parameter but it does not tell the forms of the dimensionless variables. Secondly, it does not say anything about the form of the functional relationship expressed by eqn. 2.16. The form has to be discovered by experimentation or by solving the problem theoretically.

2.6 Computer Aided Engineering (CAE) tool

Finite element analysis commonly referred to as FEA is a computerized method for predicting how a machine would react to real life forces, vibration, heat, fluid flow and other physical effects. It breaks down a real object into a large number (thousands to hundreds of thousands) of finite elements, such as little cubes and then uses mathematical equations to predict the behavior of each element. The software then adds up all the individual behaviors to predict the behavior of the actual object. This tool is adopted in the design of the hydraulic briquetting machine.

At first in FEA, the virtual model that is created from CAD forms and is the starting point of the analysis. During the analysis, the model is divided into many small domains. This process of division is called meshing and the domains resulted from the division are called elements. Every element shares common points and these points are called nodes. The reason for such divisions is to solve the complex engineering problem, portrayed in the virtual model, through solving multiple simpler engineering problems. These simpler problems are solved simultaneously and solutions obtained are assembled to approximate the solution to the complex engineering problem.

In FEA, simple shaped elements such as beam element, triangular element, quadrilateral element, tetrahedral element and brick element are utilized. Because of these simple shapes, the response of the element is well known under the load cases, by bringing together responses of these elements under the load cases of the complex model and therefore the response of the model is obtained. This is how the solution of the complex engineering problem is obtained through the solution of simpler engineering problems.

The response of the element under those load cases is actually interpolated from the response of the element's nodes which are also subjected to the same load cases. Every node is fully described by a number of parameters depending on the type of the analysis and the type of the element used.

2.7 Review of Related Research Works

Some of the related works that have been previously done by some researchers are reviewed below. The review was conducted in such a way that it covered various areas related to this intended study. They include; review on briquetting machines, review of hydraulic press machines, review on briquettes produced from biomass waste and review on mathematical modelling of biomass briquetting.

2.7.1 Review on briquetting machines

Jithesh (2016) redesigned a saw dust briquetting machine in plywood industry". He found out that Plywood, produced sawdust briquettes in western India have suboptimal densities, causing incomplete burn and excessive smoke. Therefore, he came up with the redesign of Saw Dust Briquetting Machine in Plywood Industry in order to improve the existing Technology by adjusting the screw length to diameter ratio, the screw rotation speed, feed pressure, and residence time in the extension chamber as a means of producing a higher density, better quality briquette.

Mambo *et al.* (2016) identified that imported briquetting machines are expensive, need technical expertise, lack spare parts, and require electricity for operation. In view of that, they developed a manually operated hydraulic briquette press, evaluated its performance and assessed the physical properties of the briquettes produced. The mold comprised of 100 cylinders having dimensions of 59 mm diameter, and 150 mm height. A hydraulic jack of 50 Tons capacity was used to exert the compressive force required by the pistons to compact biomass into briquettes. For sample preparation, Maize cobs were carbonized as raw material and this was also used for the purpose of machine testing. Char particles of less than 6 mm and 10% cassava binder ratio was used. The average value of production capacity was 122.928 kg/hr, machine efficiency was 100%, compressed density was 624.236 kg/m3, relaxed density was 350.093 kg/m3, relaxation ratio was 1.783, moisture content was 13.562%, and shatter index was

98.1464%. The results obtained showed the machine had higher production capacity and all briquettes were free of damage after ejection.

Sani (2008) recognized the decreasing availability of fuel wood, and the ever rising prices of kerosene and cooking gas in Nigeria and suggested alternative sources of energy for domestic and cottage level industrial use in the country. He designed and constructed a low cost briquette machine through modification of the existing CINVA RAM press and evaluated of the products produced. He prepared samples for briquette production using rice straw and rice husk, saw dust residue of softwood and a combination of 50% rice husk + 50% saw dust by weight with 30% optimum cassava starch by weight as binder. Performance characteristics of the briquette produced were evaluated based on average fuel efficiency, burning rate and specific fuel consumption. The results gotten were analyzed using least square differences in comparison to each of the fuel samples and the average performances showed that rice husk briquette had the most outstanding thermal performance.

Briquetting of carbonized agricultural residues as a possible solutions to the local energy shortages in many developing countries and constitutes a positive solution to the problem of increasing rates of desertification in many areas worldwide (Sanap et al., 2016). The production cost was found to be lower due to the lower binder requirement for the new machine, which is lower by about 65%. The initial moisture content of the feed stock required for this machine is lower by about 30 % compared to the best alternative, which results in shorter drying time for the fuel briquettes produced. The quality of the produced briquettes was found to be better and of lower smoke generation when burned due to the lower binder content.

Tumuluru *et al.* (2015) worked on impact of process conditions on the density and durability of Wheat, Oat, Canola, and Barley Straw Briquettes". Their study employed the use of analysis of Variance (ANOVA) for its analysis. The results indicated that briquette moisture content and initial density immediately after compaction and final density after two weeks of storage are strong functions of feedstock moisture content and compression pressure, whereas durability rating is influenced by die temperature and feedstock moisture content.

Sharma *et al.* (2014) improved the design of the manual small press machine. The work carried out in an attempt to improve the accuracy and efficiency of the press according to the requirement. They improved the design of the machine by designing the balls of cast iron that provides appropriate pressure to stop fluctuation in size of components. The specific dimensions of the press machine is as Improvement in design of the manual small press machine for sheet metal job under 900mm^2 area by 1mm thickness in stainless steel grade 304.

Davies and Mohammed (2013) carried out a work on the effect of processing variables on compaction and relaxation ratio of water hyacinth briquettes". They identified that Fuel wood collection has grave consequences on environment resulting in greenhouse gas emissions (GHG), forest conservation and sustainable forest resources management. They asserted that the selection of water hyacinth as alternative source of energy is an important way of managing the weed problem and contributing to environment management. The water hyacinth and plantain peels were milled into three particle sizes 0.5, 1.6 and 4.0mm, five binder levels 10, 20, 30, 40, 50% and four pressure levels 3, 5, 7 and 9MPa were considered. Manually operated hydraulic press was used for the production of briquettes. Their experimental design was 5 x 3 x 4 Randomized Complete Block Design. Their study utilized ASABE standard methods in determining the moisture contents, compaction ratio and relaxation ratio of the briquettes. The minimum compaction ratio was obtained at pressure P1 (5.19±0.27) and the maximum at pressure P4 (6.80±0.36). The effect of binder on the compaction ratio ranged from 5.87±0.31 (B3) to 6.04±0.25 (B4) for all the five binder proportions utilized. Their ANOVA results revealed that there was significant difference among all the values obtained for compaction ratio at the various binder levels ($P<0.001$). The values of compaction ratio obtained indicated more void in the compressed materials. This signifies more volume displacement which is good for packaging, storage and transportation and above all, an indication of good quality briquettes.

Osarenmwinda, and Ihenyen (2012) worked on the preliminary design and fabrication of a manually operated briquetting machine. The work remarked that the direct burning of loose agro waste residues like rice husk, palm kernel shells, and groundnut shells in a conventional manner is associated with very low thermal efficiency, loss of fuel and widespread air pollution. But when these wastes are made into briquettes, these problems are mitigated, transportation and storage cost are reduced and energy production by improving their net calorific values per unit is enhanced. To this effect, they designed and fabricated a ten (10) tonnes capacity agro waste manual briquetting machine using locally available materials. The machine principal parts are made of frame, compaction chamber and base plate. Compaction chamber contains twenty (20) moulding dies each having transmission rod, piston and ejector. The machine can produce twenty (20) briquettes at a time of about 50mm length and 28mm diameter. The compaction pressure and force was determined to be 17.5 KN/m2 and 215.3N respectively. Their machine was proposed to be useful for small and medium scale briquette manufacturers.

Amanor, (2014) in the study design, construction and testing of a briquetting machine emphasized that though there are huge amount of agricultural waste generation in the rural areas of Ghana, yet the most dominant source of energy used significantly in the domestic sector were notably charcoal and wood fuel. He therefore developed and tested an appropriate, cost effective and easy to duplicate manually operated biomass briquetting machine suitable for use in rural communities using Jatropha curcas husk at different particle sizes of ≤2mm, ≤6mm and original particle size. The physical properties of the briquette were determined at varying biomass binder ratios of 100:15, 100:25, 100:35 and 100:45 using cassava starch as the binding agent. The physical properties of the briquette were found to be significantly affected by the binder level and the particle size using 95% confidence level. The durability range of the briquette produced by the different particle sizes are higher at finer particle sizes with particle size ≤2mm having a durability range of 81.9 to 92.3% and particle size ≤6mm and original particle size ranging from 78.03 to 92.27% and 43.54 to 60.22% respectively. His result analysis showed the best biomass-binder ratio on the basis of the briquette durability (shatter index) was attained at the 100:25 blending ratio with particle sizes ≤2mm and ≤6mm having a durability of 92.3% and 92.27% respectively, also on the basis of water resistance (weathering resistance) of the briquette, the best blend was attained at 100:25 ratio with particle size ≤6mm having a higher value of 10.7 hours. He concluded that the strength (durability) of the briquettes at the optimum biomass-binder ratios were sufficient to withstand any mechanical handling compared to 83.26% reported by Sotsnde *et al.*, (2010). The biomass briquetting machine had a production capacity of about 488kg/hr.

Krizan *et al.* (2012) carried out a research on design of briquetting machine with horizontal pressing axis. Their aim was to present the process of engineering design of briquetting machine pressing chamber. They described the lonely process of briquetting machine pressing chamber design which comes from the basic input requirements and analysis of mathematical models related with process of biomass compacting and related with pressing conditions in briquetting chamber during biomass compacting. Requirements resulting from designed experimental plan, that's mean requirements regarding research of impact of structural and technological parameters changes on final briquettes quality were also included. Finally, the design was also completed by stress analysis, and by outputs of FEM analysis of designed pressing chamber construction.

2.7.2 Optimization of hydraulic press process

As hydraulic press has been used for other manufacturing process beside briquetting, the following were the reviewed works on optimization of hydraulic press for different applications.

Saleh (1992) designed heavy duty hydraulic machine by ENERPAC without any measurement or variable hydraulic system. The investigation dealt with the theoretical and experimental model of the machine to establish the accurately optimal design analysis and further development of the present machine at minimum time and lower cost. The applicability of the existing PC based Finite Element package as a computer aided design tool was also investigated. A comparison was made between the experimental and theoretically predicted results. Both the results were found to be in good agreement with each other.

Muni and Amarnath (2011) investigated the use of topology optimization on various components of scrap baling press and 5 ton hydraulic press using ANSYS WORKBENCH software. Their report inferred that topology optimization results in a better and innovative product design.

Bapat and Dessai (2009) investigated on the design and optimization of a 30 ton Hydraulic Forming Press Machine”. They studied the analysis of the frame structure in terms of its material, geometry and stresses induced in it. In this paper the researchers focused on the causes of structural failure problem in the machine because hydraulic press continuously deals with the stress that may be compressive or tensile for that press machine always works under impact load condition. And because of impact load the hydraulic press always experienced continuous stress. The study showed that different components of the machine are subjected to different types of loading condition and were analyzed using FEM tool ANSYS. Weight optimization of press frame and upper head was done, which in turn reduced the thickness of the frame structure and material.

Parthiban *et al.* (2014) carried out study on the design and analysis of C-type hydraulic press structure and cylinder. Frame and cylinder are the main components of the hydraulic press. It was found that the structural design of the frame depended on the pressing force which was determined by the required rigidity, the dimensions of dies influencing the size of the tool area, work area accessibility that determined by the shape of the press frame. The performance of a hydraulic press depended largely upon the behavior of its structure during operation which determined performance and productivity of the press. The frame and cylinder were modeled using a modeling software; CATIA. Structural analysis was carried out on the C- frame by using analyzing software ANSYS. By using ANSYS software, structural performance and stress, strain distributions were plotted for verification. According to the structural values the dimensions of the frame and cylinder were then modified to perform the functions satisfactorily as well as reduce the weight and cost.

Nikhil and Tuljapure (2016) worked on design of C-frame type hydraulic punching machine. The 25ton capacity machine has permissible tensile stress of 121.6N/mm^2, 2.5 factor of safety. The maximum force acting on the plate was found to be 24.525 N. The pump runs at 375 rpm and 2.2 watt electric motor. Result of the study showed that the system is good for punching operation.

Chauhan and Bambhania (2013) designed and analyzed frame of 63ton power press machine by using FE Analysis". Analysis of this frame was done by the simulation software. It is said that Instead of sharp corner of the c - frame, fillet is provided to reduce failure in the structure. Amount of fillet depends on load condition experienced by frame and it is analyzed by using FEM Tool. It is concluded that simulation software is the powerful tool for prediction of plate required for a given load. This analysis given the result of reduction in thickness of plate of frame structure, material saving and as well as cost benefits.

Ameet and Gulhane (2016) work on design optimization of C-Frame of hydraulic press machine attempted to acquire the FEA implementation for analysis and design optimization of C Frame of 100 ton Hydraulic Press Machine. The research was carried out in order to minimize resources for manufacturing industries thus forces optimum use of available overall resources with a basic intention of cost saving approach. According to the report, design of hydraulic press structure is of prime importance keeping in mind the design parameters and performance indicators and their relationship with proper knowledge of existing working conditions and application of load. By FEA implementation, attempts were made to reduce the thickness of the plates for the C frame structure in order to save the material and its cost by using an existing machine and optimizing it. Result of the optimization showed that thickness of the frame was reduced from 25mm to 22mm while net weight was reduced by 12%.

Ivanova *et al.* (2013) worked on theoretical modelling of the briquetting process with different pressing equipment. They identified that lack of information about the process of formation and agglomeration of briquettes of different types of processing equipment adversely affects the quality of bio-fuel, rapid and intensive wear and tear of the main working parts and higher energy compaction; this influences the cost of the final product. In view of that, they carried out an analyses of the optimal technologies for briquette production, a comparison and elaboration of mathematical multifactorial linear models of the pressing process. Their theoretical modelling focused on the analysis of the factors influencing the mechanical quality of briquettes and their calculation. The pressing chamber was divided into three pressing zones, for a more understandable description of the briquetting process in a piston press. Then followed by Analysis of forces and pressure distribution during the passage of material. The study tends to improve the design and operational parameters of the pressing equipment.

Modelling parameter for optimization of hydraulic briquetting machine are pressure, moisture content, temperature and particle size (Jarosova and Kurekova, 2013; Yadong and Yuyi 2002; Sanjeev, *et al.*, 2017; Ivanova *et al.*, 2013; Krizan *et al.*, 2016). Jarosova and Kurekova (2013) used response surface methodology (RSM) to determined optimal technological parameters for a compaction process while Jithesh (2016) optimized die design of screw press using trial and error method in adjusting entry diameter, exist diameter, taper angle of these machine and used compression ratio as the response variable.

2.7.3 Briquettes produced from biomass wastes

Many research works had been carried out in conversion of biomass waste materials into briquettes. Some of these research works are reviewed as follows;

Shekhar (2010) in his work said that there is a huge current and growing demand to find alternative clean energy sources that meet new legislation requirements to reduce emissions from fossil fuels. Agrowaste as a source of energy in India shows great potential. The process of briquetting increases the calorific value (combustion efficiency) of the product as compared to the loose material. His work analyzed the issues connected with the production and use of briquettes and highlighted the huge untapped potential of its possible wide spread use. He suggested that to Corporates and NGOs should undertake these projects as an arm of their corporate social responsibility efforts.

Singh (2013) in his work titled bio-briquetting in Nepal - Scope and Potentials: a review, showed that a close analysis of briquette production during the 1980s reveals that the entire briquetting efforts came from the private sector, without any government support in terms of policies, incentives and motivation. Also there was no technical backstopping and very little R&D to support briquetting. So because of various techno-economical problems, most of the briquetting industries closed down. The situation in the country after 2010, nearly thirty years later, is entirely different. With the increase in awareness about briquettes as renewable source of energy; climate change and global warming issues from fossil fuel use and concept of utilizing waste for energy; with the change in kerosene and briquettes fuel prices; briquettes are slowly emerging as a viable alternative source of energy for cooking, heating and many briquetting industries are again being established in the private sector. The Nepali experience on briquetting shows that, almost all of the bio-briquetting technologies have been introduced in the country. R&D institutions have emerged and research and development activities supporting biomass briquetting are constantly increasing. The assessment of agro-forest waste shows that there is a huge raw material base that can be utilized for briquetting. The technological capability in fabrication, reproduction, repair and maintenance has been well developed. Many funding, promotional and research and development (R&D) organizations are now actively involved in briquetting. The Government through the AEPC is formulating policies, plans and programs, including incentives for the promotion of Bio-briquetting. With the introduction proper policies and incentives biomass briquetting has big potentials and scope for the promotion of bio briquettes in near future.

Bhoumick *et al.* (2016) also worked on conversion of waste plastic into solid briquette in combination with biomass. Their study develop a good composition of briquette which comprises of conventional biomass and plastic waste. They identified that every year millions of tons of agricultural wastes and plastics are generated most countries of the world but still encounter the problem of energy efficiency and environmental pollution. Although waste plastics are recycled, major portion of it goes to land filling. As plastics possess high fuel value, it can be combined with biomass to prepare solid briquette. The research work was carried out in three segments namely; (i) Preparing a lab grade thermal piston press for plastic-biomass briquette manufacturing, (ii) Sample preparation with various proportion of Biomass and Waste Plastic, and (iii) Characterization of the prepared sample. From their study, it was found that the fuel value of Biomass Briquette increases with mixing of plastics, which minimizes water absorption and friability, increases storage capacity and strength. The characterization of Plastic-Biomass Briquette shows that with the addition of 10% waste plastic the calorific increases 40% by margin and doubles the compressive strength.

Yazdani and Ali (2016) in their work on properties of briquette from agricultural waste available in Brunei Darussalam and its environmental impact, assessed the calorific value of briquettes produced from mixed sawdust of three tropical hardwood species (Afzeliaafricana, Terminaliasuperba, Meliciaelcelsa) bonded with different binding agents (starch, cow dung and wood ash).They stated that the filler is used to enhance the combusting performance. To make briquette, two wastes such as saw dust and rice husks was used as the filler material. They obtained these materials from saw mills and rice fields respectively and newspaper was used as the binder material. The newspapers were first soaked in hot water for 3 hours until it reaches porridge-like consistency. They made the briquettes with a Caulk Gun, and dried in an incubator at 50 degree Celsius for 2 days. Eight different types of briquettes were made with different combination of the above mentioned filler and binder materials. Calorific value, elemental analysis and burning tests were performed for the manufactured briquettes. They compared the manufactured briquettes with a commercially available briquette and ranked them based on experimental properties. From their analysis, they concluded that there is a great potential for these briquettes in Brunei Darussalam and could possibly serve as an alternative source of energy with less environmental impact.

Onuegbu *et al.* (2012) studied comparative analyses of densities and calorific values of wood and briquettes samples prepared at moderate pressure and ambient temperature. Their study was carried out to compare some properties of bio briquettes (elephant grass and spear grass) and bio-coal briquettes prepared at moderate pressure, 5MPa and ambient temperature with wood samples. In their result, it was found that elephant grass and spear grass briqutteshave calorific values of 15.98 MJ/kg and 16.13MJ/kg, densities of 0.319g/cm3 and 0.367g/cm3, durability ratings of 92.42% and 90.54% and moisture contents of 8.00% and 7.9% respectively. Comparing these properties with some wood samples, it was observed that there is a need to enhance the heating values and energy densities of the briquettes in other for them to compete favourably with firewood especially for industrial applications. Proximate analyses shows that the elephant grass and the spear grass used contained calorific values of 14.66MJ/kg and 15.12MJ/kg, moisture content of 9.26% and 10.13% and ash contents of 5.18% and 6.18% respectively. They further stated that though at moderate pressure and ambient temperature, the resultant briquettes are of lower density and heating value compared to some wood sample, but these properties can be fortified by adding some quantity of desulfurized coal before briquetting.

Briquettes were produced from waste paper and coconut husk admixtures (Olorunnisola, 2007). In the work, a binder-less briquettes was produced from a mixture of waste paper and coconut husk particles at low pressure (< 0.20 MPa) using a locally fabricated manual briquetting machine. The study was undertaken to investigate the properties of fuel briquettes produced from a mixture of a municipal solid waste and an agricultural residue, i.e., shredded waste paper and hammer-milled coconut husk particles. The briquettes were produced at an average pressure of 1.2 x 103 N/m^2 using four coconut husk: waste paper mixing ratios (by weight), i.e., 0:100; 5: 95; 15: 85; and 25: 75. The results obtained showed that briquettes produced using 100% waste paper and 5:95 waste paper-coconut husk ratios respectively exhibited the largest (though minimal) linear expansion on drying. While the equilibrium moisture content of the briquettes ranged between 5.4 % and 13.3%, there was no clearly discernible pattern in E.M.C variation with increase in coconut husk content. A reciprocal relationship was observed between compressed/relaxed density and relaxation ratio of the briquettes. The mean durability rating of all the briquettes exceeded 95%. It was concluded that stable briquettes could be formed from waste paper mixed with coconut husk particles.

Sastry *et al.* (2013) also studied biomass briquettes and how it can be sustained as an environment friendly energy option. The study gave a highlight of how untapped option in the Caribbean-biomass briquettes, specifically countries like Jamaica where the energy import bills are very high. They presented alternatives for design analysis of bio-briquette making machine, by producing their own energy which is different from conventional fossil fuels, and this region creates jobs, reduce the impact to the environmental waste, and improve waste management. The opportunities from their study includes manufacturing of bio-briquette machines, marketing, and research on power generation using bio-briquettes. They concluded that Caribbean Governments and policy makers should take initiative on encouraging the entrepreneurs and researchers in this sector for sustainable growth.

Tembe *et al.* (2014) studied density, shatter index, and combustion properties of briquettes produced from groundnut shells, rice husks and saw dust. Their study investigated the potential use of sawdust of Danielliaoliveri (African Copaiba Balsam Tree), rice husk and groundnut shells to make briquettes for energy generation. They produced doughnut shaped briquettes from three biomass materials at 15%, 25%, and 35% level of starch binder in binary and tertiary combinations. Density, shatter index and Combustion properties of the briquettes were investigated in their study. Their result has shown that briquettes produced from binary and tertiary combinations of Danielliaoliveri, rice husk and groundnut shells produced high heating values ranging from 4710.0Kcal/kg to 4516.0 kcal. The result was however lower than 5210 kcal/kg for Anoeissusleiocaarpa (African birch) and 4908 kcal/kg for Gmelina arborea (gamhar, gumhar, gamari, beechwood, goomar teak, Kashmir tree).This makes the combination of briquettes from sawdust of Danielliaoliveri and residues from rice husk and groundnut shell a good substitute for fuel. Briquettes produced at thirty five (35%) starch binder level recorded the highest combustion properties. It is therefore recommended that briquette production using sawdust and agricultural residues of Danielliaoliveri, Rice husk and Groundnut shells be done at binary and tertiary levels because of high heating value from the combinations. Starch binder level of 35% is also recommended for briquette production from the combinations because of the relative stability and high combustion properties of produced briquettes. They therefore recommended that sawdust of Danielliaoliveri, rice husk and groundnut shells that are usually discarded as waste in Nigeria could be converted to briquettes, which will serve as alternative source of energy for domestic cooking.

Raju *et al.* (2014) developed of fuel briquettes using biodegradable waste materials. The purpose of their work was to study the moisture, ash, volatile matter, fixed carbon, sulfur, calorific value, combustion calorific value, compressive strength, and water resistance of fuel briquettes using biodegradable waste materials. Hence, they produced fuel briquettes from locally available waste materials and evaluated the briquettes for moisture content, ash, volatile matter, fixed carbon, sulfur, calorific value, combustion calorific value, compressive strength, and water resistance. Their experimental results indicated that coconut coir gave more volatile matter content, fixed carbon content, calorific value and combustion calorific value of the solid fuel briquettes while rice husk briquettes have more moisture content and paper briquette has more ash content and water absorption rate. The percentages of carbon, hydrogen, nitrogen, sulphur and oxygen for paper are 51.12%, 5.038%, 1.9832%, 0.203%, 49.8382% respectively. The percentages of carbon, hydrogen, nitrogen, sulphur and oxygen for rice husk are 43.052%, 4.0357%, 1.1254%, 0.254%, 38.159% respectively. The percentages of carbon, hydrogen, nitrogen, sulphur and oxygen for coconut are 52.012%, 5.057%, 0.9200%, 0.172%, 52.067% respectively.

Emerhi (2011) studied physical and combustion properties of briquettes produced from sawdust of three hardwood species and different organic binders. The purpose of the study was to assess the calorific value of briquettes produced from mixed sawdust of three tropical hardwood species (Afzelia Africana, Terminalia superba, Meliciaelcelsa) bonded with different binding agents (starch, cow dung and wood ash). Sawdust from each of the species was mixed with the binder in ratio of 70:30 for cow dung and wood ash and 70:15 of starch. The sawdust where mixed in a ratio 50:50 for each briquette combination produced. Combustion related properties namely percentage volatile matter, percentage ash content, percentage fixed carbon and calorific value of the briquettes where determined. All processing variables assessed in his study were not significantly different except for percentage fixed carbon at five percent level of probability. Result shows that briquette produced from sample of Afzelia Africana and Terminalia superba combination bonded with starch had the highest calorific value of 33116kcal/kg while briquette produced from sample of Afzelia Africana and Terminalia superba bonded with ash had the least calorific value of 23991kcal/kg.

Ajobo (2014) in a similar study, examined the densification characteristics of groundnut shell. Nigeria being a major producer of groundnut in the world with an average annual production of about one million tons and that groundnut production generates large amount of residues such as groundnut shell. According to the report, groundnut residues are currently of low utility value in Nigeria and are potentially viable options for energy productions. His experimental procedure involved in the development of a bottle jack press which has the capacity of producing three briquettes pieces per hour. Groundnut shell were pressed hydraulically in a compression compartment (360 x 105 x 155 cm^3), at compaction pressures of 1.5, 3.6 and 4.5N/m2, with binder ratio level of 15, 20 and 25% and particle size of 0.4, 1.8 and 2.7mm. Briquettes were produced using residue particles mixed with cassava starch binder. In his study, ultimate and proximate analyses of the produced briquettes were carried out using ASTM standard method. Experiments were carried out to determine density, durability, indices, compressive strengths and heating value of briquettes produced. The produced briquettes have densities between 356.3 and 632Kg/m^3, the optimum moisture content, compressive strengths, compaction ratio, relaxation ratio and heating value for groundnut shell briquettes are 11.25%, 1.59KN/m2, 16.33J/kg, 4.3 and 1.45 respectively. The briquette properties are quite good with resistance to mechanical disintegration, high value of relaxed density and low value of relaxation ratio obtained for the briquette imply they are good potentials as energy materials.

A research on densification of sawdust of tropical hardwoods and maize cobs at room temperature using low compacting pressure without a binder was carried out with the purpose of determining the optimum conditions for producing briquettes from sawdust of selected timber species and maize cobs at low compacting pressure and room temperature without a binder (Mitchual, 2014). Six selected tropical hardwood timber species at room temperature (25^{o}C) was compacted in a hydraulic press without a binder at low pressure (CP) varying from 10 MPa to 50 MPa and particle size ranging between 1mm and 3.35mm. Physical and mechanical characteristics of briquettes determined were briquettes' stability, relaxed density, compressive strength (CS) in cleft, impact resistance index (IRI) and water resistance (WR) quality. The study revealed that at 5% level of significance the density of timber species had significant negative correlation with CS in cleft, IRI and WR quality while it positively correlated with relaxed density of briquettes produced. Generally, species, particle size and CP had significant effect on stability in length and diameter, relaxed density, CS in cleft, IRI and WR quality of briquettes produced (p-value < 5%). Linear regression models established between the research factors and dependent variables suggested that species density, particle size and CP were good predictors of stability in length and diameter, relaxed density, CS in cleft, IRI and WR quality of briquettes produced. The multiple correlation coefficient (R) and *adjusted R2* for the regression models ranged from 0.74 - 0.93 and 0.54 - 0.87 respectively with p-values less than 5%. His result further indicated that mixing sawdust of *C. pentandra*with *P. africana*or *T. superba* significantly improved upon the CS in cleft, IRI and WR quality of briquettes produced. The mixing ratio of the sawdust also had significant effect on the mechanical and physical properties of the briquettes produced. The study also revealed that briquettes produced from maize cobs at low CP and room temperature had low CS in cleft, IRI and WR quality. However, these properties were significantly improved when maize cobs was combined with sawdust of *C. pentandra*, *T. superba*and *P. africana*. The gross calorific values of the six hardwood timber species were adequate and they ranged from 20.16 to 22.22 MJ/kg. From the study, it could be concluded that at room temperature using low CP, briquettes with adequate physical and mechanical properties could be produced from sawdust of tropical hardwood species and their mixture.

A global review with emphasis on developing countries investigated biomass energy and densification potential (Bhattacharya, 2017). The work highlighted that the share of biomass in the total energy consumption has been rising in developed countries while in most developing countries, the magnitude of biomass energy consumption is rising although the share of traditional fuels in the total national energy use has been falling. It also identified that the current market price advantage of fossil fuels, particularly coal, with respect to biomass fuels would substantially diminish if the environmental costs were considered in pricing of fuels. He further said that, since one of the main reasons behind the current interest of renewable energy is the environmental impact of large-scale use fossil fuels, it appears irrational that this concern is normally not reflected in pricing of energy today. With fair pricing of energy, biomass based energy would become viable under a wide range of situations and the pace of commercialization biomass energy technologies would accelerate. Although densification appears to have aroused a great deal of interest in recent years, actual production of densified fuels is still very low compared with their technical potential. Densified biomass produced is mostly in the form of briquettes in developing countries and in the form of pellets in developed countries. Biomass densification faces a wide range of barriers, which must be removed for promoting its wider acceptance. Growing global concerns regarding climate change and related developments are likely to improve the prospects of biomass energy technologies, including densification in the near future.

Davies and Mohammed (2013) studied the effect of processing variables on compaction and relaxation ratio of water hyacinth briquettes. The work stated that fuel wood collection has grave consequences on environment resulting in greenhouse gas emissions (GHG), forest conservation and sustainable forest resources management. The selection of water hyacinth as alternative source of energy is an important way of managing the weed problem and contributing to environment management. The water hyacinth and plantain peels were milled into three particle sizes 0.5, 1.6 and 4.0mm, five binder levels 10, 20, 30, 40, 50% and four pressure levels 3, 5, 7 and 9MPa were used. They used manually operated hydraulic press for the production of briquettes. The experimental design for their study was 5 x 3 x 4 Randomized Complete Block Design. ASABE standard methods were used to determine the moisture contents, compaction ratio and relaxation ratio of the briquettes. The minimum compaction ratio was obtained at pressure P1 (5.19±0.27) and the maximum at pressure P4 (6.80±0.36).The effect of binder on the compaction ratio ranged from 5.87±0.31 (B3) to 6.04±0 .25 (B4) for all the five binder proportions utilized. The ANOVA revealed that there was significant difference among all the values obtained for compaction ratio at the various binder levels ($P<0.001$).The values of compaction ratio obtained indicated more void in the compressed materials. This signifies more volume displacement which is good for packaging, storage and transportation and above all, it is an indication of good quality briquettes.

Oladeji (2012) selected few agro residues commonly found in Nigeria and compared briquettes produced from those residues. The study designed and fabricated a briquetting machine capable of producing four briquette pieces per batch. The compaction, density, relaxation ratios and percentage expansion of the briquettes were also determined after the production and their mechanical properties and the heating value also The mean moisture contents of corncob, groundnut shell, melon shell, cassava, and yam peels were 9.47, 11.53, 9.60, 10.19, and 9.27% respectively, while the moisture contents of their briquettes were 7.48, 9.18, 7.45, 8.78, and7.95% respectively. The maximum, relaxed densities and relaxation ratio for briquettes produced from corncob, groundnut shell, melon shell, cassava, and yam peels were respectively (650kg/m^3, 385kg/m^3, 1.60); (524kg/m^3, 236kg/m^3, 2.20); (561kg/m^3, 286.42kg/m^3, 1.95); (741.13kg/m^3, 386.2kg/m^3, 1.92); and (911.45kg/m^3, 512.54kg/m^3, 1.78). The heating value calculated for briquettes from corncob, groundnut shell, melon shell, cassava, and yam peels were 20,890, 18,634.34, 21,887, 12,765, and 17,348kJ/kg, respectively, while the corresponding values of compressive strengths in the order listed above were 2.34, 1.69, 2.30, 1.53, and 1.76kN/m^2.

Kuhe *et al.* (2013) studied the potential of using low pressure in producing agricultural waste briquettes. The variation of steady-state combustion rate (otherwise called normalized burn rate, NBR) with the density, moisture content, and geometry of sawdust, palm fibre and rice husk briquettes, burned in free air was investigated. Cylindrical briquettes were used throughout the experiment except for the effect of geometry where cylindrical briquettes with central hole and cylindrical solid briquettes were used. Their work formed briquettes by compression of the pulp in the mould with an Instron compression test machine at a pressure range between 1.5 and 7.5N mm^{-2}. The formed briquettes has densities between 200 and 500 kg/m^3. Their results shows that the NBR for the three selected briquette samples: wood sawdust, palm fibre, and rice husk, respectively, was found to decrease as the density and moisture content increases. It was observed from their result, that hollow briquette had a higher NBR than that of solid briquette of the same pressure and relaxed diameter with sawdust having the highest variation and rice husk the least. From their results, it shows that briquettes could be a viable alternative to fuel wood.

According to Romallosa and Hornada (2011), briquettes can be produced not only from biomass materials but also from urban wastes. The urban waste was mixed with biomass materials. The mixtures used were the following: Briquette 1: paper (100%); Briquette 2: carbonized rice husk or CRH (71%) + cornstarch (29%); Briquette 3: Sawdust (71%) + cornstarch (29%); Briquette 4: paper (50%) + CRH (50%); Briquette 5: paper (50%) + sawdust (50%); and Briquette 6: paper (50%) + CRH (25%) + sawdust (25%). From their result, briquettes 1 (Paper), 5 (Paper + Sawdust), and 6 (Paper + CRH + Sawdust) were found to be the most viable mixtures. This is based on practicality of production requirements and high production rate, better quality of fuel produced, fast operating performance in terms of boiling water and cooking rice and potential earnings that may be gained when adopted as an income generating project.

Sriram *et al.* (2014) produced briquettes from cotton wastes. Solid waste from flour mill (SWFM) was used as binder for the briquette production. The composition, compressive strength, calorific value, moisture content, thermal efficiency, proximate analysis of briquettes were analyzed. The calorific value of the briquette obtained from cotton waste increased with the aid of fillers and binders. The briquette of 30% binder was optimized because it had 2188.5 kN/m^2 of compressive strength, 5233 Cal/g of calorific value, 193 seconds time to attain 70^{o}C for 1 litre of water and 17.87% of thermal efficiency. Calorific value of cotton waste briquettes found nearer to coal. The binder SWFM proved to provide good mechanical strength. The briquette produced considerably less smoke. The briquette of 50% binder had least compressive strength of 1010.1 kN/m^2, 4916 Cal/g of calorific value, took 407 seconds time to reach 70 ^{o}C for 1 litre of water and 9.66 % of thermal efficiency. The result, concluded that increase in percentage of binder increased the compressive strength but calorific value of the briquette decreased.

Wilaipon *et al.* (2006) studied the effect of moderate die-pressure on banana-peel briquettes. Based on the banana productivity and the residue-to-product-ratio, the estimated quantity of banana peel generated was calculated and found to be more than 12.5 k-ton/year. The effect of moderate die pressure and binder ratio less than 30% on banana peel briquettes was investigated. It was found that the density of the briquettes was strongly influenced by the briquetting pressure and the binder ratio. It was also found that the rapid mass loss section and the slow mass loss section were separated at the temperature of about 673K. Approximately, the material is comprised of 41.47% carbon, 5.68% hydrogen and 0.37% nitrogen respectively. The heating value of the banana peel was found to be 18.89 MJ/kg. According to their test, it was found that the moisture content of the samples was about 15%. Also, the ultimate analyses results show that the banana peel is comprised of 41.47% carbon, 5.68% hydrogen and 0.37% nitrogen. Finally, it was also found that the higher heating value of banana peel on dry basis is 18.89 MJ/kg, which is rather higher compared to the values of several kinds of biomass material such as palm fibre, palm shell and hazelnut shell.

Abdulrasheed *et al.* (2015) investigated the effect of compression pressure on mechanical and combustion properties of sawdust briquette using styrofoam adhesive as binder. In their study, briquettes were produced from sawdust at different compression pressure using styrofoam (polystyrene foam) adhesive as binding material. The effects of changing the compression pressure used in moulding of briquettes on its combustion and mechanical properties were investigated. In evaluating combustion properties, 0.940 kg of water was boiled using oven-dried sample of briquette in the combustion chamber with air flow velocity supplied to the combustion chamber at 10.2 m/s. Combustion properties investigated were afterglow time, burning rate, specific fuel consumption, power output, percentage heat utilized, flame propagation rate and percentage ash content. The mechanical properties investigated included density, compressive strength, impact resistance, water resistance and abrasion resistance. The blends of sieved sawdust and binder were prepared in the ratio of 4:1 and compacted at pressures ranging from 40 – 90 kN/m^2 at 10 kN/m^2 interval in a hydraulic press machine with a dwell time of 5minutes.

2.7.4 Mathematical modeling of biomass briquetting

There are biomass compaction models which have been developed by researchers over the years to reveal the behavior of biomass grinds or particles during briquetting. Most of these developed models help to optimize the pressure required to obtain a quality briquette.

Parthiban *et al.* (2014) used CATIA modelling software to model an existing C-type hydraulic press structure and cylinder and it was analyzed using ANSYS. The structural values of the frame and cylinder were modified to perform satisfactorily. In a similar research, Kline (2016) modeled and optimized hydraulic system in other to achieve performance characteristics of the system. The model was used to predict the pressure and velocity responses of the cylinder with time. Feng *et al.* (2017) also modeled stiffness characteristics of hydraulic cylinder under multiple factors. The studies highlighted the impacts of various factors on the stiffness characteristics of the hydraulic cylinders, including the oil bulk modulus, the air content in the hydraulic oil, the axial deformation of the piston rod, the volume expansion of the cylinder barrel, the volume expansion of the metal pipes and the flexible hoses, and the deformation of the hydraulic cylinder sealing.

In the evaluation of the biomass compaction models by Mani *et al.* (2004), Spencer and Heckel models expressed density in terms of packing fractions and this packing fraction is a function of applied pressure as given in eqn. 2.16 and 2.17. The models are used to describe the compression behavior of powdered materials where the constants ‘m’ and ‘b’ describe the two stages of compression: pre-occupation and the particle rearrangement due to densification. The models have been used to explain the compression behavior of many pharmaceuticals (Garekani*et al.*, 2000), food powders (Ollet*et al.*, 1993) and alfalfa grind (Tabil and Sokhansanj, 1996) but did not fit well with the compression data of biomass grind (Mani *et al.*, 2004).

$$\ln\frac{1}{1-\rho_f}=m\rho+b \qquad 2.16$$

Where,

ρ = particle density of the material

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

$$\rho_f=\frac{P}{\rho_1 x_1+\rho_2 x_2} \qquad 2.17$$

ρ_1 and ρ_2=particle density of components 1 and 2 of the mixture

x_1 *and* x_2= weight fraction of components 1 and 2 of the mixture

P= applied pressure

m and b = constants

In Cooper and Eaton model, Mani *et al.* (2003) also found that the model classified the two broad processes that are involved in compaction. Their model (eqn. 2.18) assumes that compression is by probability which occur either by filling of voids of the same size as the particles or by filling of voids smaller than particles (Mani *et al.*,2003).

$$\frac{V_o - V}{V_o - V_s} = a_1 e^{-\frac{k_1}{P}} + a_2 e^{-\frac{k_1}{P}} \qquad 2.18$$

Where:

V_o= volume of compact at zero pressure (m^3)

V = volume of compact at void of same size as particle (m^3)

V_s = volume of compact at voids of smaller size as particle (m^3)

k_1, k_2, a_1, a_2= Cooper–Eaton model constants

However, Kawakita and Ludde model combined pressure and volume factor and these models (eqn. 2.19 and 2.20) gives a linear relationship between '$\frac{P}{C}$' and 'P' and allows the constants to be evaluated graphically (Mani *et al.,* 2004). Evaluation of the above models found out that Cooper-Eaton model fitted fairly well for biomass grind at 12% moisture content while Kawakita-Ludde model fitted very well with the compression data of biomass grinds (Mani *et al.*, 2004).

$$\frac{P}{C} = \frac{1}{ab} + \frac{P}{a} \qquad 2.19$$

$$C = \frac{V_o - V}{V_o} \qquad 2.20$$

Where:

C= degree of volume reduction or engineering strain

a *and* b= Kawakita-Ludde model constants related to characteristics of the power

Sonnergaard (2001) model (eqn. 2.21) is a log-exp equation, which consist of two processes simultaneously. The processes include the logarithmic decrease in volume by fragmentation, and exponential decay representing plastic deformation of material. The model is also used in evaluation of biomass grind compaction process.

$$V=V_1-w\log P+V_o e^{-\frac{P}{P_m}} \qquad 2.21$$

Where:

V_1= volume at pressure (1MPa)

P_m= mean pressure (MPa)

w= constant

Gatmaitan *et al.* (2012) developed an automatic hydraulic press briquetting machine that varied compression parameters (pressure and temperature) of the machine but they did not give a model equation for the relationship. Krizan and Matus (2012) also worked on impact of conical shape pressing chamber on briquette quality as shown in Fig. 2.10. Their work focused on the shape of pressing chamber in producing high quality briquettes.

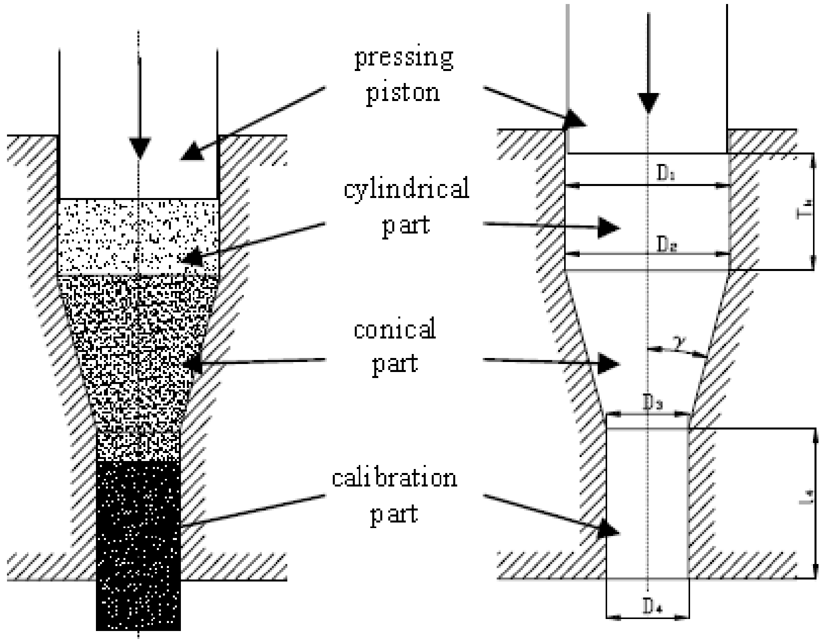

Fig. 2.10: Conical pressing chamber of a pressing machine

Source: Krizan and Matus (2012)

Matus *et al.* (2010) in a similar research gave eqn. 2.22 as the compacting pressure in a conical pressing chamber.

$$p=\sigma_{k3}\left(1+\frac{f_3+0.5}{2.\gamma}\right).\ln\frac{S}{s}+\sigma_{k3}.\frac{2.L}{D}+\sigma_{k4}.\frac{4.f_4.l}{d} \qquad 2.22$$

Where:

P= compacting pressure

σ_{k3}= back pressure affecting the compacting material at the conical part (MPa)

f_3 and f_4 = frictional factor for the conical and calibration part respectively (dimensionless)

γ = conicalness of surface (^{o})

S = cross section area of cylindrical part (mm^2)

s = cross section area of calibration part (mm^2)

L = distance between the piston and bottom end of the pressing chamber (mm)

D = diameter of cylindrical part of pressing chamber (mm)

σ_{k4} = back pressure affecting the compacting material at calibration part (MPa)

l = length of calibration part (mm)

d= diameter of calibration part (mm)

Other research works on optimization of technological parameter of a compaction process used designed experiment to find the operational conditions that ensures the optimal density of briquettes (Jarosova and Kurekova, 2013). The work was based on the effect of pressure, temperature, moisture content and particle size on the density and was examined by means of response surface modeling using central composite design (CCD).The result of the analysis indicated that the design of experiment differed slightly form the CCD.A mathematical model using similar parameters as given in eqn. 2.23 was obtained using measured data (Krizan, 2008).

$$\rho = e^{\left(\begin{array}{c}4.98371-0.0261781.p-0.0410292.T-0.620594.w_r 0.015446.L+0.000228845.p.T \\ +0.0031851.p.w_r+0.00528717.T.w_r-.00000273004.p.T.w_r\end{array}\right)} \qquad 2.23$$

Where:

ρ = density of briquettes (kg/m^3)

p = axial compacting pressure (MPa)

T = pressing temperature (^oC)

w_r = relative moisture content (%)

L = fraction largeness (mm)

There are also empirical models on briquette production which focused on the relationship between the moisture content, particle size and moisture content on the briquette density, durability etc. Arzola *et al.* (2012) empirical model expressed density and durability in term of binding agent and particle size (eqn. 2.24 and 2.25) respectively.

$$\rho = 1.76983 - 0.05110BA - 0.00081\mu_t + 0.00004BA\mu_t + 3.09736E\text{-}7\mu_t \qquad 2.24$$

$$DI = 105.471 - 0.527518BA - 0.0135533\mu_t + 0.000465041BA\mu_t + 3.09736E \qquad 2.25$$

Where:

P = briquette density

DI = Durability index

BA = binding agent

μ_t = particle size

Similar model examined the relationship between moisture content and temperature on the briquette moisture content, pellet density and durability (eqn. 2.26, 2.27 and 2.28) respectively (Tumuluru *et al.*, 2010b).

$$PMC = -4.73 + 0.077TM_W - 0.000451T^2 - 0.033M_W^2 - 0.0027TM_W \qquad 2.26$$

$$PD = -1216.1 + 4.03T - 67.38M_W - 0.031T^2 + 0.49 \qquad 2.27$$

$$D\ -111.384 - 0.11T - 1.869M_W + 0.0678TM_W \qquad 2.28$$

Where:

PMC = briquette moisture content

PD = briquette density

D = briquette durability

T = temperature

M_W = biomass waste moisture content

2.7.5 Summary of Reviewed Literatures

In summary, direct burning as means of disposal or cooking has been the major means of disposing or utilizing biomass wastes. To enhance biomass waste processing for energy resource, better means of processing that can increase their durability and ease transportation of processed material from one place to another has been advocated.

Like developed countries, ways of utilizing biomass wastes can be adopted if all information and research works on biomass waste processing into energy are clearly understood. As observed from the reviews, briquettes is one of the most versatile product gotten from processed biomass waste material and has essentially been used to generate energy for various heat applications. Also from the review, indigenous briquetting machines has not been studied extensively in terms of its operation principle and adaptability since adequate design of briquetting machine results in production of briquettes of high quality briquette that can withstand high impact during transportation and also increases durability of briquettes while in storage.

The need for this research work arose because of the limited theoretical knowledge on performance of hydraulic press briquetting machine. This type of briquetting press was identified to have several benefits when compared to other briquetting machines. The review has also recognized that it is the most fabricated briquetting machine for biomass waste materials but there is limited knowledge on assessing its performance of operation. H-frame hydraulic press and screw extruders has got more applications and reliability due to the existing models on their operations but they are not as versatile as C- frame in terms of usage. Also studies on the effect of some input factors of the machine and how they affect the performance of the briquetting machine has not be pronounced.

Most mathematical models according to the review are used universally in design calculations and predictions of effect of pressure on the bulk density and volume reduction fraction. Apparently, performance prediction models of C-frame hydraulic briquetting press is of importance in other to ascertain performance of the machine during briquetting of biomass materials as it can be a guide during machine development as performance of the machine is determined based on the physical characteristics of the biomass materials. This is important knowing that machine performance is dependent on operation of the machine as well as nature of biomass material the machine is compressing. From the literatures reviewed, it is obvious that there are limited research work that describe machine performance as function of material and machine variables. Consequently there is significant knowledge gap in terms mathematical models that can be adopted in determining performance of hydraulic briquetting machines. Mathematical models are important in evaluating the behavior of all machine and biomass waste parameters since they have to be in synergy for the optimum performance of a hydraulic briquetting machine which the existing empirical models did not consider.

Lately, researchers ha2ve been zealously developing new technologies as well as applying the use of optimization techniques in resource management hence, obtaining high quality and cost effective products. It is therefore necessary to evaluate briquettes at different variables of operation in other to obtain optimum variables for maximization of bulk density and other factors that enhances burning while in the same manner, minimize of the factors that constitute environmental hazard during briquette burning. This is of optimum importance because of variation in composition and other briquetting variables of biomass waste materials that affect briquetting operations. It is with these obvious reasons that the optimal binder ratio, compaction pressure and also the particle size of the materials that is ideal for briquetting were evaluated in other to maximize effective productivity of briquettes from biomaterials.

The intention of the study is therefore to develop mathematical models that can be used to predict performance of a hydraulic briquetting machine. This knowledge can help in the determining performance of hydraulic briquetting machine during operation. It will equally be a guide to developers of these machines on the appropriate parameters required for obtaining optimum performance of briquetting machine.

CHAPTER THREE

3 MATERIALS AND METHOD

3.1 Materials and Equipment

3.1.1 Materials

The biomass wastes used for the briquette production are rice husks and four different species of wood shavings (sawdust) namely Stool wood (Alstonia boonei) Gmelina wood (Gmelina arborea), Mahogany wood (Swietenia macrophylla) and Oil bean wood (Pentaclethra macrophylla Benth). They were considered for the study because they are widely available within the study area and can easily be sourced. Rice husks were collected from Abakaliki rice mill, Ebonyi state (Plate 3.1) while sawdust of the four wood species were sourced from Kenyetta and Abakpa timber market, Enugu state (Plate 3.2). Cassava starch (Renew brand) was used as binder and was sourced from Ogbete market in Enugu state. All materials for the analysis were healthy and fungus free.

Plate 3.1 Rice Husk dump site at Abakaliki Rice mill, Ebonyi state

Plate 3.2 Sawdust dump site at Kenyatta timber market Enugu

3.1.2 Characterization of the biomass material

The biomass wastes collected for the analysis were sun dried and taken to laboratory at National Centre for energy research and Development, University of Nigeria Nsukka for proximate and ultimate analysis of the biomass waste materials. Determining the material composition of the materials used for the study is important in other to evaluate the behavior of each material during the validation of the models and also to determine how the different compositions of each material react to different input variables that affect the height, bulk density and compression ratio on the briquettes produced from the materials. However, according to classification of trees species as hard and softwood, Mahogany and

Oil bean are classified as hardwood (Bridgewater, 2012; Oboh, 2007), Gmelina is soft to moderately hardwood (Kroya, 2017) and stool wood is softwood (Orwa et. al., 2009) which is based on biology and anatomy or their botanical distinction (Taylor, 2003). But woods are rated as hard or softwood based on the density and mechanical strength of the materials as presented in Table 3.1. Their hardness is determined by the Janka harness test (Goldstein, 2009), and from the values as stated in Table 3.1, their arrangement of hardness in descending order is as follow;

Oil bean wood >Mahogany wood >Gmelina wood >stool wood

Hardness of rice husk could not be established because it is not like wood that comes in planer forms such that Janka hardness test can be carried out on it.

Table 3.1 Mechanical properties of the wood species

Name of wood	Janka test (N)	Crushing strength (MPa)	Modulus of elasticity (MPa)	Modulus of rupture (MPa)	Reference
Stool wood	1820	6-7	5790-10500	48-73	Palla, 2005
Gmelina	4270	33.4	10800	87.4	Kroya, 2017
Mahogany	4760	49	10600	91	Meier, 2008
Oil bean	11,020	-	16,000-21,150	130-226	Oboh, 2007

3.1.3 Equipment

Equipment and apparatus used for the analysis as used in different measurement are discussed as follows;

Moisture content measurement:

Moisture content was determined using two apparatus namely; analytical weighing balance (Digital mettle Toledo, 0.0001g sensitivity) (Plate 3.3a) and conventional oven (Okhard Machine scientific and labouratory Equipment) (Plate 3.3b). Weighing balance was used for measuring mass of samples after oven drying.

(a) Weighing balance b. Oven

Plate 3.3 Moisture content determination apparatus

Elemental parameters determination

Micro-Kjedahl digestion flask (Make: Barloworld U.K, model Fk 500/3l) with capacity of 500ml (+/- 5ml) was used for elemental determination (Plate 3.4a) while Muffler furnace (3B5213C model, Gallenkamp, England) was used for burning (Fig. 3.4b) and bomb calorimeter in Plate 3.4c was used for determining the energy content of the materials.

a. Kjeldahl digestor b. Muffler furnance c. Bomb calorimeter

Plate 3.4 Proximate and ultimate measurement apparatus

Particle size determination apparatus

Hammer mill (Plate 3.5) was used for size reduction of the biomass wastes while Tyler sieve (Plate 3.6) was used for particle size analysis. The sieve sizes range used were between 163- 1250μm.

Plate 3.5 Hammer mill

Plate 3.6 Set of Tyler sieve

Volume measurement:

Measuring cylinder (250ml+/- 50ml) for measuring volume of material, water and starch. It is shown in Plate 3.7.

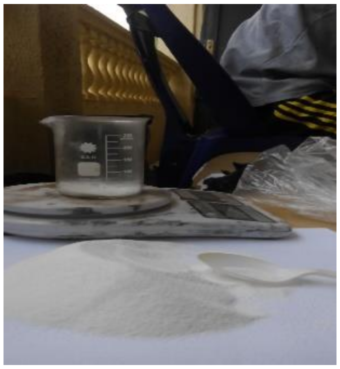

Plate 3.7 Measuring cylinder

Time measurement:

Stop watch (XL-010) was used for timing various operation. The stop watch is shown in Plate 3.8.

Plate 3.8 Stop watch

Dimension measurement:

Vernier caliper (Plate 3.9) was used for measuring the height and diameter of the briquettes.

Plate 3.9 Venier caliper

Fourier transform infrared (FTIR) analysis

An infrared spectrophotometer (Buck scientific: Model 530) was used for the analysis. It is shown in Plate 3.10.

Plate 3.10 Infrared spectrophotometer

Other tools used during the experimental analysis are; bowl and spatular– this was used for thorough mixing of the biomass material with the binder (Plate 3.11a), masking tape for identification of the briquettes (Plate 3.11b).

(a) Mixing bowl, spatula (b) masking tape

Plate 3.11 Measurement apparatus

3.2 Method

3.2.1 Relevant parameter for developing performance models

Performance of a hydraulic press is a function of the machine performance during briquette operation and also on the briquette quality. While operation of the briquetting machine depend on the machine geometry, briquette quality depends on composition, particle size, material density, compaction pressure, and moisture content (Kelly and Caddell, 1998; Mandal *et al*., 2014).

Effect of Geometry

Hydraulic press is recommended for producing briquettes with high shape precision of briquettes (Križan *et al*., 2011). Geometry configuration of hydraulic system such as compression speed, retraction speed, extrusion rate determines the machine performance in terms of the output capacity, and production efficiency of the briquetting operation.

Effect of composition

Material composition and compression are very vital in briquette making (Sastry *et al*., 2013). The composition of a material is among the factors that control burning rate (Onuegbu *et al*., 2011), density, compression strength and calorific value of briquettes (Akowuah *et al*., 2012). The composition of feedstock carbonised to produce briquettes varies with species and greatly affects their briquette quality (Antal and Gronli, 2003).

Effect of moisture

The percentage of moisture in the feed biomass is a very critical factor in briquette production. Much as moisture promotes bonding by van der Wall's forces to enhance compression (Grover and Mishra, 1996), it should be as low as possible because increase in moisture content reduces combustion efficiency (Pandey and Dhakal, 2013). The raw material should be dried to moisture content within a range of 10% to 15% for high quality briquettes (Grover and Mishra, 1996).

Effect of compaction pressure

The compaction pressure is usually exerted using a briquetting machine which can either be a screw or a piston press (mechanical or hydraulic). Compaction pressure is required in the densification of the waste which improves volumetric calorific value, and reduces transport cost of the fuel. Briquetting using a binder is sufficient at low compaction pressure (Grover and Mishra, 1996). However, the particles must bind properly during compression to prevent the briquettes from crumbling (Ugwu and Agbo, 2013). Increase in compaction pressure results into a corresponding increase in briquette density which decreases porosity (Markson *et al*., 2013).

Effect of particle size

The particle size of a material is paramount in briquette making (Katimbo *et al*., 2014). Particle size and size distribution affect the combustion properties of charcoal briquettes (Ayhan and Ayse, 2010). Increase in particle size increases volumetric calorific value, reduces ash content and increases thermal efficiency

(Davies *et al*, 2013). Despite the poor flow characteristics of very fine particles, inclusion of 10 - 20 % fine particles increases cohesion which in turn increases the compressive strength of briquettes (Grover and Mishra, 1996).

Effect of raw material density

Density is a very vital parameter because its value is directly proportional to energy to volume ratio, and ease of handling during storage and transportation (Križan *et al*., 2011). Briquette density is dependent on density of the raw material, compaction pressure, binder ratio and particle size (Davies *et al.*, 2013). However, a corresponding increase in briquette density which decreases porosity (Markson *et al*., 2013).

3.2.2 Development of Predictive Models

Model development for the performance evaluation of hydraulic briquetting machine were developed using the procedure described in section 2.4.3. Mathematical models were developed for the output capacity, quantity of damaged briquettes, machine production efficiency and briquette bulk density. Combination of the π terms were obtained as described in section 3.2.3.

Output capacity model

Output capacity model was developed by dimensional analysis using the concept of Buckingham's Pi theorem (Ndirika, 1997, Welter 1985).The independence variable considered to affect output capacity of the machine are compression speed, feed rate, pressure, extrusion rate, retraction speed, initial bulk density of material. Using [M], [L], [T] basic system of dimension, the dimension of the variables and dimension matrix are presented in Table 3.2 and 3.3 respectively.

Table 3.2 Basic dimension of variables for output capacity model

S/N	**Variable**	**Symbol**	**Unit**	**Dimensional unit**
1	Output capacity	T_c	kg/s	MT^{-1}
2	Compression speed	V_c	m/s	LT^{-1}
3	Feed rate	f	kg/s	MT^{-1}
4	Pressure	P	kg/m.s^2	$ML^{-1}T^{-2}$
5	Extrusion rate	E_r	kg/s	MT^{-1}
6	Retraction speed	R_s	m/s	LT^{-1}
7	Initial bulk density	B_i	kg/m^3	ML^{-3}

$$T_c \propto f(v_c, f, P, E_r, R_s, B_i)$$

$$T_c = Cf(v_c, f, P, E_r, R_s, B_i)$$

Total number of variables = 7

Number of fundamental dimensional units = 3

Number of dimensionless group = 7 – 3 = 4

Therefore, there will be four π-terms namely π_1, π_2, π_3 and π_4

$$\pi_1 = C_t f(\pi_2, \pi_3, \pi_4)$$

where;

C_t= output capacity constant

$\pi_1, \pi_2, \pi_3, \pi_4$ = P_i terms to be determined

Table 3.3 Dimensional matrix of variables for output capacity model

Dimensional unit	**Variables**						
	T_c	V_c	**f**	**P**	E_r	R_s	B_i
	a	b	c	d	e	f	g
M	1	0	1	1	1	0	1
L	0	1	0	-1	0	1	-3
T	-1	-1	-1	-2	-1	-1	0

The π-terms can be determined by considering the corresponding dimensional expression in the equation 3.1, 3.2, 3.3 and 3.4.

$$[MT^{-1}]^a = [LT^{-1}]^b [MT^{-1}]^c [ML^{-1}T^{-2}]^d [MT^{-1}]^e [LT^{-1}]^f [ML^{-3}]^g \qquad 3.1$$

M = a + c + d + e + g 3.2

L = b- d + f – 3g = 0 3.3

T = a - b – c – 2d – e – f = 0 3.4

Assume arbitrary values of a =1, b = 0, c = 0, d = 0

From eqn. 3.2, 3.3.and 3.4, and eqn. 3.5, 3.6 and 3.7 was obtained.

e + g = -1 3.5

f – 3g = 0 3.6

e = -1 –f 3.7

Substituting equation 3.7 into 3.5 gives eqn. 3.8

-f + g = 0 3.8

Combining eqns. 3.6 and 3.8 and solving simultaneously, substituting into eqn. 3.5, and 3.6 we obtain,

a = 1, b = 0, c = 0, d = 0, e = -1, f = 0, g = 0

Substituting into eqn. 3.1

$$[MT^{-1}]^1 = [LT^{-1}]^0[MT^{-1}]^0[ML^{-1}T^{-2}]^0[MT^{-1}]^{-1}[LT^{-1}]^0[ML^{-3}]^0$$

$$= [MT^{-1}]^1[MT^{-1}]^{-1} = \pi_1$$

$\pi_1$is obtained as given in eqn. 3.9

$$\pi_1 = \frac{T_c}{E_r} \quad 3.9$$

To obtain π_2, assume arbitrary values of a = 0, b = 1, c = 0, d = 0

Substitute the values into eqn. 3.2, 3.3, 3.4, and obtain eqn. 3.10, 3.11 and 3.12.

e = -g 3.10

f – 3g = -1 3.11

e + f = -1 3.12

Substituting eqn. 3.10 into eqn. 3.12 forms eqn. 3.13.

f – g = -1 3.13

Solving eqn. 3.11 and 3.13 simultaneously, the following values are obtain for π_2;

a = 0, b = 1, c = 0, d = 0, e = 0, f = -1, g = 0,

Substituting into eqn. 3.1

$[MT^{-1}]^0[LT^{-1}]^1[MT^{-1}]^0[ML^{-1}T^{-2}]^0[MT^{-1}]^0[LT^{-1}]^{-1}[ML^{-3}]^0$

π_2 is obtained as given in eqn. 3.14

$$\pi_2 = \frac{V_c}{R_s} \qquad 3.14$$

To obtain π_3, assume arbitrary values of a = 0, b = 0, c = 1, d = 0

Substitute the values into eqn. 3.2, 3.3, 3.4 and obtain eqn. 3.15, 3.16, 3.17.

e = -1 – g 3.15

f – 3g = 0 3.16

-f –e = 1 3.17

Substituting eqn. 3.15 into 3.17 to forms eqn. 3.18

- f + g = 0 3.18

Solving eqn. 3.16 and 3.18 simultaneously, the following values are obtained for

π_3

a = 0, b = 0, c = 1, d = 0, e = -1, f = 0, g = 0

Substituting into eqn. 3.13

$[MT^{-1}]^0[LT^{-1}]^0[MT^{-1}]^1[ML^{-1}T^{-2}]^0[MT^{-1}]^{-1}[LT^{-1}]^0[ML^{-3}]^0$

π_3 is obtained as given in eqn. 3.19

$\pi_3 = \frac{f}{E_r}$ 3.19

To obtain π_4, assume arbitrary values of a = 0, b = 0, c = 0, d = 1

Substitute the values into eqn. 3.2, 3.3, 3.4 and obtain eqns. 3.20, 3.21 and 3.22.

e = -1 – g 3.20

f -3g = 1 3.21

-e – f = 2 3.22

Substituting eqn. 3.20 into 3.22 to form eqn. 3.23

-f + g = 1 = 1 3.23

Solving eqn. 3.21 and 3.23 simultaneously, the following values were obtained for π_4

a = 0, b = 0, c = 0, d = 1, e = 0, f = -2, g = -1,

Substituting into eqn. 3.1,

$$[\mathrm{MT}^{-1}]^0[\mathrm{LT}^{-1}]^0[\mathrm{MT}^{-1}]^0[\mathrm{ML}^{-1}T^{-2}]^1[\mathrm{MT}^{-1}]^0[\mathrm{LT}^{-1}]^{-2}[\mathrm{ML}^{-3}]^{-1}$$

π_4 is obtained as given in eqn. 3.24

$\pi_4 = \frac{P}{{R_s}^2 B_i} =$ 3.24

Since,

$$\pi_1 = C_t f(\pi_2, \pi_3, \pi_4)$$

Combining π_2, π_3, π_4, to form π_5 (refer to section 3.3.1),

$$\pi_5 = \left[\frac{\pi_2 \times \pi_3}{\pi_4}\right] \quad 3.25$$

The required relationship is therefore obtained by combining the π-terms in eqn. 3.9, 3.14, 3.19 and 3.24.

$$\frac{T_c}{E_r} = C_t\left[\left(\frac{V_c}{R_s} \times \frac{f}{E_r}\right) \div \frac{P}{R_s^2 B_i}\right] = C_t\left[\frac{V_c R_s f B_i}{E_r P}\right] \quad 3.26$$

In most briquetting press, compression speed is same as the retraction speed (Grover and Mishra, 1996). Thus $V_c = R_s$ as given in eqn. 3.25.

$$\frac{T_c}{E_r} = C_t\left[\frac{v_c{}^2 f B_i}{E_r P}\right] \quad 3.27$$

Eqn. 3.25 is further arranged as given in eqn. 3.26.

$$T_c = C_t\left(\frac{V_c{}^2 B_i f}{P}\right) \quad 3.28$$

Damaged briquettes model

Independent variables considered to cause damage of briquettes incudes: moisture content of the material, particle size and pressure exerted on the biomass material, mass of the material, and initial bulk density of the biomass material.

Using [M], [L], [T] basic system dimension, the dimension of the variables and dimension matrix are presented in Table 3.4 and 3.5 respectively.

Table 3.4 Basic dimension of variables for damaged briquettes model

S/N	Variable	Symbol	Unit	Dimensional unit
1	Damaged Briquettes	D	kg/s	MT^{-1}
2	Initial bulk density	B_i	kg/m^3	ML^{-3}
3	Particle size	S	m	L
4	Pressure	P	$kg/m.s^2$	$ML^{-1}T^{-2}$
5	Weight of briquette	m_b	kg	M
6	Moisture content	M_c	%	dimensionless

$$D \propto f(B_i, S, P, m_b, M_c)$$

$$D = C_d f(B_i, S, P, m_b, M_c)$$

Total number of variables = 6

Number of fundamental dimensional units = 3

Number of dimensionless group = 6– 3 = 3

Therefore, there will be three π-term namely; π_1, π_2, π_3.

$$\pi_1 = C_d f(\pi_2 \times \pi_3)$$

where;

C_d = damaged briquette constant

π_1 = P_i term to be determine

Since moisture content is a dimensionless unit, π_2 is expressed as dimensionless unit of moisture content in eqn. 3.29.

$$\pi_2 = M_c \quad 3.29$$

Table 3.5 Dimensional matrix of variables for damaged briquette model

Dimensional Unit	**Variables**				
	D	m_b	P	$B\iota$	S
	a	B	c	d	e
M	1	1	1	1	0
L	0	0	-1	-3	1
T	-1	0	-2	0	0

The π-term can be determined by considering the corresponding dimensional expression in equation 3.30, 3.31, 3.32, and 3.33.

$$[MT^{-1}]^a [M]^b [ML^{-1}T^{-2}]^c [ML^{-3}]^d [L]^e \quad 3.30$$

M: a + b + c+ d= 0 3.31

L: -c -3d + e = 0 3.32

T: -a - 2c = 0 3.33

Assume arbitrary values of a =1, e=0

From eqn. 3.33, d = 0, therefore substituting into eqn. 3.31 and 3.32

c = - ½ , d = 1/6, b = -2/3, a = 1

Substituting into eqn. 3.30, to obtain π_1 in eqn. 3.34.

$$[MT^{-1}]^1[M]^{-2/3}[ML^{-1}T^{-2}]^{-1/2}[ML^{-3}]^{1/6} = \frac{D(B_i)^{1/6}}{m_b^{2/3}p^{1/2}} = \pi_1 \qquad 3.34$$

To obtain π_3

Assume arbitrary values of a = 0, e = 1,

Solving eqns. 3.31, 3.32, 3.33;

a = 0, b = - 1/3, c = 0, d = 1/3, e = 1.

Substituting into eqn. 3.30, to obtain π_3 in eqn. 3.35.

$$[MT^{-1}]^0[M]^{-1/3}[ML^{-1}T^{-2}]^0[ML^{-3}]^{1/3}[L]^1 = \frac{S(B_i)^{1/3}}{m_b^{1/3}} = \pi_3 \qquad 3.35$$

Since,

$\pi_1 = C_d f(\pi_2, \pi_3)$

Combining π_2, π_3 to form π_4 (refer to section 3.2.3),

Let $\pi_4 = [\pi_2 \times \pi_3]$

The required relationship is therefore obtained by combining the π-terms in eqn. 3.29, 3.34 and 3.35 to obtain eqn. 3.36.

$$\frac{D(B_i)^{1/6}}{m_b^{2/3}p^{1/2}} = C_d\left[\left(M_c \times \frac{S(B_i)^{1/3}}{m_b^{1/3}}\right)\right] \qquad 3.36$$

However, from the preliminary experiment conducted in section 3.2.3, damaged briquettes is related to pressure in exponential form as given in eqn. 3.37.

$$D = C_d\left(M_c S m_b^{1/3} B_i^{1/6}\right)e^{p^{1/2}} \qquad 3.37$$

Production efficiency model

Production efficiency of the machine is given as the ratio of mass of undamaged briquettes produced to the total mass of briquettes produced and this was calculated using eqn. 3.38.

$$\eta_m = \frac{T_c - D}{T_c} \qquad 3.38$$

η_m = Machine efficiency

T_c = output capacity of the machine (kg/s)

D = quantity of damaged briquette (kg/s)

Substituting eqn. 3.28 and 3.37 into eqn. 3.38, the production efficiency model is given in eqn. 3.39.

$$\eta_m = \quad 1 - \frac{C_d S M_c m_b^{1/3} B_i^{1/6} P e^{P^{1/2}}}{C_p (v_c^2 B_i f)} \qquad 3.39$$

Briquette bulk density model

The independent variables that affect briquette bulk density are pressure, particle size, compression speed, particle size, compression speed, initial bulk density, area of pressing die and area of crucible.

Using [M], [L], [T] basic system dimension, the dimension of the variables and dimension matrix are presented in Table 3.6 and 3.7 respectively.

Table 3.6 Basic dimension of variables for bulk density model

S/N	Variable	Symbol	Unit	Dimensional Unit
1	Briquette bulk density	B_k	kg/m^3	ML^{-3}
2	Pressure	P	kg/ms^2	$ML^{-L}T^{-2}$
3	Initial bulk density	B_i	kg/m^3	ML^{-3}
4	Particle size	S	m	L
5	Compression speed	V_c	m/s	$L^{-}T^{-1}$
6	Area of pressing die	A_p	m^2	L^2
7	Area of crucible	A_c	m^2	L^2

$B_k \propto f(P, B_i, S, V_c, A_p, A_c)$

$B_k = C_b f(P, B_i, S, V_c, A_p, A_c)$

Total number of variables = 7

Number of fundamental dimensional units = 3

Number of dimensionless group = 7– 3 = 4

Therefore, there will be four π-terms namely $\pi_1 \pi_2 \pi_3$ and π_4

$\pi_1 = C_k f(\pi_2, \pi_3, \pi_4)$

Where;

C_k =bulk density constant

$\pi_1 \pi_2 \pi_3 \pi_4 = P_i$ terms to be determine

Table 3.7 Dimensional matrix of variables for bulk density model

Dimensional unit	Variables						
	B_k	**P**	***B_i***	**S**	**V_c**	**A_p**	**A_c**
	a	b	c	d	e	f	G
M	1	1	1	0	0	0	0
L	3	-1	-3	1	1	2	2
T	0	-2	0	0	-1	0	0

The π-terms can be determined by considering the corresponding dimensional expression in the equation 3.40, 3.41, 3.42 and 3.43.

$$[ML^{-3}]^a[ML^{-1}T^{-2}]^b[ML^{-3}]^c[L]^d[LT^{-1}]^e[L^2]^f[L^2]^g \quad 3.40$$

M: a + b + c = 0 3.41

L: -3a - b – 3c + d + e + 2f + 2g = 0 3.42

T: -2b-e = 0 3.43

Assume arbitrary values of a =1, e = 0, f = 0, g = 0

From eqn. 3.41, 3.42.and 3.43,

b = -1- c

e = 0, b = 0, c = -1 and d = 0

Substituting into eqn. 3.40

$$[ML^{-3}]^1[ML^{-1}T^{-2}]^0[ML^{-3}]^{-1}[L]^0[LT^{-1}]^0[L^2]^0[L^2]^0 = \pi_1$$

π_1 is obtained as given in eqn. 3.44

$$\frac{B_k}{B_i} = \pi_1 \qquad 3.44$$

To obtain π_2

Assume arbitrary values of a = 0, e = 1, f = 0, g = 0

Solving eqns. 3.39, 3.40 and 3.41;

a = 0, b = - ½, c = ½, d = 0, e = 1, f = 0, g = 0

Substituting into eqn. 3.40

$$[ML^{-3}]^0[ML^{-1}T^{-2}]^{-\frac{1}{2}}[ML^{-3}]^{\frac{1}{2}}[L]^0[LT^{-1}]^1[L^2]^0[L^2]^0 = \pi_2$$

π_2 is obtained as given in eqn. 3.45

$$\frac{B_i^{1/2} V_c}{P^{1/2}} = \pi_2 \qquad 3.45$$

To obtain π_3

Assume arbitrary values of a = 0, e = 0, f = 1, g = 0

Solving eqn. 3.41, 3.42 and 3.43,

a = 0, b = 0, c = 0, d = -2, e = 0, f = 1, g = 0

Substituting into eqn. 3.40

$$[ML^{-3}]^0[ML^{-1}T^{-2}]^0[ML^{-3}]^c[L]^{-2}[LT^{-1}]^0[L^2]^1[L^2]^0 = \pi_3$$

π_3 is obtained as given in eqn. 3.46

$$\frac{A_p}{S^2} = \pi_3 \qquad 3.46$$

To obtain π_4

Assume arbitrary values of a = 0, e = 0, f = 0, g = 1

Solving eqns. 3.41, 3.42, 3.43,

a = 0, b = 0, c = 0, d = -2, e = 0, f = 0, g = 1

Substituting into eqn. 3.40

$[\mathrm{ML}^{-3}]^0[M\mathrm{L}^{-1}\mathrm{T}^{-2}]^0[\mathrm{ML}^{-3}]^c[\mathrm{L}]^{-2}[\mathrm{LT}^{-1}]^0[L^2]^0[\mathrm{L}^2]^1 = \pi_4$

π_4 is obtained as given in eqn. 3.47

$$\frac{A_c}{S^2} = \pi_4 \qquad 3.47$$

Combining the π-terms in eqn. 3.44, 3.45, 3.46 and 3.47,

$$\pi_1 = C_k(\pi_2, \pi_3, \pi_4)$$

Combining π_2, π_3, π_4, to form π_5(eqn. 3.48) (refer to section 3.2.3),

$$\pi_5 = \frac{\pi_3 \times \pi_4}{\pi_2} \qquad 3.48$$

Such that

$$\pi_1 = C_k(\pi_5)$$

Therefore, the relationship is given in eqn. 3.49.

$$\frac{B_k}{B_i} = C_k\left[\frac{P^{1/2}}{B_i^{1/2}V_c} \times \left(\frac{S^2}{A_p} \times \frac{S^2}{A_c}\right)\right] \qquad 3.49$$

Therefore, bulk density model is predicted using eqn. 3.50.

$$B_k = C_k\left[\frac{P^{1/2}}{B_i^{3/2}}\left(\frac{S^4}{V_c A_p A_c}\right)\right] \qquad 3.50$$

3.2.3 Preliminary experiment for Pi-term combination and coefficient determination

As at the time of this research, there has not been in any published data on performance parameters and model coefficients of briquetting press thus, preliminary experiments were conducted on biomass materials to evaluate the effect of the independent variables on the performance parameters thereby determine the combination pi-terms in the model equations. The preliminary experiments were also used to estimate the coefficients for the models.

Output capacity model

This analysis was conducted using Mahogany sawdust to produce briquettes at randomly selected pressures, initial bulk densities. From the experimental data (Table 3.8), it is deduced that the π terms in the output model are combined as presented in eqn. 3.51.

$$\pi_5 = \frac{\pi_2 \times \pi_3}{\pi_4}. \qquad 3.51$$

The output capacity constant, C_p was determined by linearizing eqn. 3.27 using method of least squares. Plotting the data in Table 3.7, the line of best fit was drawn as shown in Fig. 3.1 and the slope of the line gives the value of the output constant (C_p) which was found to be 1.03. The R^2 value obtained was 0.9932. The linear regression ANOVA in Appendix A also show that the intercept was significant at 5%.

Table 3.8 Data used to determine output capacity constant C_p

T_c (Kg/s)	V_c (m/s)	B_i (kg/m^3)	F (kg/s)	E_r (kg/s)	P (bar)	π_1	π_5
0.15	0.016	200	52	0.025	18	6.0	6.0
0.19	0.016	220	52	0.021	20	7.0	6.9
0.14	0.016	240	52	0.034	22	4.1	4.3
0.17	0.016	260	52	0.033	20	5.0	5.2
0.20	0.016	280	52	0.020	18	10	10.4
0.18	0.016	300	52	0.027	22	6.7	6.7

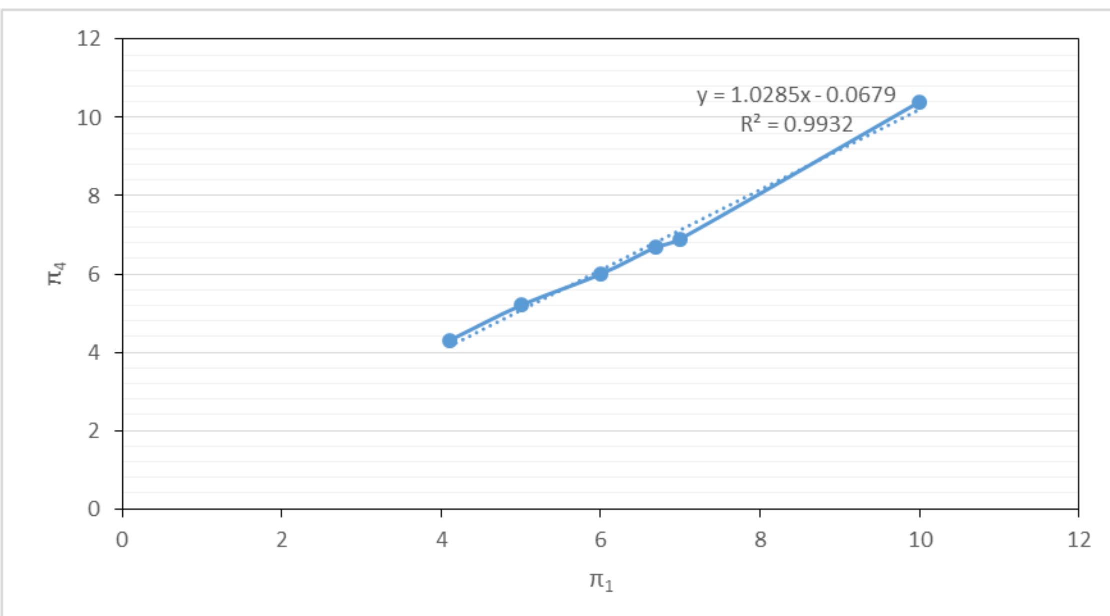

Fig. 3.1 Determination of output capacity coefficient

Damaged briquettes model

Oil bean wood sawdust was used for the analysis. Three particle sizes of the saw dust was used to produce briquettes at randomly selected pressure, bulk densities and moisture content. From the experimental data, it is deduced that the π terms in the damaged briquettes model are combined as presented in eqn. 3.52.

$$\pi_4 = \pi_2 \times \pi_3 \qquad 3.52$$

The damaged briquettes constant, C_d was determined by quadractic eqn. 3.36 using method of least squares. Plotting the data in Table 3.9, the line of best fit was drawn as shown in Fig. 3.2 and the slope of the line gives the value of the damaged briquette constant (C_d) which was found to be 0.32. R^2 value obtained was 0.57. The polynomial regression ANOVA in Appendix A also show that the intercept was significant at 5%.

Table 3.9 Data used to determine damaged briquette constant (C_d)

D(Kg/s)	P	B_i (kg/m^3)	M_b (kg)	M_c (%)	S	π_1	a
0.025	22	330	33	12	160x10^{-6}	0.000512	0.000606
0.017	18	310	31	12	315 x10^{-6}	0.000402	0.001217
0.025	22	300	30	8	425 x10^{-6}	0.000546	0.001107
0.033	20	300	30	10	425 x10^{-6}	0.000756	0.001383
0.083	18	220	22	7	160 x10^{-6}	0.002469	0.000404

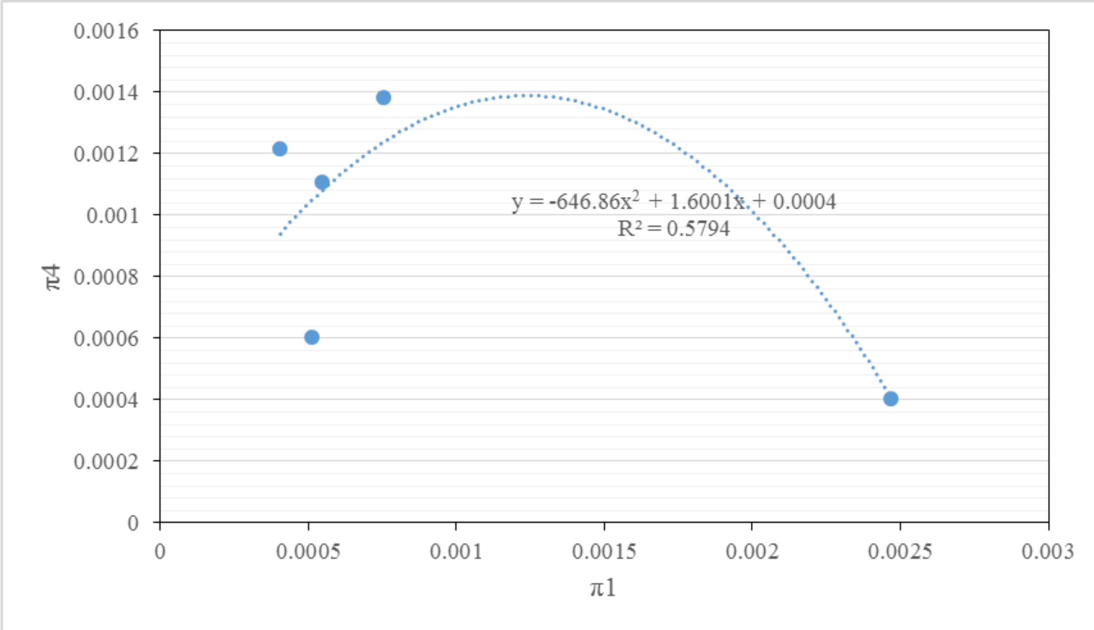

Fig. 3.2 Determination of damaged briquette coefficient

Bulk density model

Five materials namely stood wood, Gmelina, Mahogany, Oil bean sawdust and rice husk were used for this experimentation. Initial bulk densities of the materials were determined.

From the experimental data, it is deduced that the π terms in the bulk density model are combined as given in eqn. 3.53.

$$\pi_5 = \frac{\pi_3 \times \pi_4}{\pi_2} \qquad 3.53$$

The bulk density constant, (C_k) was determined at different particle sizes namely, 160µm, 315 µm, 425µm, 630µm and 1250µm by linearizing eqn. 3.49 using method of least squares. Plotting the data in Table 3.10 - 3.14, the line of best fit was drawn as shown in Fig. 3.3, 3.4, 3.5, 3.6. 3.7. The slope of the line gives the value of the bulk density constant (C_k) for each particle size. Bulk density constant for 160µm, 315µm, 425µm, 630µm and 1250µm are 1.62×10^{10}, 8.75×10^{8}, 2.53×10^{8}, 4.04×10^{7} and 2.28×10^{6} respectively. The linear regression ANOVA in Appendix A also show that the intercept was significant at 5%.

Table 3.10 Data used to determine bulk density constant at 160um for all biomass waste

160µm								
B_k (Kg/m^3)	V_c (m/s)	B_i (kg/m^3)	S (µm)	A_p (m^2)	A_c (m)	P (bar)	π_1	π_5
588	0.016	100	160	0.188	0.793	18	5.8	3.68×10^{11}
631	0.016	110	160	0.188	0.793	20	5.74	3.70×10^{11}
623	0.016	150	160	0.188	0.793	18	4.15	3.4×10^{11}
767	0.016	170	160	0.188	0.793	22	4.51	3.47×10^{11}
774	0.016	170	160	0.188	0.793	22	4.3	3.45×10^{11}

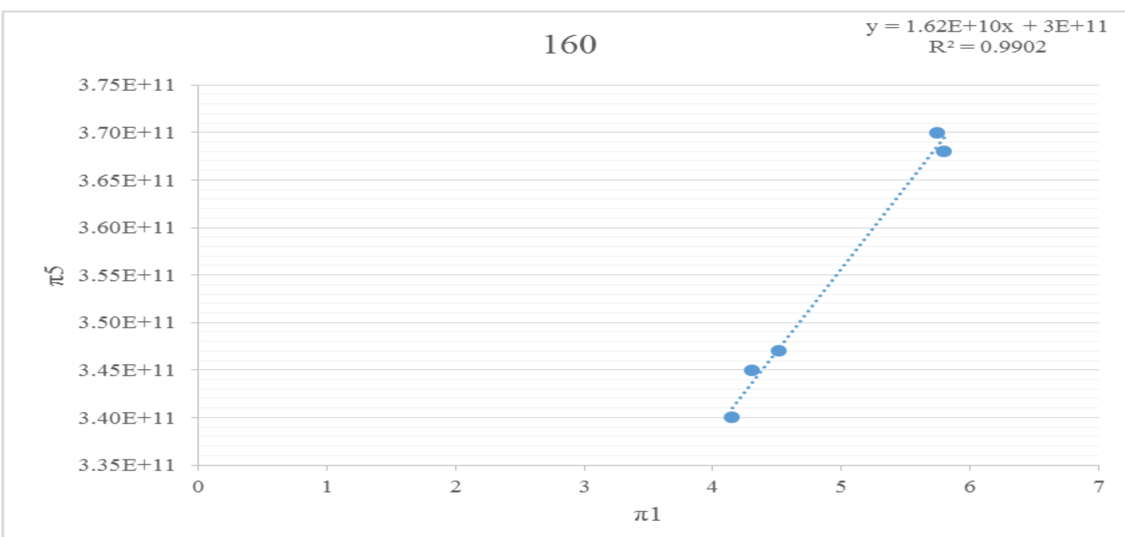

Fig. 3.3 Determination of bulk density coefficient for 160µm

Table 3.11 Data used to determine bulk density constant at 315um for all biomass waste

315µm								
B_k (Kg/m^3)	V_c (m/s)	B_i (kg/m^3)	S (µm)	A_p (m^2)	A_c (m)	P (bar)	π_1	π_5
490	0.016	100	315	0.188	0.793	18	4.45	$5.27\text{x}10^9$
590	0.016	90	315	0.188	0.793	20	6.56	$7.15\ \text{x}10^9$
600	0.016	140	315	0.188	0.793	18	4.29	$5.13\ \text{x}10^9$
830	0.016	150	315	0.188	0.793	22	5.53	$6.22\ \text{x}10^9$
910	0.016	170	315	0.188	0.793	22	5.35	$4.06\ \text{x}10^9$

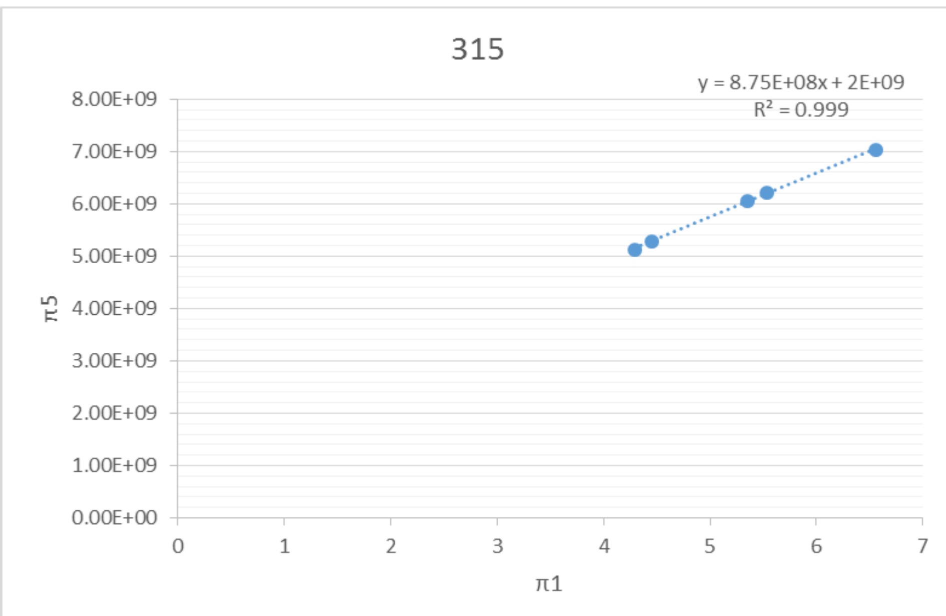

Fig. 3.4 Determination of bulk density constant for 315µm

Table 3.12 Data used to determine density constant at 425um for all biomass waste

425µm								
B_k (Kg/m³)	**V_c (m/s)**	**B_i (kg/m³)**	**S (µm)**	**A_p (m²)**	**A_c (m)**	**P (bar)**	**π_1**	**π_5**
510	0.016	100	425	0.188	0.793	18	5.1	1.83×10^9
580	0.016	90	425	0.188	0.793	20	6.44	2.03×10^9
540	0.016	140	425	0.188	0.793	18	3.86	1.55×10^9
740	0.016	150	425	0.188	0.793	22	4.93	1.79×10^9
810	0.016	170	425	0.188	0.793	22	4.76	1.74×10^9

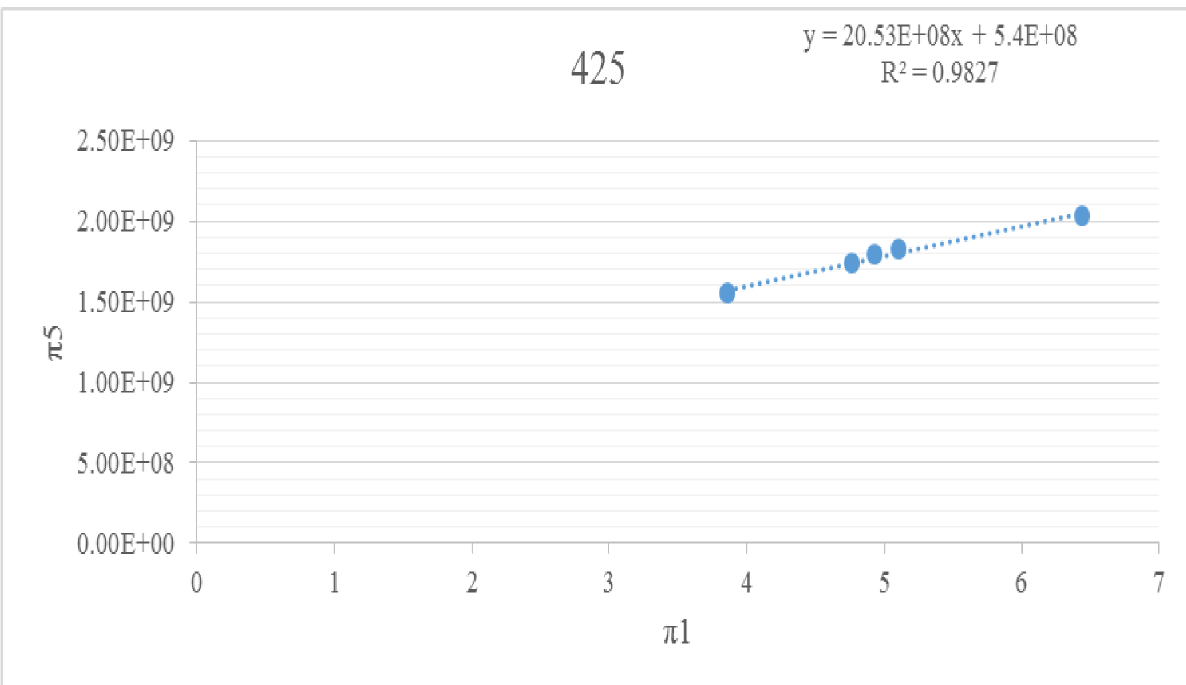

Fig. 3.5 Determination of bulk density coefficient for 425µm

Table 3.13 Data used to determine density constant at 630um for all biomass waste

630µm								
B_k (Kg/m^3)	V_c (m/s)	B_i (kg/m^3)	S (µm)	A_p (m^2)	A_c (m)	P (bar)	π_1	π_5
387	0.016	110	630	0.188	0.793	18	3.52	8.45×10^8
395	0.016	70	630	0.188	0.793	20	5.64	9.29×10^8
473	0.016	80	630	0.188	0.793	18	5.91	9.4×10^8
800	0.016	140	630	0.188	0.793	22	5.71	9.32×10^8
727	0.016	170	630	0.188	0.793	22	4.28	8.74×10^8

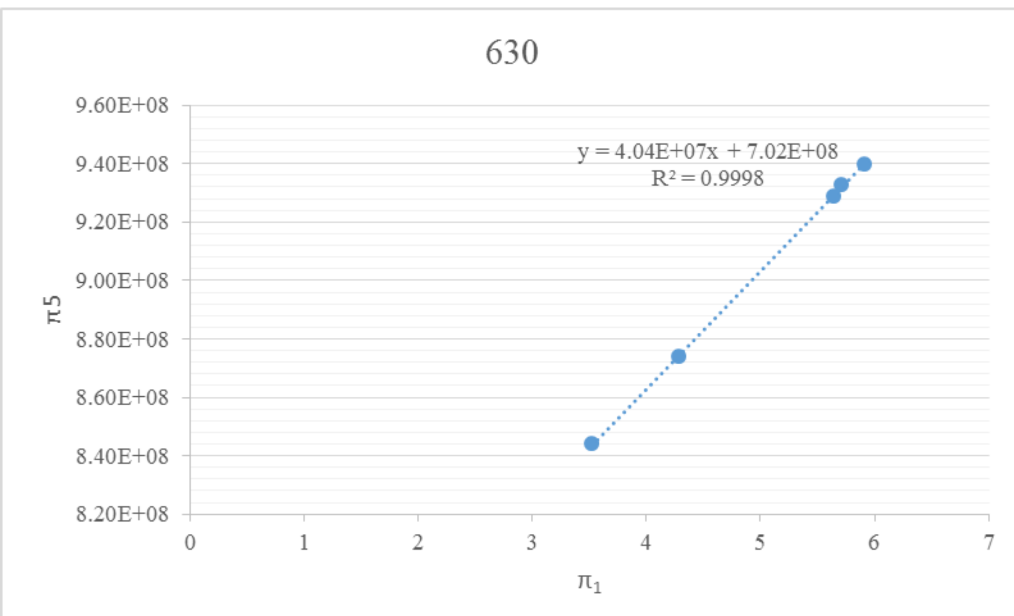

Fig. 3.6 Determination of bulk density coefficient for 630µm

Table 3.14 Data used to determine density constant at 1250um for all biomass waste

1250µm								
B_k (Kg/m^3)	V_c (m/s)	B_i (kg/m^3)	S (µm)	A_p (m^2)	A_c (m)	P (bar)	π_1	π_5
366	0.016	120	1250	0.188	0.793	18	3.05	1.25x10^7
469	0.016	80	1250	0.188	0.793	20	5.86	1.88 x10^7
438	0.016	70	1250	0.188	0.793	18	6.26	1.97 x10^7
779	0.016	140	1250	0.188	0.793	22	5.56	1.8 x10^7
497	0.016	170	1250	0.188	0.793	22	2.92	1.16 x10^7

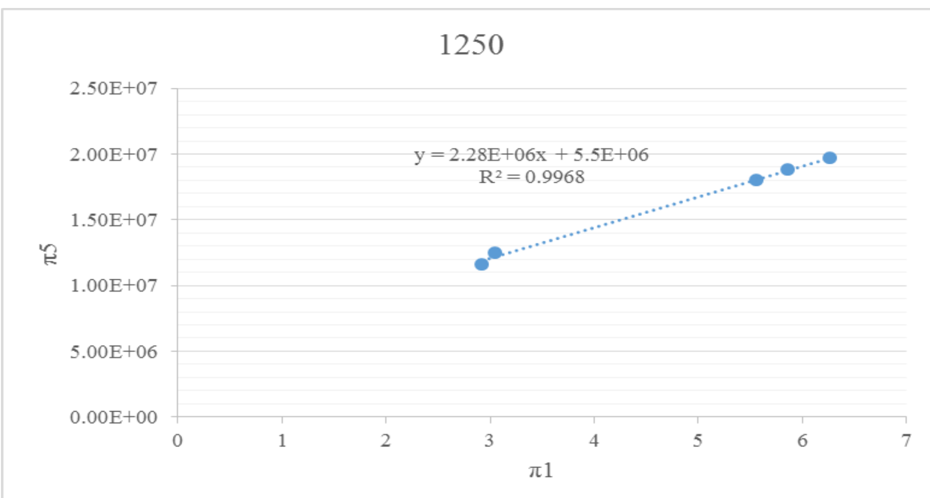

Fig. 3.7 Determination of bulk density coefficient for 1250µm

3.2.4 Model boundary conditions

Boundary condition is an important element in model development effective in controlling when and where the mathematical equations can be utilized. As a result of the analysis of various boundary conditions for briquette production in the literatures reviewed, it is important to state conditions for optimal utilization of the mathematical models for predicting the performance of the hydraulic briquetting machine. From the literatures reviewed, performance of hydraulic press for briquetting biomass waste is largely dependent on pressure (Ndiema *et al.*, 2002; Ndiema *et al.*, 2002 and Demirbas *et al.* (2004), moisture content (Li and Liu, 2000; Mani *et al.*, 2006; Theerarattananoon *et al.*, 2011 and Thomas *et al.*, 1997) and particle size Mani *et al.* 2003 and Arzola *et al.* (2012). Mean of these conditions were used in the preliminary analysis found to be responsible for the performance of the briquetting machine as well as the quality of the briquettes produced. Boundary conditions for the mathematical equation are stated as follows;

Pressure (P_r)

$0 \leq P \leq 50\ bar$

Moisture content (Mc)

$7 \leq Mc \leq 12\ \%$

Particle size (P_s)

$160 \leq Ps \leq 1250\ \mu m$

3.3 Experimental Design and Statistical Analysis

Three experimental designs were developed in the course of this research namely; model validation, physical properties of the briquettes and briquette quality optimization.

3.3.1 Model validation

The developed models in eqn. 3.28, 3.37, 3.39 and 3.50 were validated for predicting the performance of hydraulic briquetting press for output capacity, quantity of damaged briquettes, production efficiency and bulk density respectively. Each of these performance parameters were validated using variables that has most significant effect on the performance parameter.

Measured data obtained from experimentation from the developed briquetting machine was used to validate the performance models by plotting the graph of measured against the predicted data for all the models and the goodness of fit and coefficient of correlation (R^2) was used to measure how well the predicted values correlated with the measured values. The experimental design for the model validation was based on the mathematical models that were verified. Model validation experimentation was designed using randomized complete block design (RCBD). From the experimental design for output capacity, quantity of damaged briquettes and production efficiency models, a total of 66 briquettes were produced from three biomass materials at two replicates. Production efficiency was determined from experimental design of output capacity and quantity of damaged briquette. Experimental data for the model validation were measured as follows.

Output capacity

The output capacity of the machine was determined by using 315µm Mahogany sawdust at bulk densities of 370kg/m^3. These samples were weighed after sample preparation and three briquettes were produced from the hydraulic press at 16bar, 18bar, 20bar, 22bar and 24bar. Mean unit mass of the briquettes was recorded as 25kg per briquette. Total time from sample preparation to producing the briquettes were recorded. This experiment were replicated twice. Output capacity of the press was calculated using eqn. 3.54.

$$\text{Output}(kg/s)=\frac{\text{mass of briquette}}{\text{time of production}} \qquad 3.54$$

Damaged briquettes

The quantity of damaged briquettes were determined by visual inspection considering presence of cracks, texture and irregularity in shape. The model calculated the number of damaged briquette in kilogram per hour, the value obtained was divided by the unit mass of briquette in order to calculate the number of damaged briquette per hour.

Production efficiency

Production efficiency of the machine was calculated by producing a total of 30 per hour and determining the number briquettes that were damaged during the process. Due to the fact that performance of hydraulic press is dependent on pressure developed in the system, briquettes were produced at varying pressures and increase pressure signifies higher bulk density which in turn increases the production efficiency of the machine. Eqn. 3.55 was used to calculate the production efficiency of the briquetting press.

$$PE(\%) = \frac{\text{average mass of unbroken briquette}}{\text{average mass of briquette produced}} \times 100 \qquad 3.55$$

Bulk density

Bulk density model was validated using Stool wood, Gmelina, Mahogany, Oil bean sawdust and Rice husk at five particle sizes. Bulk density of the briquettes were verified using eqn. 3.70. Mass of the briquettes were determined using a weighing balance while volume of the cylindrical briquettes were calculated by measuring the height (h) of the briquettes using Vanier caliper. Internal diameter of the crucible (50mm) was used as diameter of the briquettes (d). Briquette height and diameter were substituted into eqn. 3.56 to obtain the briquette volume.

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} \qquad 3.56$$

3.3.2 Briquette physical properties

Experiment design for briquettes physical properties done using randomized complete block design (RCBD) and significant of the process variables were performed using analysis of variance (ANOVA). The design is presented in Appendix B. A total of 150 briquette samples were produced at factor treatment levels of 5x5x3x2 for five biomass material, five particle sizes, three pressures and two replications respectively. The dependent factors that were studied were height, bulk density and compression ratios of the biomass briquettes. The five particle sizes studied were 1250μm, 630μm, 425μm, 315μm, 160μm were obtained from each of the five biomass materials. Three pressures namely, 18bar, 20bar and 22bar were used to be produce briquettes from all the materials samples and the experiment was replicated twice. The data obtained in the analysis was analyzed using analysis of variance (ANOVA) and Fisher's–least significant difference (F-LSD) for prediction of difference between treatment means for any significant effect of the treatment means.

However, for bulk density model experimental design, five materials were utilized because of the high effect of biomass materials on the bulk density of briquettes. A total of 150 briquettes were produced for the bulk density model validation.

3.3.3 Briquette quality optimization

Mambo (2016) method of briquette quality optimization used was adopted. The optimization was performed using linear multiple regression model. Three independent variables (compaction pressure, binder and particle size) were optimized for high quality briquettes. The aim of the optimization process was to obtain briquettes of high heating value and environmentally sustainable. The briquettes should also be hard enough to withstand transportation and this is justified by the density of the briquettes. The dependent variables (ash content, volatile matter, fixed carbon, calorific value and density) were utilized in the optimization process.

R-statistical software (IBM SPSS statistics 20) was used for data analysis and the design is presented in Appendix C. Since two of the independent variables (compaction pressure and binder ratio) and all dependent variables (calorific value, volatile matter content, fixed carbon content, ash content, and density) are continuous, multiple linear regression models were chosen to investigate the impact of compaction pressure, binder ratio and particle size on each of the dependent variables thus the optimal values were obtained. Compaction pressure, binder and particle size were combined at treatment combination of 3x3x4 to produce a total of 360 briquettes for rice husk and oil bean sawdust. Optimization formulation is stated as follows;

i. An objective function stating the quality of briquette to be minimized or maximized and its functional dependence on the process variables.

ii. The constraints on the design variables under which an optimum is to be obtained.

Optimization formulation is represented in eqn. 3.57 and each of the objective function is presented in eqn. 3.58-62.

$$Maximize\ (Y) = f\,(Y_1, Y_2, \ldots, Y_5) \quad 3.57$$

The objective functions are as follows;

$$\text{minimize}\ (Y_1) = f(X, X_2, X_3) \quad 3.58$$

$$\text{minimize}\ (Y_2) = f(X, X_2, X_3) \quad 3.59$$

$$\text{maximize}\ (Y_3) = f(X, X_2, X_3) \quad 3.60$$

$$\text{maximize}\ (Y_4) = f(X, X_2, X_3) \quad 3.61$$

$$\text{maximize}\ (Y_5) = f(X, X_2, X_3) \quad 3.62$$

Eqn. 3.58 is subject to constraints as presented in eqn. 3.63.

$$a_o \leq X_n \leq b_o \qquad 3.63$$

Where;

Y =Briquette quality

Y_1= ash content

Y_2= Volatile matter

Y_3= fixed carbon

Y_4= calorific value

Y_5= density

f = relationship function

X_1 = particle size

X_2 = compaction pressure

X_3= binder ratio

a_o and b_o = lower and upper boundary respectively, while the lower and upper limits of the process variables which are incorporated as constrains for materials used are as follows;

$18 \leq P_r \leq 22$ (bar)

$160 \leq P_s \leq 425$ (μm)

$6 \leq h \leq 12$ (%)

3.4 Experimental Procedures

3.4.1 Procedure for material characterization

1. Nitrogen/Crude Protein Determination

The micro-Kjedahl method as described in Pearson (1976) was used. This method involves the estimation of the total nitrogen in the waste and the conversion of the nitrogen to protein with the assumption that all the protein in the waste is present as nitrogen. Using a conversion factor of 6.25, the actual percentage of protein in the waste was calculated as follows;

% crude protein = % Nitrogen x 6.25.

Digestion

Apparatus used: Micro-Kjedahl digestion flask (500ml capacity) (Make: Barloworld U.K, model Fk 500/3l), Ohaus weighing balance (0.001g accuracy, model AR3130, Made in England).

Reagents used: Catalyst mixture (Mixture of 20g potassium sulphate, 1g copper sulphate and 0.1g selenium powder), concentrated tetraoxosulphate (vi) acid.

Procedure

One gram of the ground sample was weighed into the Kjedahl digestion flask. One gram of the catalyst mixture was weighed and added into the flask. 15 ml of conc. H_2SO_4 was also added. Heating was carried out cautiously on a digestion rack in a fume cupboard until a greenish clear solution appeared. The digest was allowed to clear for about 30 minutes. It was further heated for more 30 minutes and allowed to cool. 10 ml of distilled water was added to avoid caking. Then the digest was transferred with several washings into a 100 ml volumetric flask and made up to the mark with distilled water.

Distillation

Apparatus used: micro Kjedahl distillation unit (Make: Barloworld, UK model 734205) 100 ml conical flask. (Receiver flask)

Reagents used: 40% NaOH, Boric acid indicator solution

Procedure

A 10ml aliquout was collected from the digest and put in the flask. A 100ml receiver flask containing 5ml boric acid indicator solution was placed under the condenser of the distillation apparatus so that the tip was 2cm inside the indicator. 10ml of 40% NaOH solution was added to the digested sample through a funnel stop cork. The distillation commenced by closing the steam jet arm of the distillation apparatus. The distillate was collected in the receiver flask (35ml).

Titration

Titration was carried out with 0.01M standard HCl to first pink colour of the material. The percentage Nitrogen was calculated using eqn. 3.63.

$$\%Nitrogen = \frac{Titration\ volume \times 0.014 \times M \times D}{weight\ of\ sample} \times 100 \qquad 3.63$$

$$D = \frac{100}{10}$$

Where;

M= molarity of std HCl

D = dilution factor

% crude protein =% N x 6.25

Equation of the Reaction

N in waste + conc. $H_2SO_4 \longrightarrow (NH_4)_2SO_4$

$(NH_4)_2SO4 + 2NaOH \rightarrow Na_2SO_4 + 2H_2O + 2NH_3$

The ammonia generated was collected in excess boric acid.

$NH_3 + H_3BO_3 \rightarrow NH_4BO_2 + H_20$

After complete ammonia distillation, the ammonium borate solution is titrated with a standard HCl solution. Strong acid (HCl) displaces weak boric acid from its salt.

$NH_4BO_2 + HCl \rightarrow NH_4Cl + HBO_2$

One mole of ammonia is equivalent to 1 mole of ammonium borate which is equivalent to 1 mole of HCl.

Knowing the amount of 0.01 M HCl used for the titration, the amount of ammonia bound to borate can be calculated. From this amount, the quantity of nitrogen in the sample was calculated.

2. Determination of Moisture Content

The A.O.A.C method (1990) was used. Porcelain crucibles were washed and dried in an oven at 100^{o}C for 30 minutes and allowed to cool in a desiccator. One gram of the sample was placed into weighed crucibles and then put inside the oven set at 105^oC for 4 hours. The samples were removed from the oven after this period and then cooled and weighed. The drying was continued and all the samples with the crucibles weighed until a constant weight was obtained. Percentage moisture content of the material was calculated using eqn. 3.64.

$$\% \text{ moisture (wb)} = \frac{A-B}{A}\times 100 \qquad 3.64$$

Where;

A = original weight of sample
B = weight of dried sample

3. Ash Content Determination

The residue remaining after all the moisture have been removed and the fats, proteins, carbohydrates, vitamins and organic acids burnt away by ignition at about 600^{o}C is called ash. It is usually taken as a measure of the mineral content of the raw waste.

Using AOAC (1990) method, 1g of the finely ground samples were weighed into porcelain crucibles which have been washed, dried in an oven at 100^{o}C, cooled in a desiccator and weighed. They were then placed inside a muffle furnace and heated at 600^{o}C for 4 hours. After this, they were removed and cooled in a desiccator and then weighed. Percentage ash was calculated using eqn. 3.65.

$$\% \text{ Ash} = \frac{A-B}{C}\times 100 \qquad 3.65$$

Where;

A = weight of crucible + ash
B = weight of crucible

C = weight of original sample

4. **Determination of Volatile Matter**

The dried residue was heated in a muffle furnace at 600^{o}C for two hours. The heated residue was cooled in a desiccator and weighed. The volatile solid was calculated using eqn. 3.66.

$$\text{Volatile solid (VS)} = \frac{B-C}{g} \times 100 \qquad 3.66$$

Where;

B = Weight of dried residue

C = Weight of residue after further heating at 600^{o}C

g = Original weight of sample.

5. **Energy Content/Calorific value Determination**

A.O.A.C (1975) method was used. This was done with bomb calorimeter (model XRY-1A, make: Shanghai Changji, China). It involves igniting the waste sample in oxygen bomb calorimeter (under a high pressure of oxygen gas). The heat energy that was released was absorbed by the surrounding water inside the bomb calorimeter. This gave rise to a temperature increase of the surrounding water and this was used to estimate the energy value of the sample. 1g of the sample was pelleted and turned in the oxygen bomb calorimeter. The heat of combustion was calculated as the gross energy as given in eqn. 3.67.

Energy content = $\frac{E\Delta T - 2.3L - V}{g}$ (KJ/Kg) 3.67

Where;

E = energy equivalent of the calorimeter

ΔT = temperature rise

L = length of burnt wire

V = titration volume

g = weight of sample

6. Fixed Carbon

Percentage fixed carbon was calculated using eqn. 3.68.

% FC= 100-(% Moisture + % Volatile matter +% Ash) 3.68

7. Carbon Content Determination

Walkey and Black (1934) method was used for this analysis. 0.05g of the finely ground sample was weighed into a 500ml conical flask. 10ml of 1M potassium dichromate was poured inside the flask and the mixture was swirled. 20ml of conc. H_2SO_4 was added and the flask was swirled again for 1 minute in a fume cupboard. The mixture was allowed to cool for 30 minutes after which 200ml of distilled water; 1g NaF and 1ml of diphenylamine indicator were added. The mixture was shaken and titrated with ferrous ammonium sulphate. The blank was also treated in the same way. Percentage carbon content was calculated using eqn. 3.69.

% carbon = $\frac{B - T \times M \times 1.33 \times 0.003 \times 100}{g}$ 3.69

Where;

B = titration volume (Blank)

T = titration volume (Sample)

M = molarity of Fe solution

g = weight of sample

8. Specific gravity

Specific gravity measurement can be used for pure substances as an indication of total solids. The specific gravity helps determine the purity of a liquid. The specific gravity is dimensionless and density changes with temperature. (Balami*et al*, 2014). Specific gravity bottle method as described by Balami*et al*, 2004 was used for the determination. Materials used are specific gravity bottle, weighing balance (Ohaus, Model AR 3130. Readability: 0.001g. Range: 0-300g) and measuring cylinder

Procedure

A clean empty specific gravity bottle was weighed on an electronic balance and the weight (W_1) noted. It was then filled with the sample and weighed W_2). All the determinations were at 25^{o}C. The volume (V) of the specific gravity bottle was noted. Eqn. 3.70 was used to calculate the specific gravity.

$$S.G = \frac{W_2 - W_1}{V}$$ 3.70

9. Sulphur Content (Eschka Method)

One gram of the pulverized sample was mixed with 3 g of a mixture of magnesium oxide and anhydrous sodium carbonate in the ratio of 2:1. The mixture was heated to 400 ^{o}C for two hours in a muffle furnace. Cool and digest in water. Barium chloride was added to precipitate the sulphate as barium sulphate. The precipitate was then filtered and the amount of sulphur was determined using eqn. 3.71.

$$\%\ sulphur\ content = \frac{ppt(BaSO_4)\times 0.1373}{Weight\ of\ sample} \times 100 \qquad 3.71$$

10. Bulk density before briquetting

Materials used for the analysis are measuring cylinder, weighing balance (Ohaus, Model AR 3130. Readability: 0.001g. Range: 0-300g).

Procedure

A clean empty measuring cylinder was weighed on an electronic balance and the weight (W_1) noted. It was then filled with the sample, tapped on a wooden table for thirty times and the weight (W_2) noted. The volume of the sample after tapping was noted as *V*. All the determinations were at 25^{0}C and the bulk density of the material was calculated using eqn. 3.72.

$$BD = \frac{W_2 - W_1}{V} \qquad 3.72$$

3.4.2 **Procedure for briquette production**

The sample materials were subjected to size reduction process through the use of hammer mill at PRODA, Enugu, and were sieved (Plate 3.12) at Civil engineering laboratory, Enugu state university of science and technology (ESUT) to obtain five different particle sizes namely, 160µm, 315µm, 425µm, 630µm and 1250µm from each materials. Moisture content (wet basis) was determined using ASAE S269.4 (2003) standard. Moisture content of the materials were maintained within the acceptable moisture content of 7-15% for making briquettes (Erikkson and Prior, 1990; Jaan, *et al*. 2010).

Plate 3.12 Sieving process

The five materials were designated with A, B, C, D, and E for Stool wood sawdust, Gmelina sawdust, Mahogany sawdust, Oil bean sawdust and Rice husk respectively. Equal volume of $100cm^3$ of each sample was measure out and weighed in a digital weighing balance and the mass recorded (Appendix D). Each sample was tied together to the quantity of binder required for the briquette production (Plate 3.13).There were three divisions of sample preparations. These were production of briquettes for models validation, process optimization and statistical effect study on the physical properties of the briquettes.

Plate 3.13 Sample preparation for the four materials

The procedure for the briquette production for all the three sets of experiment were the similar else that there is variation pressure applied. There were also variation in physical characteristic of the materials and process variable during briquetting operation.

During the briquetting operation, each identified set sample material as shown in Plate 3.14 was prepared for briquetting operation by adding 25g of water to the measured starch tied to the sample and they were mixed thoroughly after which the sample material was added into the bowl containing binder (starch) mixture and the entire mixture were blended together. The blended material is fed into the steel cylindrical crucible (die) of dimension 82mm height and 50mm in diameter of the briquetting machine and positioned in the hydraulic briquetting press machine for compression. The piston was actuated to compress the samples and the pressure was monitored using the pressure gauge. After pressure was applied at a time to the material in the die, the briquette formed was extruded. The briquetting activities are shown in plate 3.13.

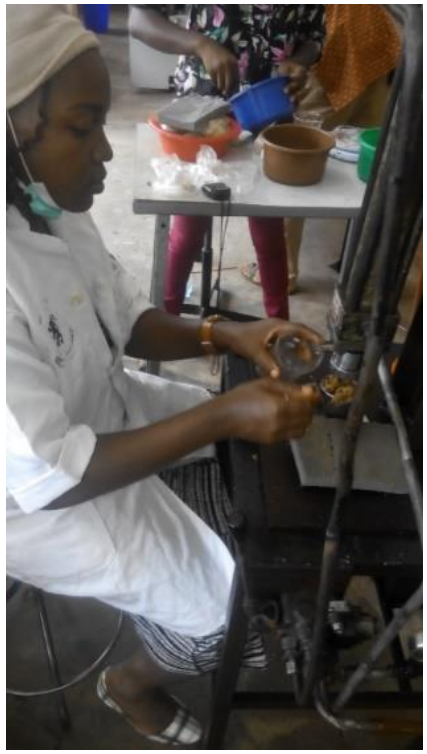

Plate 3.14 Briquetting activities

3.4.3 Procedure for Fourier transform infrared analysis

A Buck scientific M530 USA FTIR was used for the fourier transform infrared (FTIR) analysis. This instrument was equipped with a detector of deuterated triglycine sulphate and beam splitter of potassium bromide. The software of the Gram A1 was used to obtain the spectra and to manipulate them. An approximately of 1.0g of samples was properly placed on a salt pellet. During measurement, FTIR spectra was obtained at frequency regions of 4,000 – 600 cm-1 and co-added at 32 scans and at 4 cm-1 resolution. FTIR spectra were displayed as transmitter values.

3.5 Briquette Property Tests

3.5.1 Briquette physical characteristics

It was important to study process parameters and ascertain to the extent some of the input variables affect bulk density of biomass materials of different compositions. The target in briquetting operations is to have briquette of low height, high bulk density and high compression ratio as a result of the compression operation. Low briquette height entails high bulk density and compression ratio. Physical properties of the briquettes were studied at varying pressures and particle sizes for the five sawdust materials. The properties studied were height, bulk density and compression ratio and their effect on height, bulk density and compression ratio of briquettes were statistically analyzed.

Determination of bulk density of briquettes

The height, mass, diameters of the briquettes were determined. These measurements were used to compute the volume and density of each of the samples of briquettes produced for the various groups. The height and diameter of the briquettes were determined by direct measurement of the briquettes using the venier caliper. The volume of the briquettes were calculated using eqn. 3.73. The weights of briquettes were determined using digital weighing balance in the laboratory. Bulk density were calculated as the ratio between the weight and volume of the briquettes. Meanwhile, the ratio of the initial density before briquetting and briquette density was calculated and called the compression ratio (eqn. 3.74). Compression ratio describes the rigidity, hardness, and deformation capacity of the particles during the compression.

$$\text{Volume} = \frac{\pi d^2 h}{4} \qquad 3.73$$

$$\text{Compression ratio} = \frac{\text{Density of briquette after briqqeting}}{\text{Density before briquetting}} \qquad 3.74$$

3.5.2 Briquette quality test

A good quality briquette should produce sufficient amount of heat, burn without smoke to promote indoor air quality, and must be convenient for the user. The quality of a briquette can be measured from its calorific value, density, compressive strength, ash content, volatile matter content, ignition time, and burn time among others (Sastry et al., 2013). Calorific value of a fuel is the measure of its energy content (Ikelle and Joseph, 2014), and a high value is desirable (Sellin et al., 2013). Briquette density and compressive strength are influenced by material composition and the type of briquetting machine used (Križan et al., 2011). An increase in ash content increases the slagging behavior of biomass, hence the preference of low to high ash content (Akowuah, 2012). Much as the rise in volatile matter content improves ignition ability, it increases smoke during combustion (Pandey and Dhakal, 2013). Briquette intended for barbecue use should have volatile matter content less than 30% dry basis. Briquette basis , fixed carbon of greater than 60% dry basis, ash content less than 18% dry basis (Zagreb, 2008), and 10% - 18% moisture content on wet basis (Kers et al., 2010).

3.5.3 Fourier transform infrared spectroscopy analysis

Fourier transform infrared (FTIR) spectroscopy analysis was performed on optimized briquettes of rice husk and oil bean briquettes. An infrared spectrum characterizes a sample with absorption peaks which correspond to the frequencies of vibrations between the bonds of the atoms making up the material. Because each different material is a unique combination of atoms, no two compounds produce the exact same infrared spectrum. Therefore, infrared spectroscopy can result in a positive identification (qualitative analysis) of every different kind of functional groups that makes up the material. In addition, the size of the peaks in the spectrum is a direct indication of the amount of material present in a given sample.

In infrared spectroscopy, IR radiation is passed through a sample. Some of the infrared radiation is absorbed by the sample and some of it is passed through (transmitted). The resulting spectrum represents the molecular absorption and transmission, creating a molecular fingerprint of the sample. Like a fingerprint no two unique molecular structures produce the same infrared spectrum. This makes infrared spectroscopy useful since it will detect the functional groups of the briquettes produced from the two different materials.

3.6 Hydraulic Briquetting Machine for Model Validation

It was observed that the press available for the model validation was not suitable for producing briquettes at different pressure ranges as is required from the developed models thus, the machine was modified by fitting in pressure gauge into the system. It was also suspected that the existing one have the tendency for failure in future as the result of the tensile and bending stress from the cylinder. The machine was however refabricated to improve on the existing one. This is to ensure that there is no failure resulting from insufficient stiffness and buckling of the machine. The frame and cylinder hanger depended on the pressing force while the pressing force determined the required rigidity and the dimension of the die for briquetting. The frame being the base machine element in hydraulic press has the major function of withstanding the force developed by the hydraulic cylinder (Parthiban et al., 2014). The weight of the cylinder and its load are the major forces acting on the frame structure.

3.6.1 Frame and cylinder

The selection of materials considered the pressure range required for the operation of the machine, mounting style of the hydraulic cylinder and the environmental conditions. The refabricated hydraulic press has the highest possible specific structural stiffness within the allocated design time in other to ensure stability during operation. Since the machine is required for a compaction process, a straight line mount hydraulic cylinder for linear motion was considered and the hydraulic cylinder that produces greater force for extending than when retracting was required so a flange mounted double acting cylinder was considered appropriate for the operation. This is in accordance with the existing standard designs. Mild steel (IS2062) was considered for the frame because it is soft and ductile and can be welded easily and machined. Mild steel was considered for others for corrosion resistance from water and other fluid.

3.6.2 Calculations for selections of components

Selection of the hydraulic cylinder and pump motor size are the integral parts of the machine development.

Hydraulic cylinder size selection

The hydraulic cylinder is a tubular structure in which a piston slides when hydraulic fluid is admitted into it. There are standard cylinders that have been designed to meet the wide range of applications for designers and these hydraulic cylinders are selected based on certain factors such as operating pressures of the system, force needed by the cylinder to extend (forward force), force needed by the cylinder to retract (return force) and volumetric flow rate of the hydraulic fluid needed by the cylinder to move forward or retract (Gatmaitan *et al.*, 2012). It is expected that the cylinder will produce an average pressure of 2.5MN/m^2 (25bar) and minimum diameter (d_{min}) of the piston required is 0.052m, therefore pushing force (F) is calculated using eqn. 3.67 and 3.68.

$$d_{min} = \sqrt{\frac{4 \times F_p\,(N)}{\pi \times P\,(\frac{N}{m^2})}} \qquad 3.67$$

$$F_p = \sqrt{\frac{\pi \times 2.5 \times 10^6 \times 0.052^2}{4}} = 5.31KN$$

$$A_c = \frac{\pi \times d_{min}^2}{4} \qquad 3.68$$

$$= \frac{\pi \times 0.052^2}{4} = 2.7 \times 10^{-3} m^2$$

Where:

A_c = cylinder area (m^2)

F_p = push force (N)

P = average pressure (N/m^2)

d_{min} = minimum diameter (m)

Hydraulic fluid volume and volumetric flow rate

The speed of the piston depends on the volumetric flow rate of the hydraulic fluid entering the piston cylinder and this is equivalent to the change in volume of the hydraulic fluid per unit time. Volume of oil (V) into a standard cylinder stroke of 0.04m is calculated using eqn. 3.69 (Gatmaitan *et al.*, 2012).

$$V = A_c \times l \qquad 3.69$$

$$= 2.7 \times 10^{-3} m^2 \times 0.04 = 1.08 \times 10^{-4} m^3$$

Where:
V = volume of fluid into the hydraulic cylinder (m^3)
l = cylinder stroke (m)
A_c = cylinder area (m^2)

At an expected piston speed of 0.02m/s, the volumetric flow rate of hydraulic fluid from the pump entering the piston cylinder (Q) is calculated using eqn. 3.70 (Roemheld Inc., 2012; Gatmaitan *et al.*, 2012).

$$v = \frac{Q_p}{A_c} \qquad 3.70$$

$$Q_p = 0.02 m/s \times 2.7 \times 10^{-3} m^2$$

$$= 5.4 \times 10^{-5} \frac{m^3}{s} = 3.24 \times 10^{-3} \frac{m^3}{min}$$

Where:

v = piston speed (m/s)

Q_p = volumetric flow rate (m^3/min)

A_c = cylinder area (m^2)

Hydraulic Pump/ Hydraulic fluid motor

In choosing the appropriate size of pump to be used for the hydraulic briquetting machine, the pump displacement, torque, input power and overall pump efficiency are calculated.

Pump displacement:

For the pump to deliver sufficient flow which will advance the cylinder at the required piston speed, the pump displacement is calculated based on a 3-phase induction motor operating at 1750 rpm at volumetric efficiency of 0.85 using eqn. 3.71 (Milwaukee, 2012).

$$D_p = \frac{Q_p}{\omega_i \times \eta_{vp}} \qquad 3.71$$

$$= \frac{(3.24 \times 10^{-3} \frac{m^3}{min})}{(1750 \frac{rev}{min}) \times (0.85)}$$

$$= 2.18 \times 10^{-6} \frac{m^3}{rev}$$

Where:

D_p = pump displacement (m^3/rev)

ω_i = speed of revolution of pump (rpm)

η_{vp} = pump volumetric efficiency (dimensionless)

Q_p = volumetric flow rate (m^3/min)

Fluid motor torque:

The torque required to drive the pump at the required pressure is calculated using eqn. 3.72 (Milwaukee cylinder company, 2012).

$$T_r = D_p\left(\frac{m^3}{rev}\right)\times P\left(\frac{N}{m^2}\right)\times\frac{1}{2\pi}\left(\frac{rev}{rad}\right) \qquad 3.72$$

$$= \frac{2.18\times10^{-6}\times2.5\times10^{6}}{2\times\pi}$$

$$= 0.9\frac{N.m}{rad}$$

Pump input power

Eqn. 3.73 is used to determine the input power needed for the pump to operate (Industrial Hydraulic services Inc., 2007).

$$P_{input} = T_r\times\omega_i \qquad 3.73$$

$$= (0.9\frac{N.m}{rad})\times(1750\frac{rev}{min})\times(\frac{2\pi\ rad}{rev})(\frac{min}{60sec})$$

$= 164.9$ Watts

$=0.165kW$

$$=0.165kW\times\frac{Horse\ power}{0.7456kW}$$

$=0.22hp$

Fluid output power:

There are two kinds of power to be considered in the hydraulic cylinder namely fluid power and mechanical power. Fluid power refers to the power that a hydraulic fluid can produce or deliver to the hydraulic cylinder while mechanical power refers to the overall power that was transmitted from the fluid to cylinder (Gaitmaitan *et al.*, 2012). In general, fluid power is greater than mechanical power because of the friction losses occurring inside the cylinder. Eqn. 3.74 is used to determine the power the hydraulic fluid will produce (Industrial Hydraulic services Inc., 2007).

$$P_{output} = P\,(\frac{N}{m^2}) \times Q_p\,(\frac{m^3}{min}) \quad 3.74$$

$$Q_p = 2.5\times10^6(\frac{N}{m^2})\times3.36\times10^{-3}(\frac{m^3}{min})\times\frac{min}{60sec}$$

$$=140\ \frac{N.m}{sec} = 0.14\ kW$$

$$= 0.14kW\times\frac{\text{Horse power}}{0.7456kW}$$

$$=0.19Hp$$

Where:

P_o = Fluid output power (Hp)

P = System pressure (M/m^2)

Q_p = Volumetric flow rate (m^3/min)

Pump overall efficiency:

Eqn. 3.75 is used to calculate the overall efficiency of the pump (Industrial Hydraulic Services Inc., 2007).

$$\text{Pump efficiency } (\eta_p) = \frac{\text{Fluid output power}}{\text{Pump input power}}\times100 \quad 3.75$$

$$= \frac{0.19Hp}{0.22Hp}\times100$$

$$= 0.86\%$$

3.7 Machine Component Description

The major determining components in the performance of hydraulic press is the frame and hanger of the cylinder (Parthiban et al., 2004). This is because briquette production depends on the actions of these two components. The stress on the frame depends on the operations of the cylinder during briquette production and due to the sensitivity of these two components in the operation of hydraulic briquetting press, the adjusted design of the machine was modeled in computer aided design (CAD) software before the machine was eventually fabricated. The essence of the 3D model is to ensure that the stress, displacement and strain are within the allowable range for machine operation. The 3D model drawing of the machine is shown in Fig. 3.8. Component parts of the machine are described below and detailed drawing presented in Appendix E.

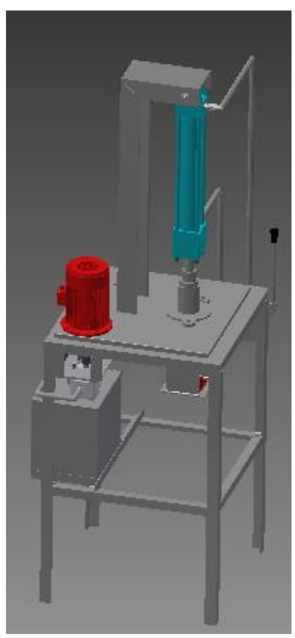

Fig. 3.8 3D model of the machine

Cylinder hanger

The cylinder hanger in an inverted L-shaped structure that holds the cylinder in place. Cylinder is attached to the hanger by means of a lock bolt. It comprises of two frames namely, vertical and horizontal frames. The hanger is welded to the table top. Material selected for its construction is carbon steel. The design details of the two components are presented in Appendix E1.

Table top

This gives base for mounting the cylinder hanger, electric motor and briquette blank. Electric motor and briquette blank is bolted to the table top while the cylinder hanger is welded to the unit. The table top frame is $864mm^2$ and is made of steel. Detailed drawing is given in Appendix E2.

Hydraulic cylinder

The cylinder provides a linear drive and consists of a piston located in a tubular housing and a piston rod that passes through one of the end covers. The cast iron end covers are held together by four tie rods. The port at the end covers permit entry and return of hydraulic oil. The piston rod is made of steel carbon. The detailed features of the hydraulic cylinder is shown in Appendix E3.

Briquetting blank and push out die

The briquetting blank holds the biomass waste material for compression. Underneath of the cup is the push out die that covers the bottom of the blank. The die is then connected to the hydraulic jack that ensures the unit is very firm during operation. The blank and die are made of carbon steel. The detailed drawing of the 3D model drawing is presented in Appendix E4.

Hydraulic jack

A hydraulic jack help to remove the briquettes from the matrix cup and it is manually actuated. The detailed drawing is shown in Appendix E5.

Connecting elements

The interconnection of various elements in the hydraulic system is obtained through suction pipe, pipe connectors, hose tee connector and elbow union. These elements determine movement of hydraulic fluid within the system. Suction pipe draws hydraulic fluid up to the pump. The six pipe connectors in the design move fluid from reservoir to pump, from pump to distributor and then to top cover end of the cylinder. Also a 370mm flexible hose is connected to return pipe that return fluid back to reservoir while Tee connector joins two connection pipes to pressure gauge. The suction pipe and all connecting pipes are made of carbon steel. The hose is made of reinforced synthetic rubber. See Appendix E6.

Frame

The frame provides support to the entire unit of the hydraulic machine. It has four supports and a provision for oil reservoir stand. The assembled drawing of the frame is shown in Appendix E7.

Directional control valve

This valve controls the movement of hydraulic oil in and out of the cylinder. It consist of a valve with four internal passages and a sliding spool which connects and disconnects the passages. Its operation involves movement of the sliding spool in either end of the valve such that when the spool is at one extreme position, the channel where oil from the pump passes to the cylinder is opened and it allows oil to pass to the cylinder. But when the spool is in the opposite rear end, the channel that allows oil to flows back to the tank the cylinder is activated open. A manual lever attached to the distributor helps in activating these processes. It is lowers piston rod during briquetting and lifts it afterwards. It comprises of two units namely, the lever handle and lever suspender. The two units are made of steel carbon. See Appendix E8 for the 3D models of the control valve and lever.

Oil tank

This store the hydraulic oil and its volume is 3-5 times the pump discharge per minute. It is rectangular in shape and is mounted at base of the frame. The tank has three opening at the top of the tank. These opening are for outlet and inlet of the hydraulic fluid in the operating system and the third opening is for refilling and discharging the oil in and out of the tank respectively. It is located outside the machine main frame because of thermal condition which affects the viscosity of the oil. Its location also help in easy servicing of the tank. The oil reservoir is made of steel. Configuration of the oil reservoir is given in Appendix E9.

Pressure gauge

Pressure gauge reads the pressure developed in the system. Its reading ranged from 0-25bar. Specifications of the pressure gauge is presented in Appendix E10.

Pump

The selected pump is a gear pump and consist of spur gears of equal diameter meshing with each other and enclosed in a casing with two intersecting bores, with suitable bearings in the end covers. The materials used for the housing and end cover of the pump is Aluminum alloy, bearing is copper cast alloy and aluminum alloy, gear and shaft is alloy steel and shaft seal is high grade rubber. For detailed drawing of the pump, see Appendix E11.

Motor

The electric motor turns the hydraulic pump and causes the pump to push out the hydraulic oil. Its speed is 1750 rpm and power capacity of 0.5 hp. The 3D model of the electric motor is shown in Appendix E12.

3.8 Fabrication of the Hydraulic Briquetting Press

Construction of the briquetting machine was done at scientific equipment development institute, Enugu (SEDI-E). The production process cut across three sections of the institute and it employed the services of skilled workers in these sections. Some component of the hydraulic briquetting machine used were acquired following the design calculations. The hydraulic cylinder (Parker-Hannifin NMF, EP-21R314C model), electric motor (Transitube, Moteurasynchronetriphase model), hydraulic pump (HESSELMAN P113MD6 model) and actuator (Salam Modena VDM 06 620106830 model) and pressure gauge (Olajveszelyesi-0-25bar) were procured from Onitsha market, Anambra state, Nigeria while the hydraulic jack was acquired from coal camp motor parts market, Enugu state, Nigeria. After the machine fabrication, various part of the machine were assembled. The procedures for construction of the components are described as follows;

3.8.1 Sheet-metal production process

This was the first stage of the production process after acquiring all the materials needed for the construction of the briquetting machine. It involved the cutting of metallic plates, pipes, angle bars and bending of pipes. Sheet metal process fabrication was carried out in construction of frame, cylinder hanger, table, oil tank, connecting pipes, and hydraulic jack casing.

For the table frame, four 732 mm was cut out from a square pipe of 30.5cm length while cylinder hanger, table top cover and oil tank were fabricated from a 7mm thickness plate sheet metal. Dimension of 55 x 55 mm and 649 x 649 mm were cut out for top frame and vertical frame of the cylinder hanger respectively. Square of 432 mm plate for table top, and two 236 x 228mm, two 183 x 228 mm and one 236 x 183 mm plate for oil tank reservoir fabrication, were also cut out.

Casing for the hydraulic jack was constructed using 3mm thick metal plate where the four component parts were mapped out. The dimensions of the plates constructed are 204 x 90mm for left side, 170 x 125mm for top and 204 x 137mm for right hand side of the casing. The right hand side plate was bent at an angle of 90^o and 12mm to the horizontal then 135^o vertical. This is to give stability to the hydraulic jack.

A total of six connecting pipes were cut from 3048mm (10ft) length carbon steel cylindrical pipe of 8mm nominal diameter (DN). Length of 394mm, 1085mm, 590mm, 509mm, 91mm, 140mm were obtained for construction of suction pipe, cylinder inlet pipe, cylinder outlet pipe, pump to gauge inlet pipe, gauge to actuator inlet pipe and return pipe respectively.

Devices used for sheet-metal processes fabrication are jack saw, G-clamp device, sheet plate cutting machine. Some of the sheet plate production operations are shown in Appendix F1.

3.8.2 Welding process

The plate metals obtained from sheet metal operation were welded together using shielded metal arc welding (SMAW) method. The support frame, cylinder hanger, table top cover, oil tank and jack casing were joined together as specified in the sheet metal production. Some of the welding operation is shown in Appendix F2.

3.8.3 Machining process

Machining process was also applied in the construction of the following component parts of the machine namely; piston die, push out die, crucible cup and briquetting blank. To construct the piston die a 40 mm diameter cylindrical solid of 50mm long was reduced to 43 mm length using lathe machine. The diameter was reduced to 30mm height and a 25 mm internal diameter hole (where piston head will be fixed) was created to the depth of 30mm using drilling machine. A 5mm thread for bolting the piston head was made 22.7mm across the 40mm diameter pipe.

The push out die was machined using 80 x 125mm carbon steel cylindrical solid as work piece. Two units were created from the work piece. The 29mm diameter x 68mm high and 49mm x 14mm high sections. They were machined using lathe machine as shown in Appendix F3.

Briquette blank holds the cylindrical crucible to the base of the frame while the function of the crucible cup is to contain the biomass material during compression. The outer diameter of the crucible cup is 60mm, height of 76mm high and 10mm thickness and is welded to a 137mm outer diameter x 6mm high x 17mm thickness circular plate fastened to the table by two bolts. The two units were machined using lathe machine.

3.8.4 Working principle of the machine

The machine works on the principle of Pascal law on transmission of fluid pressure as shown in Fig. 3.9. Firstly, ISO 68 hydraulic oil is filled into the tank and on switching on the power source, the pump through the rotation of electric motor pushes the oil from tank through the directional valves to the cylinder. This movement is controlled by the control valve which is actuated by hand operated lever. The 3-way actuator controls the movement of oil into and out of the cylinder. This ability of the actuator makes the different stages of the pressing cycle possible. Depending on the position of the control unit, pressure is directed to the directional valves which either directs the oil into the cylinder or returns it to the reservoir tank. These valves opens/closes depending on the pressure provided by inlet valve which enable the system to switch between the three states.

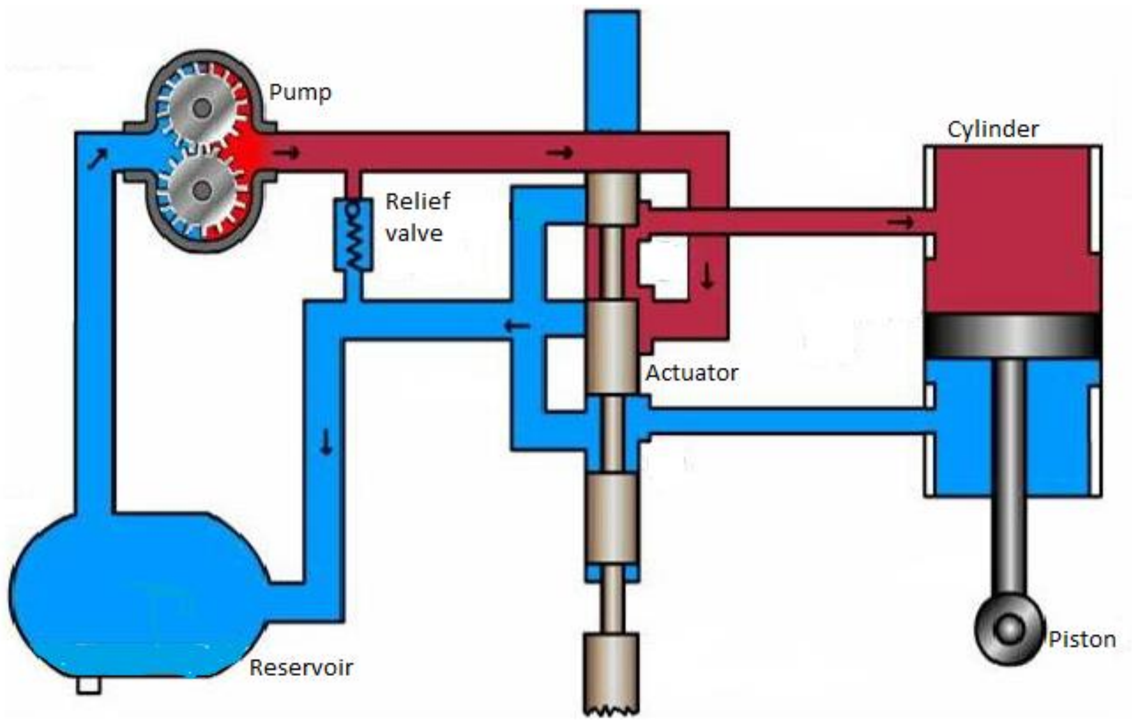

Fig. 3.9 Operation of the hydraulic press briquetting machine

3.8.5 Testing of the machine

Sawdust material collected from the wood workshop section of SEDI-E was used for test running the machine. Cassava starch (Renew brand) was used as binding agent. The starch and sawdust material were well mixed and fed into the crucible cup of the machine and compacted at 18, 20 and 22 bar as the case may be to form briquettes.

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1 Characterization of Biomass Materials

Results for the material characterization of sawdust and rice husk materials are presented in Table 4.1. It also presents the standard deviation (Std) and coefficient of variation (Cov) for sawdust and Rice husk materials and also for sawdust materials exclusively. This is necessary in other to detect the source of variation when comparing sawdust and rice husk composition as it affect the difference in mean of the parameters.

Table 4.1: Mean values biomass composition-proximate and ultimate analysis

Parameter	**Gmelina sawdust**	**Stool sawdust**	**Oil bean sawdust**	**Mahogany sawdust**	**Rice husk**	**Sawdust + Rice husk**		**Sawdust**	
						Std	**Cov %**	**Std**	**Cov %**
Volatile matter (%)	86.22	80.28	81.76	83.38	75.65	3.5	44.1	2.2	2.6
Ash content (%)	0.55	0.87	1.26	1.11	15.11	5.6	150	0.26	27
Moisture content (%)	9.90	15.57	13.90	12.50	8.93	2.4	20.2	2.0	16
Fixed carbon (%)	3.33	3.28	3.08	3.01	0.31	1.1	44.1	0.13	4.1
Calorific value (kJ/kg)	30,010	28,002	28,420	28,941	14,994	5580	21.4	751.1	2.6
Carbon content (%)	47.08	43.89	38.30	51.87	39.90	4.9	11.1	5.1	11.28
Nitrogen content (%)	0.55	0.46	0.38	0.50	0.50	0.05	11.7	0.06	13.1
Sulphur content (%)	0.10	0.08	0.04	0.08	0.10	0.02	25	0.02	29
Specific gravity (%)	0.15	0.13	0.14	0.21	0.28	0.05	30.7	0.03	19.7

The proximate analysis summaries the moisture content, volatile matter, fixed carbon, ash content in the samples (Table 4.1). Each of these parameters is responsible for material performance during briquetting, combustion or other thermo chemical process (Forero *et al.*, 2015). The moisture content of the raw material plays vital role both in the compression and in the thermochemical process. It acts both as a binding agent and a lubricant. Moisture in the raw materials also increases the gelatinization of starch, helps develop van der Waal's forces and diffusion of water-soluble substances throughout the matrix (Mani *et al.*, 2003). Nevertheless, when raw materials are so wet, water might encumber short-range intermolecular forces acting as an interface between the solid particles. Sawdust materials had the highest moisture content, average mean of 13% wb, which is 31% larger than that of rice husk.

The volatile matter has not a remarkable incidence on the synthesis of stronger bound during densification, however, this parameter directly affects the performance and physical stability of the solids briquette during thermal decomposition. The higher the volatile matter in the raw material, the faster its use as source of biomass energy will catch fire. Because of the rapid volatile release, the solid matrix could decompose becoming powder instantaneously. The mean volatile matter content of sawdust materials is 82.9 % which is 8.8 % higher than that of rice husk.

Fixed carbon is the most valuable parameter in terms of the energy potential; raw materials with higher fixed carbon content have higher heating values. Sawdust material is characterized by similar fixed carbon content ranging between 3.01-3.33 %. The average value (3.175 %) is 90% higher than fixed carbon content of rice husk.

Ash content of wood sawdust was also observed to be far below that of rice husk because rice husk is herbaceous biomass and is known to contain higher ash than that of woody biomass (BISYPLAN, 2012). The ash in biomass materials are also identified as one major reasons for the remarkable effect on their heating value, combustion characteristics and equipment design (Forero *et al.*, 2015). Their importance in equipment design is because of the production of slagging, fouling and blocking problems in the equipment (Giri, 2012). Hence high ash content material require a more erudite design to guarantee complete combustion and decrease the quantity of burnable substances remaining with ash after combustion. Among all the materials studied, rice husk had the highest ash content (15.11%). Between the sawdust materials, oil bean and mahogany sawdust had the highest, 1.26 and 1.11 respectively. The mean decrease of ash content between rice husk and sawdust material is 94%.
Results of proximate analysis are in accordance with the findings reported by Syamsiro *et al.* (2012)

Also from Table 4.1, wood sawdust contains higher calorific value (28,002.43-30,009.93kJ/kg) when compared to rice husk (14,994.24kJ/kg) but both materials met the biomass standard for use as renewable fuel (Stahl, et. al., 2004). In other words, with this high calorific value, these materials can be good sources of energy.

The ultimate analysis summaries the carbon content, hydrogen, and sulphur content in the samples (Table 4.1). Carbon and Hydrogen content have the closest relationship with the energy content of the materials. This is because the oxidation of these parameters releases more energy during burning. Carbon content of rice husk was observed to be lower (39.9%) than wood sawdust (51-43%) because of its lower lignin (14.3%) when it is compared with wood biomass (25.5%) (UNEP, 2013). Meanwhile carbon content recorded for oil bean sawdust is lower that of rice husk. This is an indication that there is variation in the structural make up of biomass materials. Sulfur is one material component that has to be taken into account due to its capacity of forming pollutant such as sulphur oxide. It is most complicate to control because of sulphur reaction with air. The result obtained however revealed that these materials contributes less to environmental degradation because of low (<0.1%) amount of sulphur they contain thus their indiscriminate disposal which constitutes environmental hazards can be curbed by increasing their bulk density in briquette form, thereby making it easy to be transported from one point to another and also maximize their storability.

Wood specific gravity is one of the most important variables used in tropical ecology and differs generally among and within species and also within individual trees. (Bastin *et al.*, 2015 and Wiemann and Willianson, 2013). It integrates many aspects of tree mechanical and functioning properties and is an important parameter used in analysis of tree biomass. Specific gravity of the material where within the range 0.13- 0.28% and within the reported values for most biomass materials.

Considering the deviation from the mean for the five biomass materials, the result showed that there is wide Std for the proximate parameters (+/-1.1-3.5) when compared to ultimate parameters (+/- 0.1-0.5). Carbon content deviated (+/-4.9).

Cov implies that there is wide variation between the means as a result of differences in material composition but lower Cov when only the wood sawdust were analyzed.

Comparing the results of the Std and Cov for sawdust + Rice husk and sawdust, there is reduction in Cov for the parameters considered signifying that wood sawdust materials have similar characteristics in composition that differs significantly with rice husk.

4.2 Model Validation

Samples of briquettes produced during the model validation analysis are shown in Fig. 4.1. The predictive models were validated as follows: Output capacity, damaged briquettes, production efficiency and bulk density.

Plate. 4.1 Samples of briquettes from the five materials

The briquettes produced using the developed hydraulic press briquetting machine has uniform cross-section and circular in shape. The outer surface of the briquettes were carbonized and solid with no holes at the center. The briquettes from the both samples of the sawdust and rice husk assumed a brown coloration and solidifies within two days of production depending on the prevailing weather condition.

4.2.1 Output capacity model

The result of the predicted output was calculated using eqn. 3.28 while the measured was obtained as the actual output per unit time with eqn. 3.54. The data used for the comparison of output capacity is presented in Appendix G1. Fig. 4.1 is the graphical representation of output capacity at pressure variation while Fig. 4.2 represent the relationship between predicted and measured output capacity values.

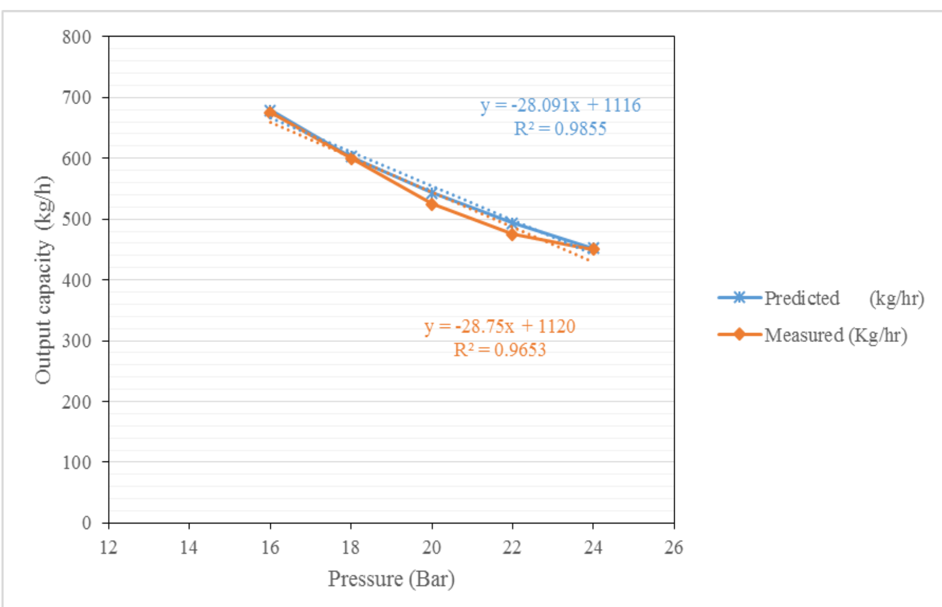

Fig. 4.1 Output capacity with pressure variation

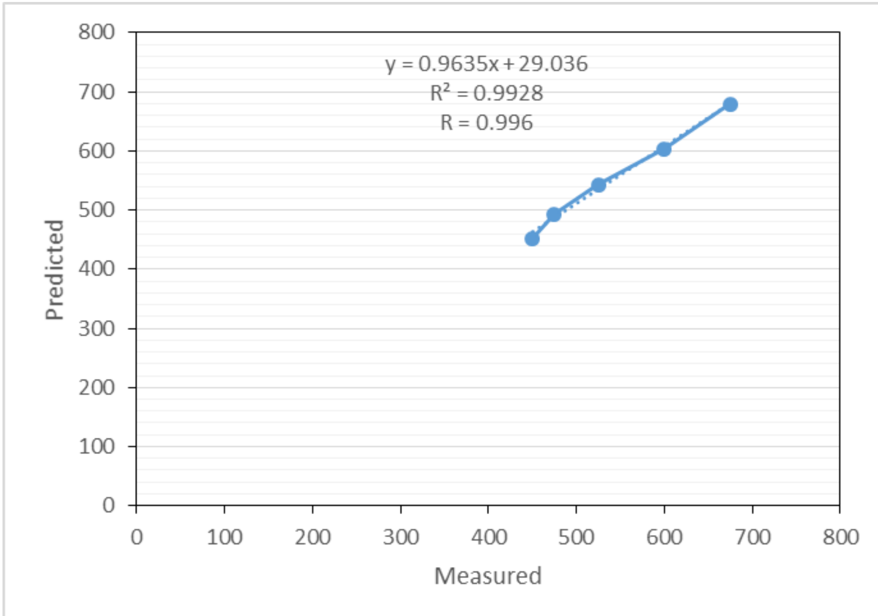

Fig. 4.2 Relationship between predicted and measured output capacity

From the regression equations (y = 0.9635x+29.036) and (y = 0.9635x+29.036) in Fig. 4.1, it revealed that as the pressing pressure increases from 16 bar to 24 bar, the quantity of briquettes produced decreases by 33.3%. Thus, this result is in in agreement with Li and Liu (2000), 2.5 – 50 pressure application, and has also shown that there is significant effect on output capacity of the hydraulic briquetting machine. However, this is only obtainable within the stated boundary conditions of 0 – 50bar. The relationship is also in agreement with that of vacuum pump which has been found to that the gas throughput capacity is a function of inlet pressure (Pfeiffer, 2009).

Also from relationship between predicted and measured values, it is established that the model ($T_c = C_t\left(\frac{V_c^2 B_i f}{P}\right)$) described the measured value for the hydraulic briquette machine with coefficient of correlation value (R) of 0.996 (Fig. 4.2).

However, analysis on the quality of the briquettes shows that higher pressure produced better quality briquettes during the analysis and will be discussed in subsequent section. From the graph, the output model was verified for the output capacity of the machine.

4.2.2 Damaged briquettes

The damaged briquettes are shown in Plate. 4.2. The data used for the comparison of quantity of damaged briquettes is presented in Appendix G2. Fig. 4.3 is the graphical representation of the number of briquettes damaged per hour of operation at varying moisture content and Fig. 4.4 shows the relationship between the predicted and measured values.

Plate 4.2 Samples of damaged briquettes

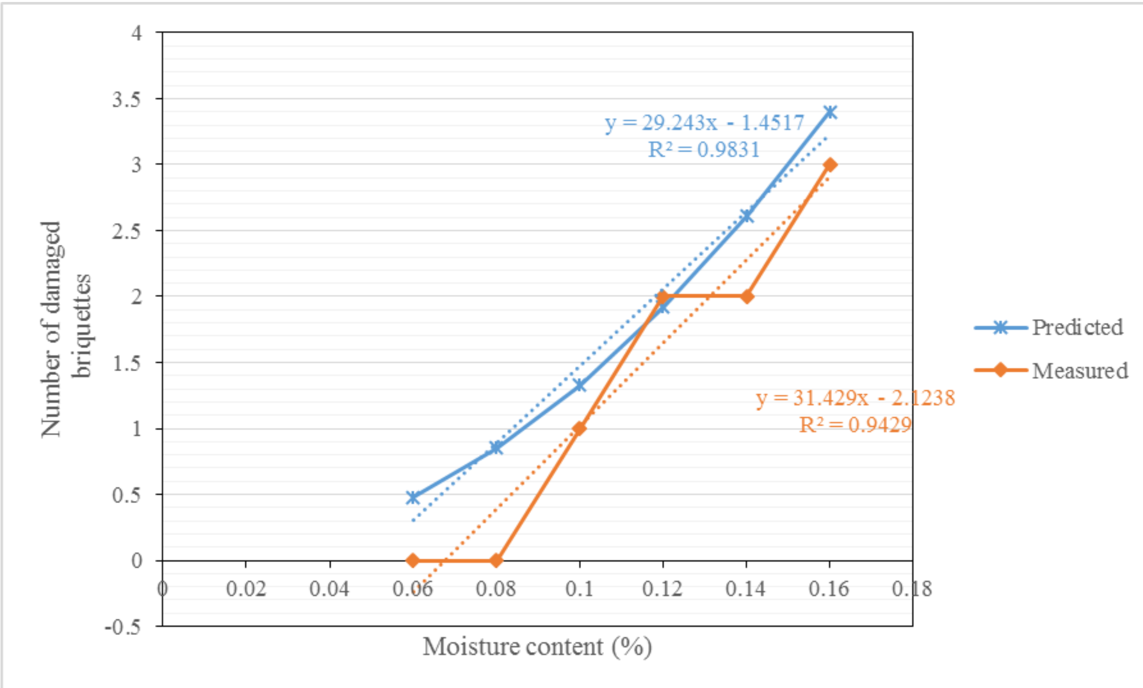

Fig. 4.3 Damaged briquette at moisture content variation

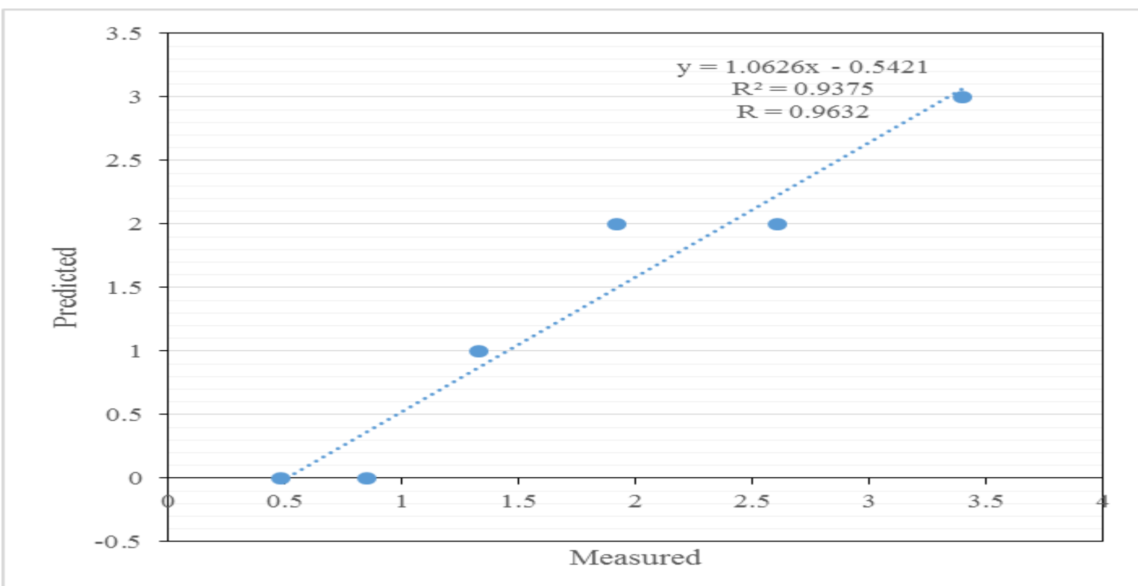

Fig. 4.4 Relationship between predicted and measured number of damaged briquettes

From Fig. 4.3, increase in moisture content increases the number of damaged briquettes as shown in the regression equation y = 29.243x - 1.4517 for predicted values and y = 31.429x - 2.1238 for measured values. This is in in harmony with Mkini and Bakari, (2015) report and indicated that moisture content effect friability (ability to resist mechanical action) potential of briquettes. This implies that there is low particle cohesion and resulted in unwanted swelling and disintegration of the briquettes a shown in Fig 4.5. Report in Krizan *et al*. (2015) indicates that moisture content is a limiting parameter influencing the quality of briquettes. The report gave 11.7 % as optimum required moisture content and highlighted that above moisture content of 14.5 %, there will be increase in the porosity at the surface of the briquette and causes cracks to appear on the briquettes.

Correlation coefficient (R) for the predicted and measured data is 0.96 (Fig. 4.4) which implies high correlation between the values. This implies that the predictive model $(D = C_d\left(M_c Sm_b{}^{1/3} B_i{}^{1/6}\right)e^{P^{1/2}})$ for determining the quantity of damaged briquettes is acceptable. The graph also verifies the views from literatures that optimum moisture content requirement for briquette production is within the range of 7-12% (Theerarattananoon *et al.*, 2011, Huang, 2014 and Mani et al., 2006). Sasa (2014) recorded 10.8 % as the optimum moisture content for briquettes Physical damages noticed on the briquettes are cracks and deformations in shape. These damaged briquettes were further studied and compared with the undamaged ones and it was found that the damaged briquettes took longer time to dry and they were loose as compared to undamaged briquettes as shown in Plate 4.1. However, it is important to note the model boundary condition (7≤Moisture content≤16%). Beyond this moisture content, it might be difficult to from briquette because the material would behave as plastic.

4.2.3 Production efficiency

Results of predicted values were obtained by using eqn. 3.39 while measured values were calculated using eqn. 3.55. The data used for validating the production efficiency of the machine are presented in Appendix G3. Fig. 4.5 is the graphical representation of the production efficiency at varying pressure and Fig. 4.6 shows the relationship between the predicted and measured production efficiency values.

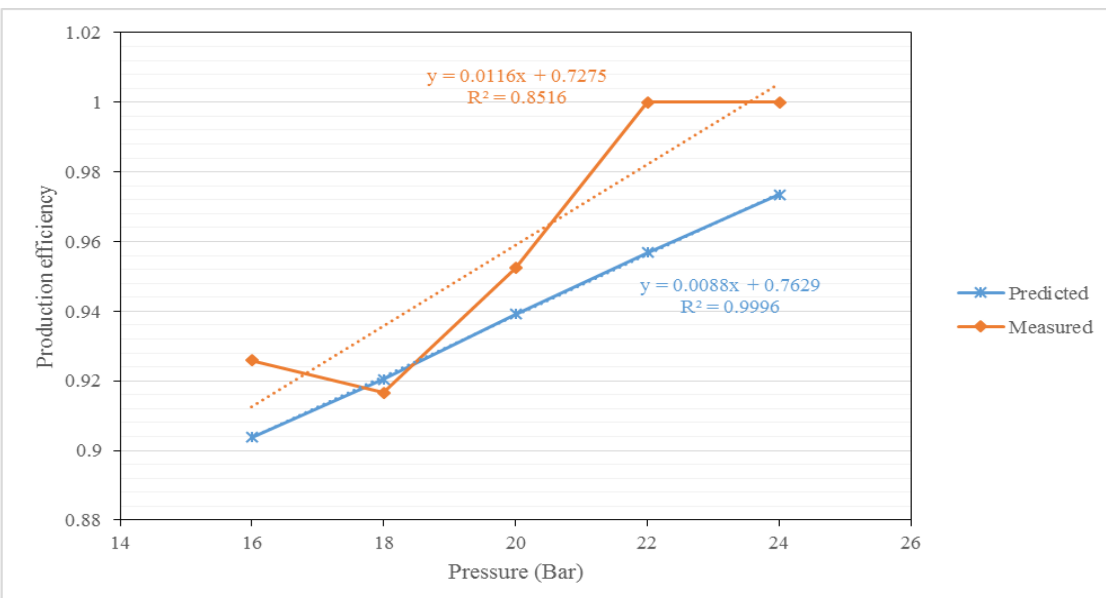

Fig. 4.5 Production efficiency at varying pressures

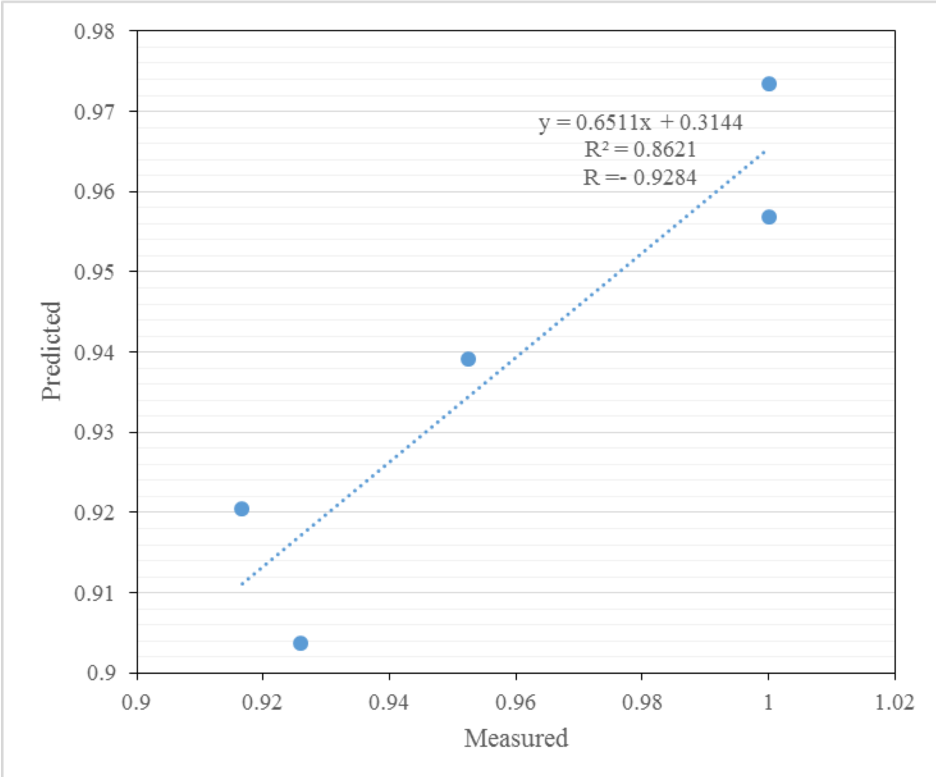

Fig. 4.6 Relationship between predicted and measured production efficiency values

From the graph, production efficiency of the hydraulic press in a function of pressure exerted on the material (Fig. 4.5) and increases as pressure increased. This can be established because of the low quantity of damaged briquettes recorded at high pressure. With coefficient of correlation value (R) of 0.92 in Fig 4.6, the model $\left(\eta_m = 1 - \frac{C_d S M_c m_b^{\frac{1}{3}} B_i^{\frac{1}{6}} P e^{P^{1/2}}}{C_p\left(v_c^2 B_i f\right)}\right)$ is said to be suitable in predicting the production efficiency of hydraulic press briquetting machine. Comparing the behavior of the measured and predicted values, it was also observed that the predicted result gave a more predetermined result with consistent increase as pressure increases. It is so because the measured values with obtained in units/hr and later weighed and converted to kg/hr while the values from the model equation were obtained at kg/hr.

4.2.4 Bulk density

The results of bulk density validation for the five biomass materials are presented in Appendix G4. Mean values of each material at each particle size is graphically presented in Fig. 4.7, 4.8, 4.9, 4.10 and 4.11 for Stool wood, Gmelina, Mahagony, Oil bean and Rice husk respectively.

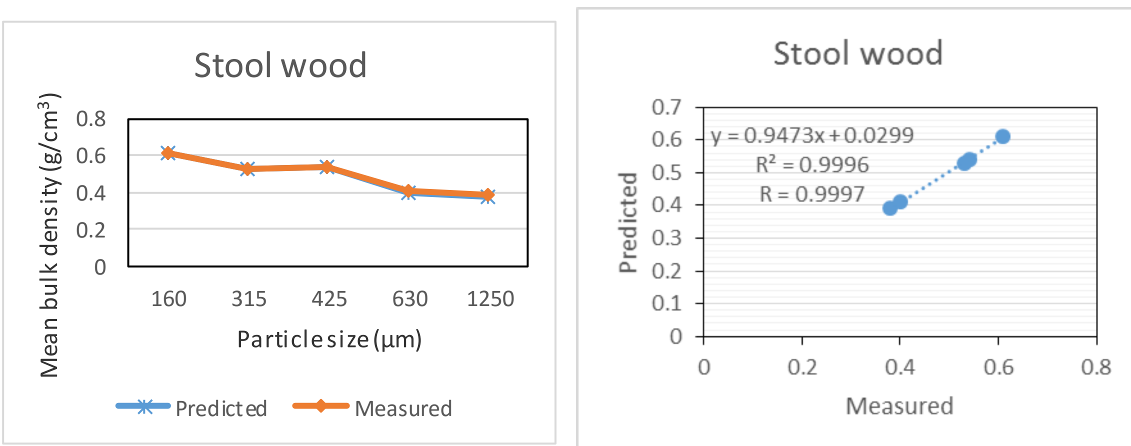

Fig. 4.7 Bulk density validation using stool wood sawdust

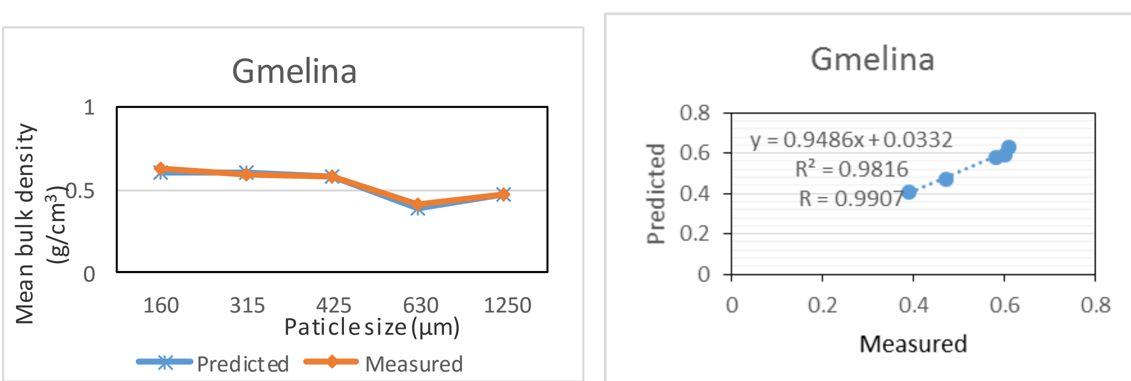

Fig. 4.8 Bulk density validation using Gmelina sawdust

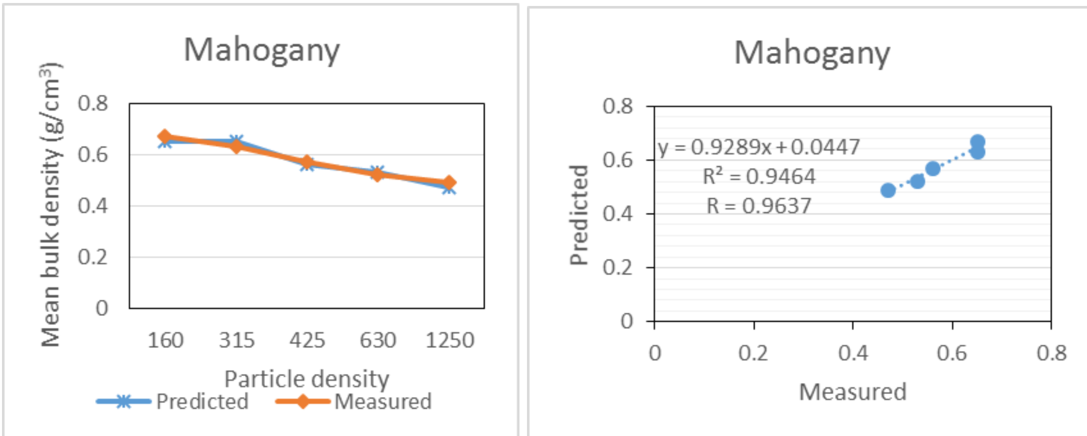

Fig. 4.9 Bulk density validation using Mahogany sawdust

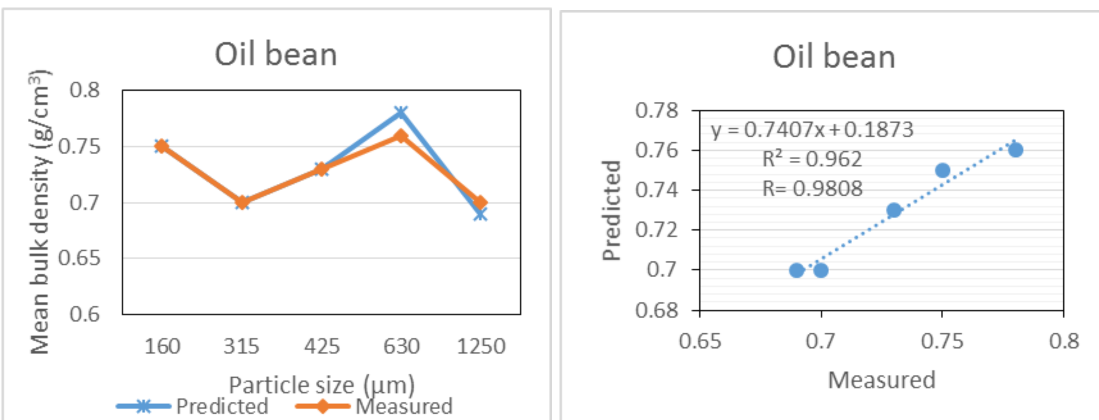

Fig. 4.10 Bulk density validation using Oil bean sawdust

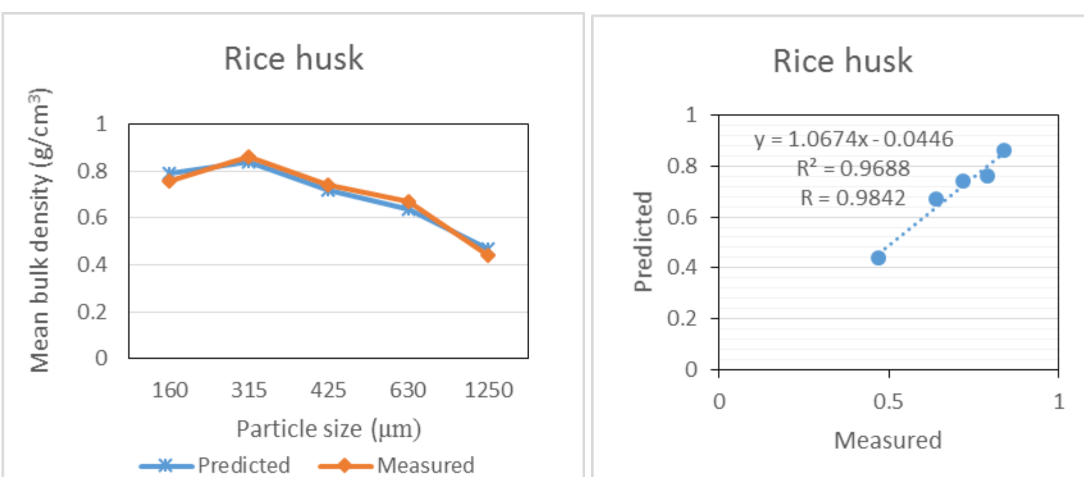

Fig. 4.11 Bulk density validation using Rice husk

From the results presented, the predicted model $\left(B_k = C_k\left[\frac{P^{1/2}}{B_i^{3/2}}\left(\frac{S^4}{V_c A_p A_c}\right)\right]\right)$ was validated for the five biomass materials with R value ranging between 0.96-0.99. Stool wood sawdust and Gmelina showed higher coefficient of correlation value of 0.99 (Fig. 4.7 and Fig. 4.8 respectively) compared to Mahogany (0.96), oil bean sawdust (0.98) and rice husk (0.98). (Fig. 4.9, Fig. 4.10 and Fig. 4.11 respectively). This is as the result of their differences in composition as shown in Table 4.1.

However, the value of bulk density constant (C_k) was plotted against particle size as presented in Fig 4.12 and found to increase as the particle sizes of materials were reduced. This can be attributed the surface areas created as the particle sizes increase could contribute to the high bulk density constant. It was also observed in the course of the model validation, that each biomass material has unique value known as n-value. The n-value has to be multiplied with bulk density constant bulk density at each particle size for the model validation. Since the n-value is as a result in differences in material composition, mean n-values for the materials were observed to increase as the hardness of the material increases (Fig. 4.13). When n-value was correlated with ash content of the each material, it was deduced that this n-value has correlation coefficient value of 0.53 with ash content of the materials (Fig. 4.14). So possibly, the ash content a given biomass material determines the briquette bulk density obtainable from the material.

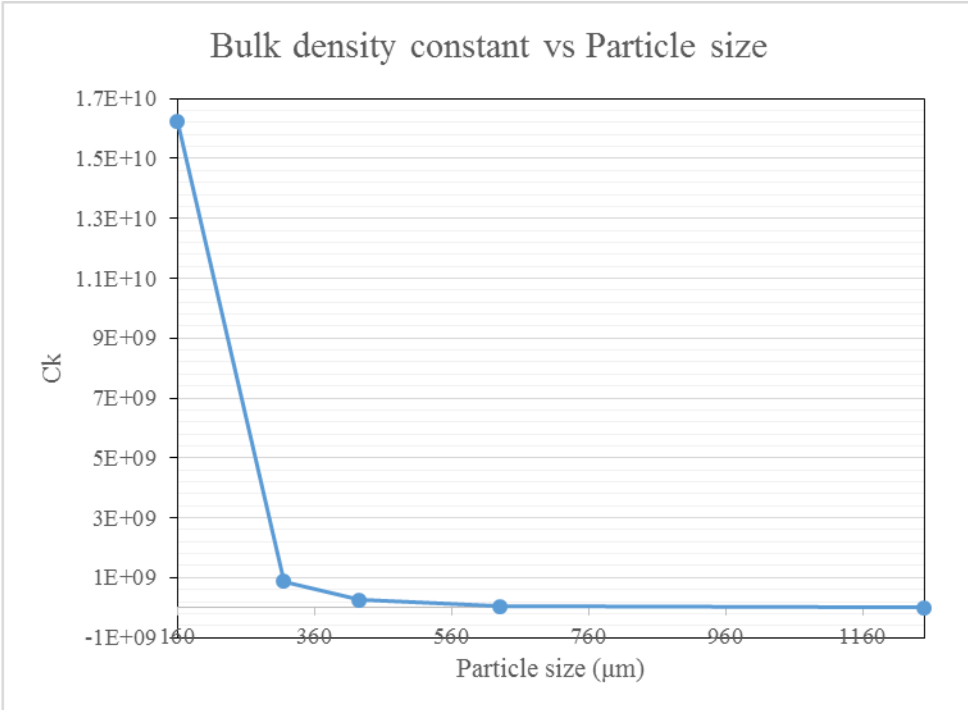

Fig.4.12 Relationship between C_k and particle size

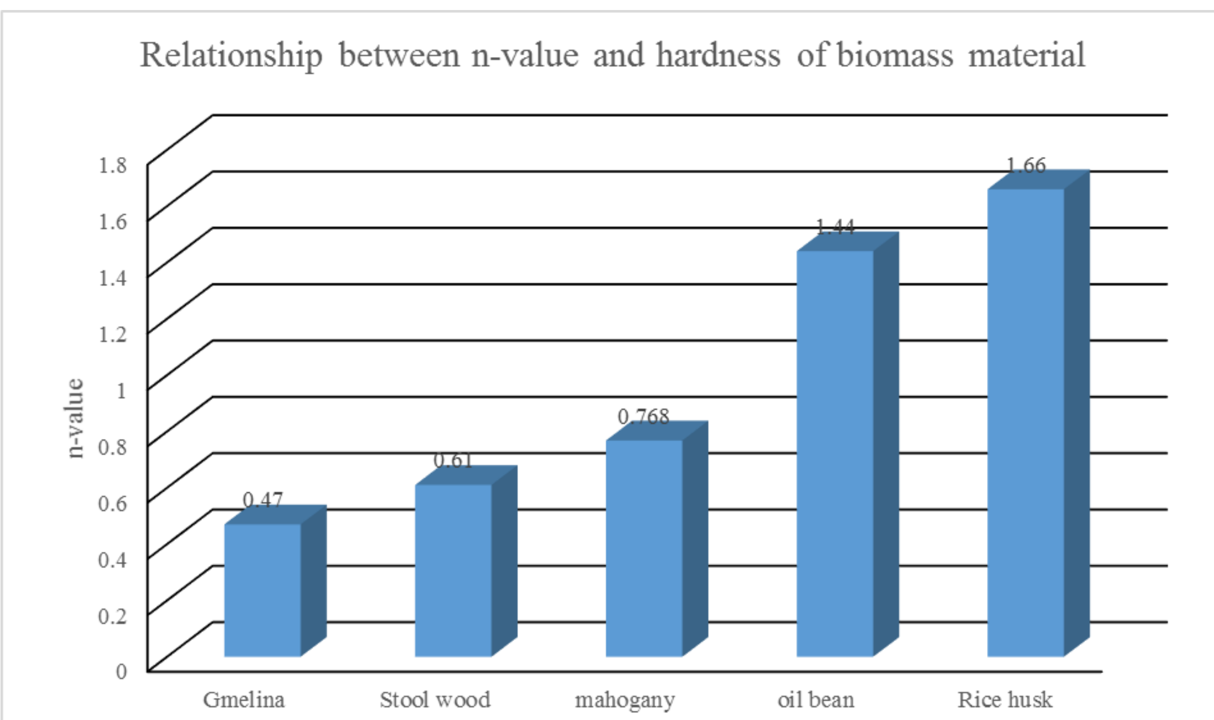

Fig. 4.13 Relationship between n-value and hardness of biomass material

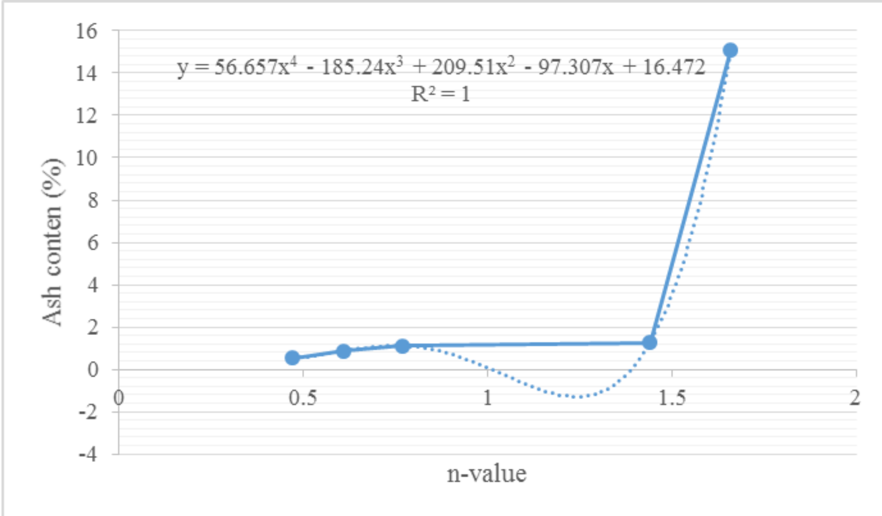

Fig. 4.14 Relationship between n-value and ash content

4.3 Physical characteristics of the briquettes

Results obtained for the physical characteristics as affected by the composition of the material for each the materials are presented according to the material under study; Stool wood sawdust, Gmelina sawdust, Mahogany sawdust, Oil bean sawdust and Rice husk.

Stool wood sawdust

Result of physical characteristics of stool wood sawdust is presented in Fig. 4.15, 4.16 and 4.17 for height, bulk density and compression ratio respectively. ANOVA for the effect of pressure and particle size on the bulk density of stool wood sawdust is presented in Table 4.2.

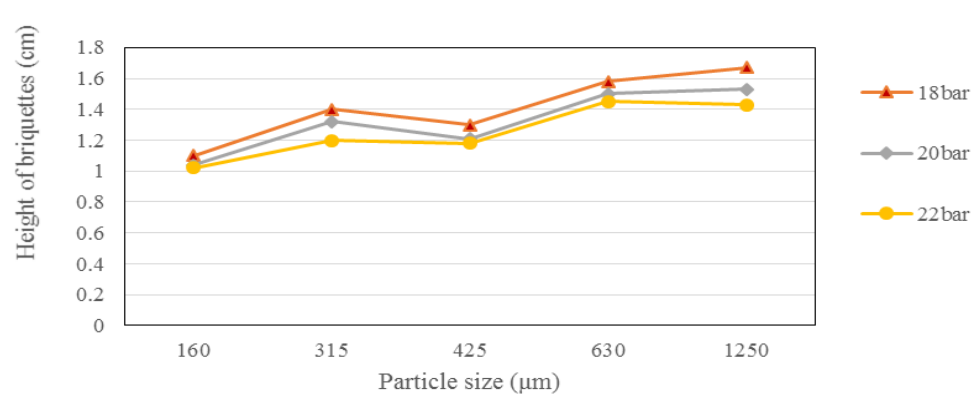

Fig. 4.15 Height vs particle sizes at varying pressures (stool wood)

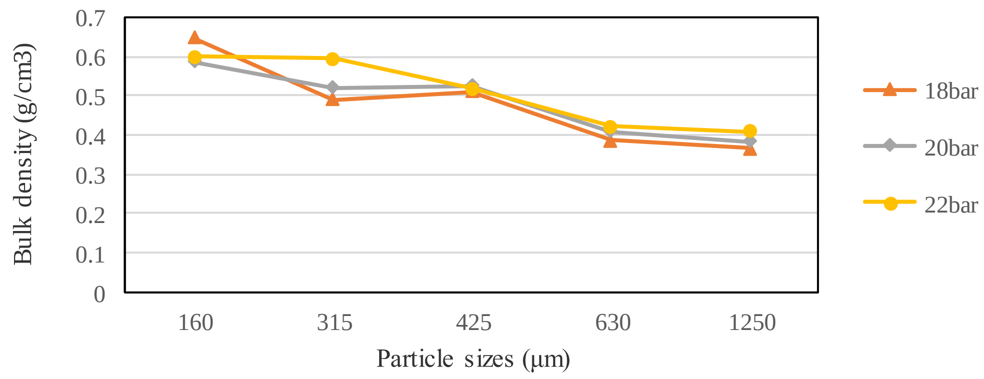

Fig. 4.16 Bulk density of briquette vs particle sizes at vaying pressures (stool wood)

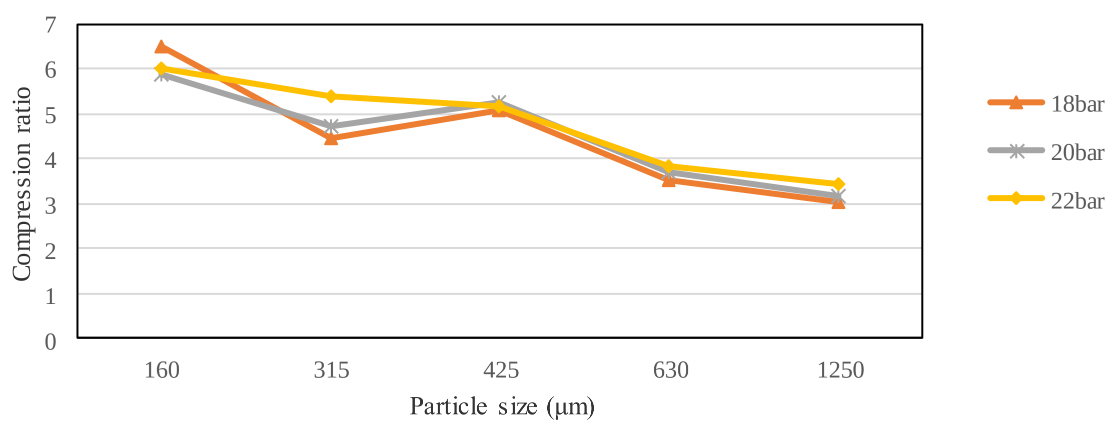

Fig. 4.17 Compression ratio vs particle size (Stool wood)

Table 4.2 ANOVA for effect of pressure and particle on Stool wood sawdust

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Pressure	0.002281	2	0.00114	1.279573	0.329492	4.45897
Particle size	0.106786	4	0.026696	29.955	7.29E-05	3.837853
Error	0.00713	8	0.000891			
Total	0.116196	14				

Stool wood sawdust is recognized soft wood because of it low hardness and as such it is much affected by pressure because of its high compressibility, porosity and lower mechanical properties as shown in Table 3.1. Taylor (2003) categorically stated that hardness of wood is a function of the heaviness or density of the wood and the amount of wood material compared to air spaces it contain. It can be observed from Fig 4.5 that for the three pressures analyzed, height of briquettes reduces with reduction in particle size and briquette of lower height was obtained at 22bar. Similarly, bulk density of Stool wood sawdust briquettes increased from 0.409 to 600 g/cm^3 with reduction in particle size from 1250 to 160 µm at 22bar, (Fig. 4.16). This is because of the compressibility of the Stool wood when subjected to high pressure. Relating to wood properties, Basri and Hadjib (2004) described every wood species as having effect to its drying and other related properties. Thus, less dense wood has the tendency to be greatly affected by higher force when compared to higher dense materials. This can be attributed to the inter particle spaces and walls collapse due to the high porosity of the particulates thereby increasing the bulkiness of the loose materials. Observing the trend of bulk density as particle size is reduced from 1250 to 630µm and 425 to 315µm, the percentage increase is very low (< 11%) as when compared to colossal increase of 46% (22 bar), 54% (20bar), and 77% (18 bar) from 1250 μm to 160μm. Peak increment was attained each after two sieve mesh. It is an indication that gradual decrease in particle size may not produce drastic increase in bulk density at a given pressure.

Result of compression ratio presented in Fig. 4.17 shows there is record of high record of 1:7, 1: 6 compression ratio at 18 bar and 22bar for 160μm. This result is comparable to those obtained in other briquettes produced from other biomass materials (Ali *et al*., 2015). This compression ratio is also commonly observed in pharmaceutical industries in drug formulations (Wiacek et al., 2017).

However, Table 4.2 shows high significant difference of particle size on bulk density of the stool wood briquette (F-test of 29.955 > F-crit. of 3.83) but no significant difference of pressure on bulk density (F-test of 1.27<F-crit. 4.45). Absence of significant difference of pressure on bulk density of the briquette can be attributed to fewer treatment levels of pressure during briquette production and it signifies that Stool wood material attains more density at slightest pressure application. Their resistance to force is low and because of this, their intermolecular walls are easily broken and collapses easily. Very high significance difference of particle size on bulk density at probability level, <0.01% (7.29 x10^5) is an indication that fine particles are more densed than coarse materials. Thus particle size is an important factor in examining the performance of densification process.

Gmelina sawdust

Fig. 4.18, 4.19 and 4.220 presents result of physical characteristics of Gmelina sawdust with respect to height, bulk density and compression ratio respectively. ANOVA for the effect of pressure and particle size on the bulk density of Gmelina sawdust is presented in Table 4.3.

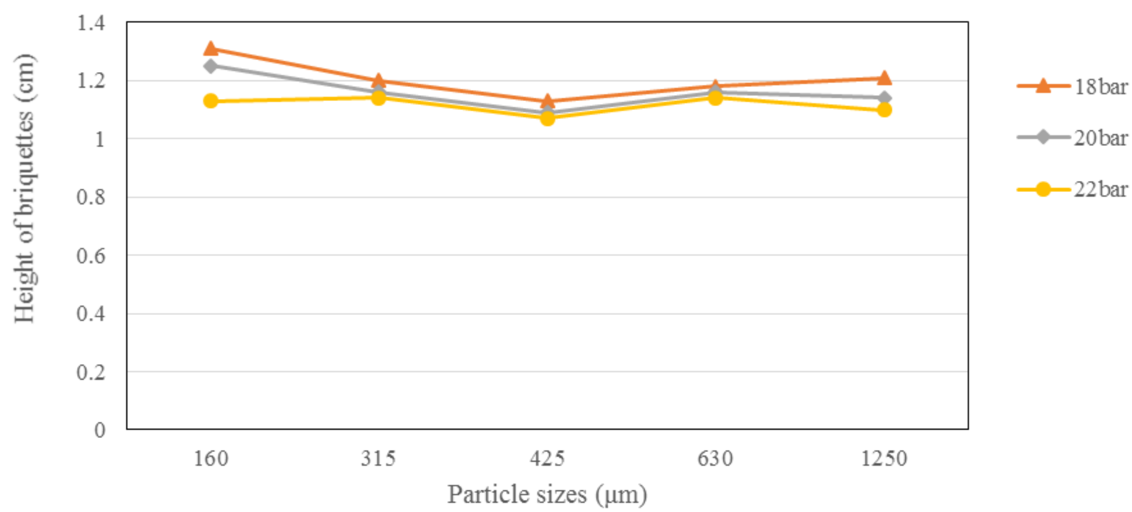

Fig. 4.18 Height of briquettes vs particle sizes at varying pressures (Gmelina)

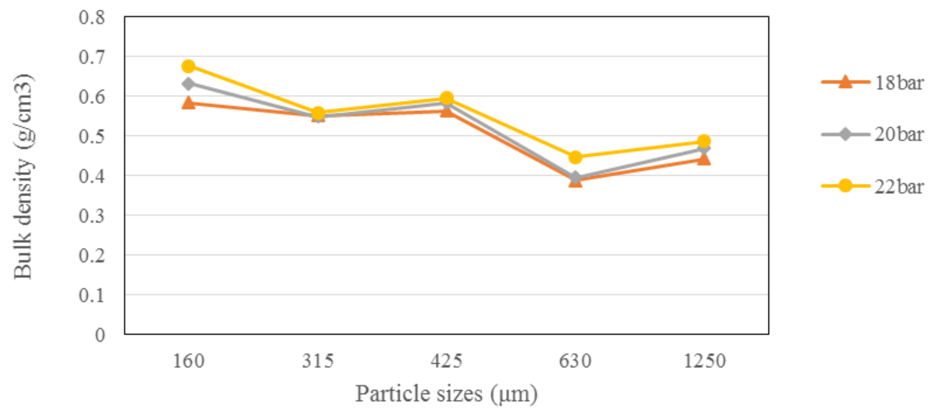

Fig. 4.19 Bulk density of briquette vs particle sizes at varying pressures (Gmelina)

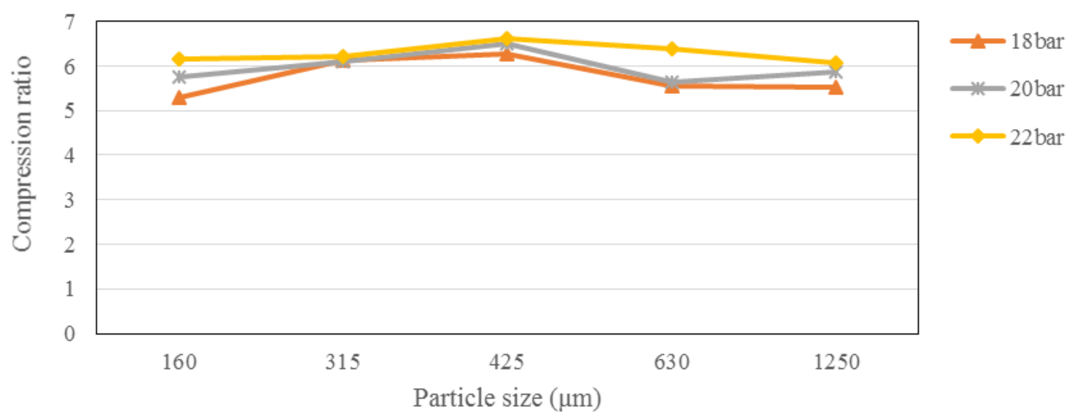

Fig. 4.20 Compression ratio vs particle size at varying pressure (Gmelina)

Table 4.3 ANOVA for effect of pressure and particle on Gmelina sawdust

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Pressure	0.005498	2	0.002749	9.122876	0.008632	4.45897
Particle size	0.094903	4	0.023726	78.74351	1.84E-06	3.837853
Error	0.00241	8	0.000301			
Total	0.102811	14				

For Gmelina sawdust, briquette's height was higher at 160µm (1.3cm) and reduces (1.2cm) as the particle size increases (Fig. 4.18). However, its bulk density (Fig. 4.19) maintained the same trend as Stool wood sawdust thus every analysis attributed to stool wood are applicable to Gmelina. It was also noticed that bulk density at the three pressures was highest (0.68g/cm^3) at 160µm followed by 425µm (0.56 g/cm^3) as indicated in Fig. 4.19. This is as a result of mild hardness of Gmelina (4270 N) when compared Stool wood sawdust (1820 N) as presented in Table 3.1.

Considering Fig. 4.20, compression ratio was at its peak at 425µm being 6.7 compression ratio value and reduces as particle size increased for 315µm (6.4), 1250µm (6.1) at 22 bar. This indicates that arrangement of particle before compression in each particle sizes differs for a given material such that pressure application aids in rearrangement of the particles and collapse all inter particle spaces that were existing prior compression.

From ANOVA in Table 4.3, within the pressure levels analyzed, there was significant difference (F-test of 9.12 > F-crit. of 4.45) on the bulk density of Gmelina sawdust at probability level <1% and also very high significant difference (F-test of 78.74 > F-crit. of 3.83) of particle sizes at probability level <0.001% on the bulk density of Gmelina sawdust briquettes. This however inform us of that difference in wood properties has effect on compression process. With higher mechanical strength 6-7N/mm^2, 1820N, 10800N/mm^2, 87.4 N/mm^2 compared to that of stood wood, 87.4N/mm^2, 4270N, 5790N/mm^2, 48-73 N/mm^2 for crushing strength, hardness, modulus of elasticity and rupture respectably, Gmelina has the tendency to crumble easily from coarse to fine particles when subjected to compression. There was high significance of pressure on bulk density but not observed for stool wood because of the high porosity in stool wood grinds as opposed to Gmelina. As a result stool wood attains high density quicker than Gmelina material and as observed (Table 4.1), specific gravity of Gmelina (0.15%) is slightly higher than stool wood 0.13%).

Mahogany sawdust

Physical characteristics of Mahogany sawdust is presented in Fig. 4.21, 4.22 and 4.23 for height, bulk density and compression ratio respectively. ANOVA for the effect of pressure and particle size on the bulk density of Mahogany sawdust is presented in Table 4.4.

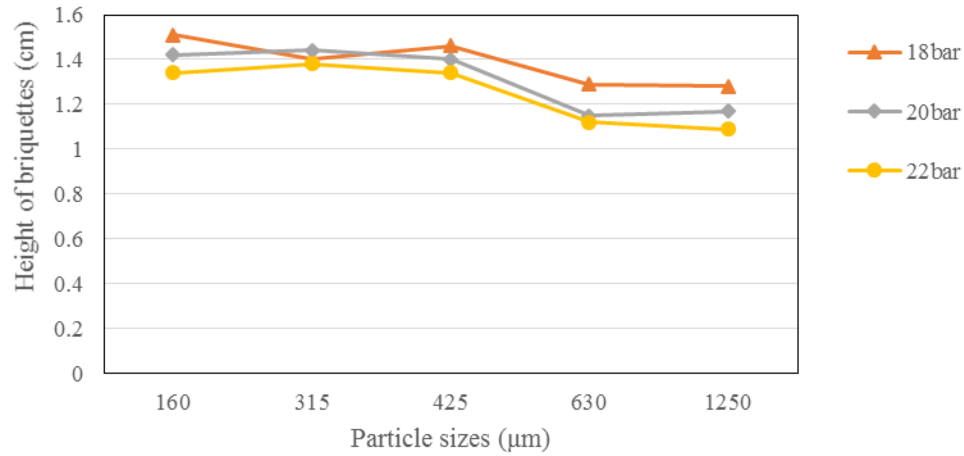

Fig. 4.21 Height of briquettes vs particle sizes at varying pressures (Mahogany)

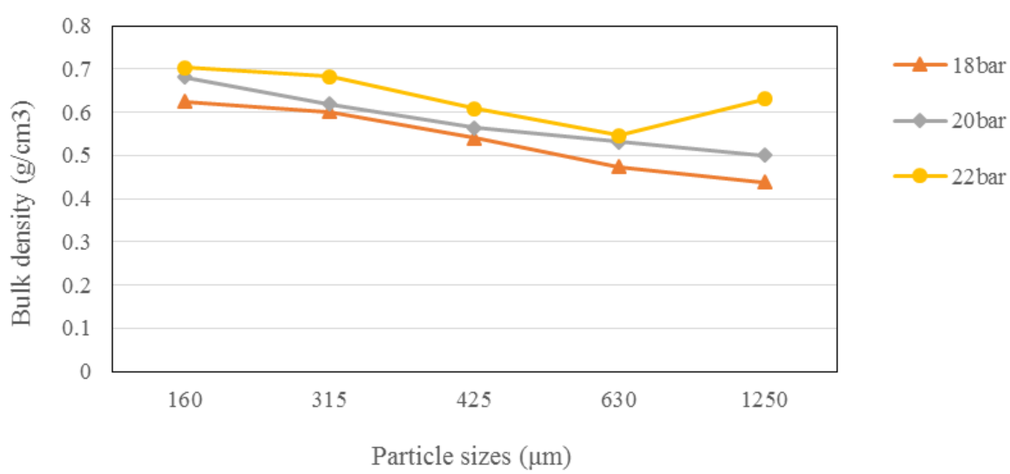

Fig. 4. 22 Bulk density of briquette vs particle sizes at varying pressures (Mahogany)

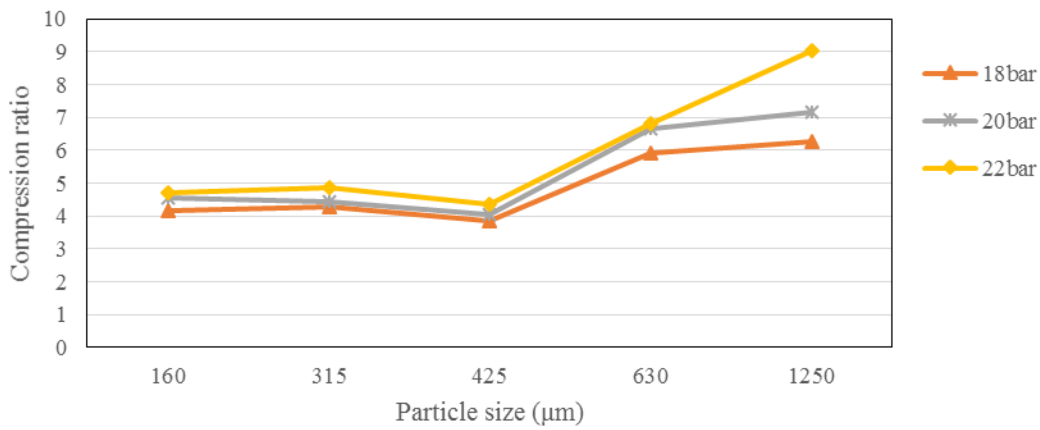

Fig. 4.23 Compression ratio vs particle size at varying pressure (Mahagony)

Table 4.4 ANOVA for effect of pressure and particle on Mahogany sawdust

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Pressure	0.024506	2	0.012253	13.57344	0.002684	4.45897
Particle size	0.054557	4	0.013639	15.109	0.000846	3.837853
Error	0.007222	8	0.000903			
Total	0.086284	14				

Height of briquettes produced from Mahogany sawdust showed similar behavior to that of Gmelina (Fig. 4.21) which is contrasting to the result of briquettes produced from Stool wood sawdust. This differences could be ascribed to the initial bulk density of the materials before briquetting (See Appendix H). However, bulk density of the briquettes produced behaved in similar manner to that of Stool wood and Gmelina sawdust. Optimum bulk density of 0.703, 0.68, and 0.623 was obtained at 22, 20, and 18 bar respectively at 160µm (Fig. 4.22).

Compression ratio was also found to decrease by 52%, 40% and 33% for 22, 20 and 18 bar respectively as particle size decreases from 1250μm to 425μm. This trend is in accordance with results obtained in Forero-Nunez (2015). It also explains there inter particle spaces are at 1250μm that requires closure during densification. It is obvious that higher particle size has higher compression ratio for Mahogany sawdust which was not as observed with that of Stool wood and Gmelina sawdust. This behavior occurred due to the different densification mechanisms that took place during compression, e.g., air releasing, solid particles rearrangement, fragmentation, and elastic and plastic deformation which differed for each of the materials.

Table 4.4 is the ANOVA on effect of pressure and particle size on bulk density of Mahogany sawdust. It can be seen that the pressure levels studied has high significant difference (F-test of 13.57 > F-crit. of 4.4) at <0.5% probability level and particle size has very high significant difference (F-test of 15 > F-crit. of 3.8) at <0.1% probability level. This result corresponds to other works on wood densification which state that there is high effect of particle size and pressure on bulk densities of briquettes (Oladeji, 2012 and Davies and Mohammed, 2013).

Oil bean wood sawdust

Result of physical characteristics of oil bean wood sawdust is presented in Fig. 4.24, 4.25 and 4.26 for height, bulk density and compression ratio respectively. ANOVA for the effect of pressure and particle size on the bulk density of stool wood sawdust is presented in Table 4.5.

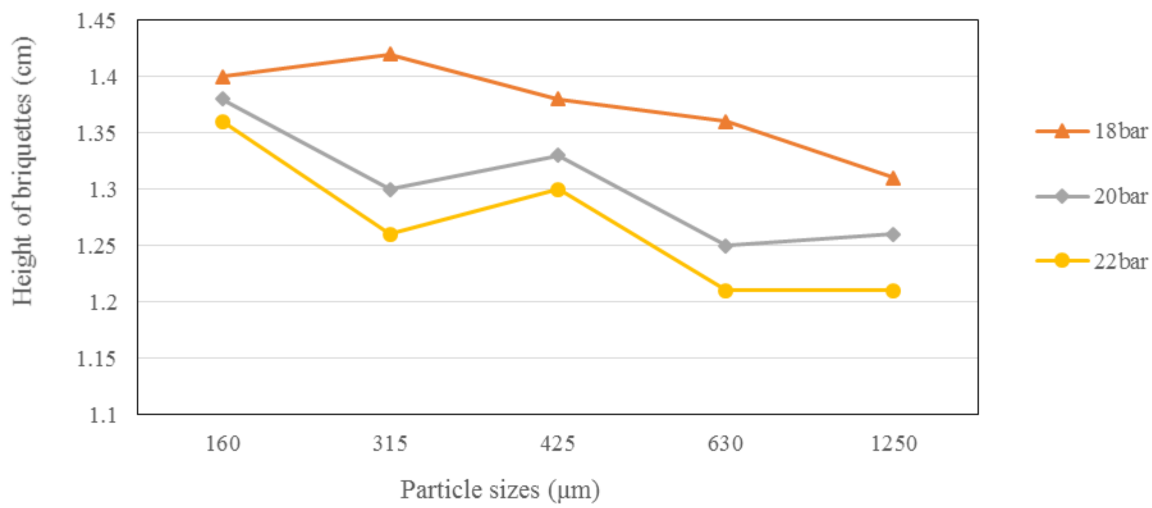

Fig. 4.24 Height of briquettes vs particle sizes at varying pressures (Oil bean)

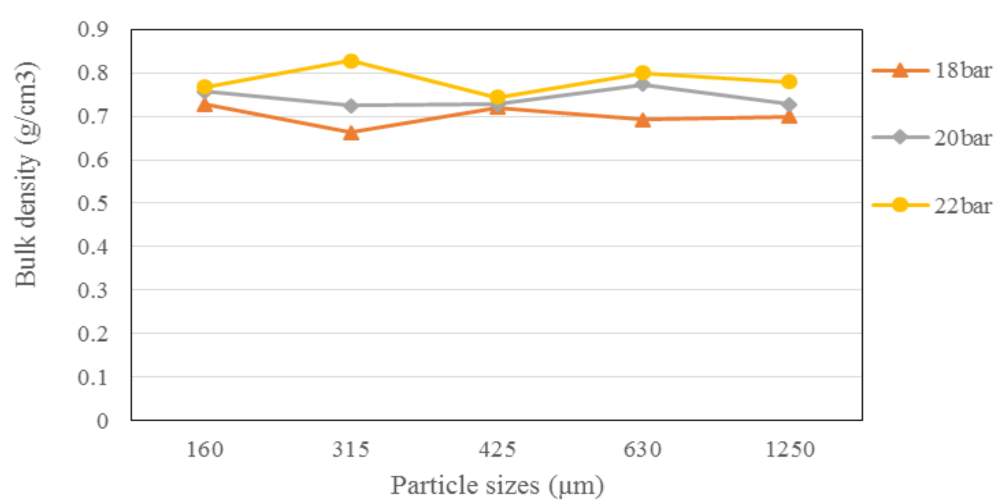

Fig. 4.25 Bulk density of briquette vs particle sizes at varying pressures (Oil bean wood sawdust)

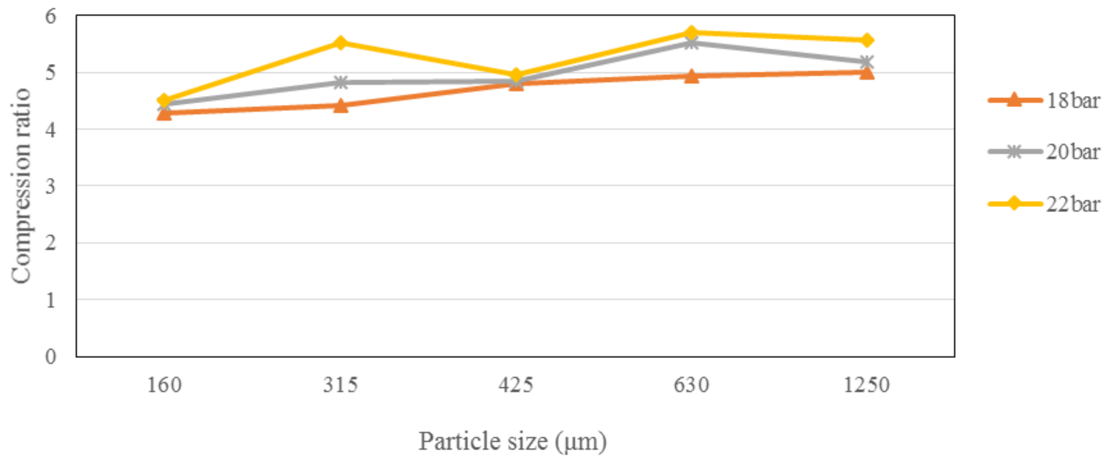

Fig. 4.26 Compression ratio vs particle size at varying presure (Oil bean wood sawdust)

Table 4.5 ANOVA for effect of pressure and particle on Oil bean sawdust

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Pressure	0.017278	2	0.008639	9.520969	0.00766	4.45897
Particle size	0.001327	4	0.000332	0.365672	0.826723	3.837853
Error	0.007259	8	0.000907			
Total	0.025865	14				

From Fig. 4.24, there was fluctuation in trend as it concern height of briquettes produced from oil bean sawdust at 20 and 22bar. It is supposed that at 20 and 22bar, the pressure exerted on the material are not sufficient to harmonize the binding of the loose material steadily. This reaction of the material to this effect is seen as the material behaving as an elastic material. For this reason, it is therefore possible that height of the briquettes produced increased at 425µm (1.33 and 1.3cm), reduced for 315µm (1.26 and 1.3cm), increased again at 160µm (1.38 and 1.36cm) for 20 and 22bar respectively. However, there is increase in height from

1.31 to 1.42cm as particle size decreases from 1250 to 315μm at 18bar. This explanation could be affiliated with the inconsistent differences in height between 18-20bar. Similar performance was exhibited in bulk density as presented in Fig. 4.25. Though 22bar produced high densed briquettes (0.7-0.8g/cm^3) like in other materials but it was difficult distinguish the relationship in terms of particle size. The results obtained on density is higher than those recorded in other works for other materials at similar pressure and particle size (Onuegbu *et al.*, 2012; Tembe *et al.*, 2014 and Ajobo, 2014).

Nevertheless, compression ratio of the material in Fig. 4.26 increased as particle size increases similar to Mahogany which is also identified as hard wood.

The ANOVA indicate significant effect (F-test of 9.5 > F-crit. of 4.45) of pressure at <5% probability level and no significant effect (F-test of 0.36 < F-crit. of 3.8) of particle size at <1% on bulk density of oil bean briquette (Table 4.5). Meanwhile, it was understood that because of the hardness (11,020N) of the Oil bean sawdust, it must have affected the compression of the material such that during compression, the material rebound at the force application which must have resulted to insignificance of pressure of the bulk density of the oil bean briquette. This result contrasted Li and Liu (2000) and Demirbas *et al.*, (2004) reports on pressure application which explained that mechanical strength increases as the briquetting pressure increases as a result of the plastic deformation. It could be described that maximum pressure was attained and beyond which there was no significant gain in cohesion as observed in (Ndiema *et al.*, 2002).

Rice husk

Result of physical characteristics of rice husk is presented in Fig. 4.27, 4.28 and 4.29 for height, bulk density and compression ratio respectively. ANOVA for the effect of pressure and particle size on the bulk density of rice husk sawdust is presented in Table 4.6.

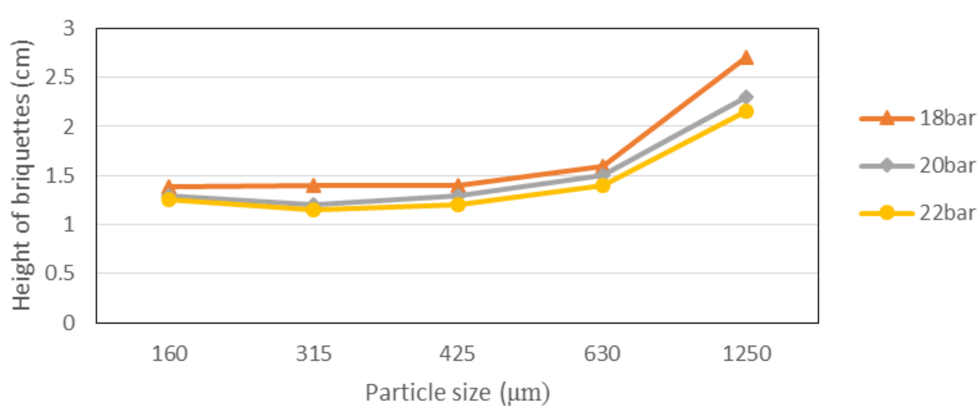

Fig. 4. 27 Height of briquettes vs particle sizes at varying pressures (Rice husk)

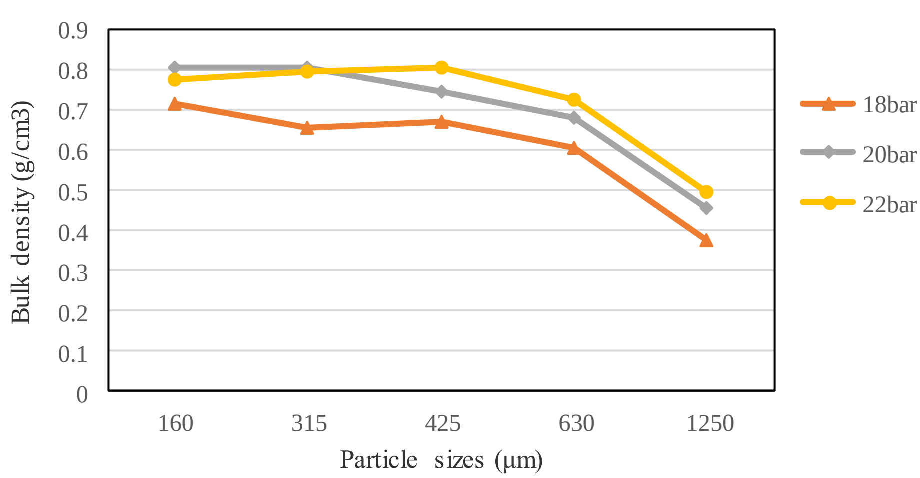

Fig. 4.28 Bulk density vs particle size at varying pressure (Rice husk)

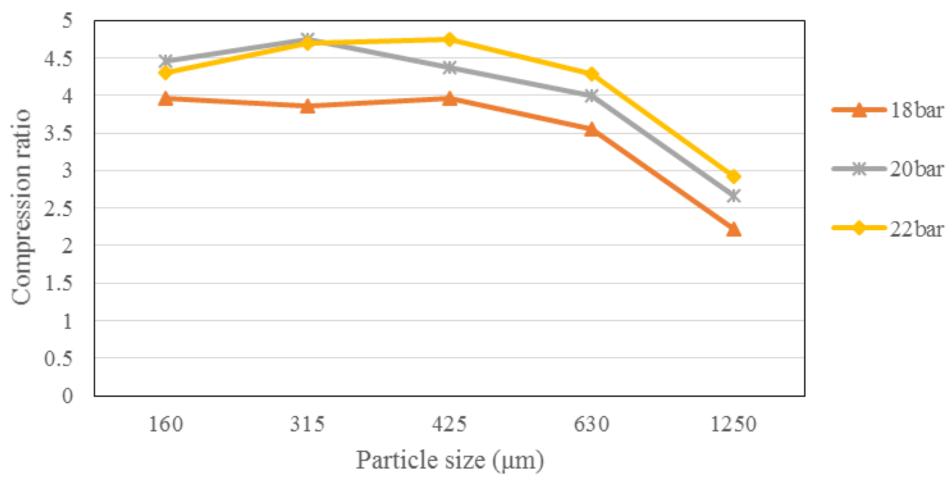

Fig. 4.29 Compression ratio vs particle size at varing pressure (Rice husk)

Table 4.6 ANOVA for effect of pressure and particle on Rice husk

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Pressure	0.037447	2	0.018723	29.75622	0.000197	4.45897
Particle size	0.216665	4	0.054166	86.08398	1.3E-06	3.837853
Error	0.005034	8	0.000629			
Total	0.259146	14				

Height of briquettes produced from rice husk showed similar behavior to Stool wood sawdust. It decreased as particle size reduces for the three studied pressure (18, 20, 22bar) (Fig. 4.27). There was drastic reduction from 2.7, 2.3, 1.15cm to 1.6, 1.5, 1.4cm (18, 20, 22bar respectively) as the particle sizes were reduced from 1250 to 630µm.

Density of the briquettes were observed to increase by 62 % (425µm), 77% (160µm) and 89% (160µm) at 22, 20 and 18bar respectively (Fig. 4.28). This however supports the inverse relationship between porosity and density (Lopez-Cordoba and Goyanes, 2017). From the result, the density at the 425, 315 and 160µm particle sizes stabilized at 0.8g/cm^3 difference at 22bar, but slight increase by 8% and 6% for 20 and 18 bar respectively. Density of the briquettes produced were within the range obtained in (Sani, 2008; Osarenmwinda, and Ihenyen (2012); Tembe *et al.* (2014) and higher than 0.2-0.5g/cm^3 that obtained in (Kuhe *et al.* (2013).

Compression ratio of the briquette followed similar trend as that of bulk density. It peaked at 425µm (4.74), 315µm (4.68) and 160µm (3.97) for 22, 20 and 18bar respectively (Fig. 4.29). Hamad et al. (2015) reported that the finer the particles does not necessarily mean the higher the compressibility. But form the result obtained for rice husk, the finer the particles of the higher the compressibility. Difference in the 18bar and 20/22bar is a clear indication that the material can attain optimum compressibility beyond which the compression ratio is constant. By this result, 160µm can be adopted as the best quality for storage and transportation. And judging by the calorific value of 160µm, it will be a very good source of energy.

In other words, for rice husk material, fine particle sizes possess more pore than coarse particles. Analysis of the effect of pressure and particle on bulk density of the briquettes is presented in Table 4.6 and it shows very high significant (F-test of 29.75 > F-crit. of 4.4) and (F-test of 86 > `*F-crit. of 3.8) difference at

<0.001% probability level. This result is consistent with the result on the graphs as there were distinct effect these parameters have on bulk density of rice husk briquettes produced. Rice husk distinguished itself in their physical characteristics because of its different composition when compared with sawdust materials. Evidently, its compression was characterized by regularity in behavior.

4.4 Briquette Quality Optimization

The detailed results and discussion of each dependent variables (ash content, volatile matter, fixed carbon and density) as it relate to the quality optimization of briquettes is presented in this section. By fitting the four significant linear regression models, factor levels in each model were ranked based on importance, followed by average ranks for all models, and then the optimal condition determined by selecting the levels with the least rank for each factor as discussed in the following sub section.

Ash content

The average values for the mean ash contents of the briquettes are presented in Appendix I1. The result of the multiple linear regression analysis is also presented in Table 4.7 and the fitted model for ash content is given in eqn. 4.1. The relationship between particle size and ash content is graphically represented in Fig. 4.30.

Table 4.7 Ash content model

Model			t	Sig.
	Coefficient	Std. Error		
Intercept	15.395	1.529	10.066	.000***
Pressure	.012	0.069	.174	0.863
Binder	-.015	0.051	-.292	0.772
Particle Size	0.124	0.001	1.180	.0421*

AC= 15.395+0.124Ps 4.1

Where;

AC = Ash content

Ps = Particle size

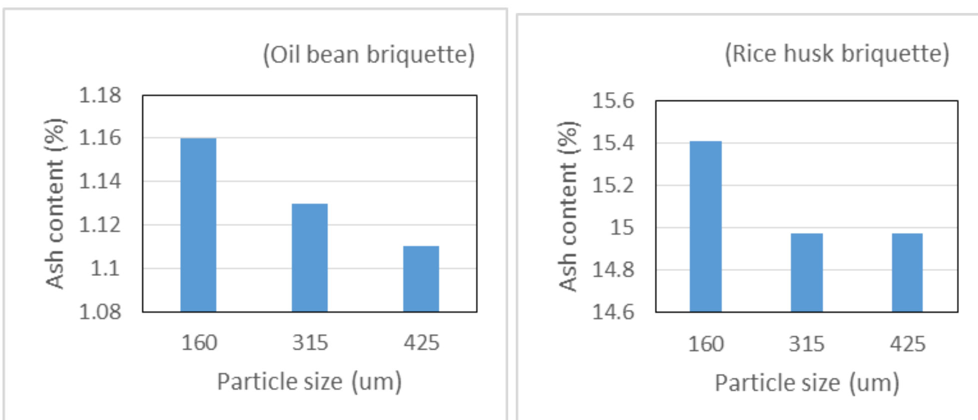

Fig. 4.30 Relationship between ash content and particle size

From Table 4.7, it was observed that there is no significant effect of binder ratio and compaction pressure on ash content at 5% level of significance (P-value >5%). As a result of increase in density as compaction pressure increases, this reduces porosity that could have limited the amount of oxygen required for combustion (Chirchir et al., 2013) thus result in increased ash content. However, binder (starch) contains 0.2% ash content (Eze and Azubuike, 2010) which is very negligible at low binder ratios. This explains why compaction pressure and binder ratio had no significant effect on ash content. Furthermore, particle size had significant effect on ash content at 5% level of significance (p-value: $0.0421 < 0.05$) and the model explains 4.5% of the total variation in ash content.

From Fig. 4.30, it can be observed that reduction in particle size gives rise to increase in ash content of the briquettes. However, briquettes are required to have as minimum ash content as possible to reduce slagging behaviour during combustion and for effective heating. Small particles had more ash content than the rest which implies that small particles are the least preferred in the model. The ranks of 160, 315, and 425µm particles sizes are 3, 2, and 1 respectively.

Volatile matter

The average values for the mean volatile matter of the briquettes are presented in Appendix I2. While the result of the multiple linear regression analysis is presented in Table 4.8. From the analysis, binder ratio was the only factor that has significant effect on the volatile matter thus the fitted model for volatile matter is given in eqn.4.2. The relationship between binder ratio and volatile matter is graphically represented in Fig. 4.31.

Table 4.8 Volatile matter model of briquette quality

Model			t	Sig.
	Coefficients	Std. Error		
(Constant)	72.932	3.338	21.850	.000***
Size	.001	.002	.402	.691
Pressure	-.211	.151	-1.395	.173
Binder	.629	.110	5.696	.000***

Dependent Variable: Volatile matter

$$V.M = 72.932 + 0.629Br \quad (4.2)$$

Where;

Br = Binder ratio

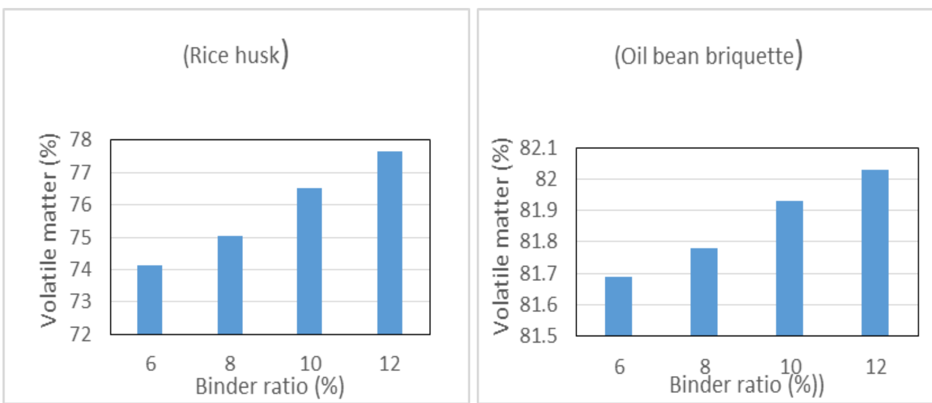

Fig. 4.31 Relationship between volatile matter and binder ratio

Unlike compaction pressure and particle size, binder ratio had a significant effect on volatile matter content at 5% level of significance and it accounts for 51.9% of the total variation in volatile matter content. Compaction pressure does not alter the composition of particles, hence its insignificant effect on volatile matter content. Volatile matter content corresponds to the smoke level of the briquettes which therefore makes low volatile matter most preferential to high volatile matter content. The volatile matter content increases with increase in binder ratio which implies that the least binder ratio is the most preferred for the model. Ranks for 6%, 8%, 10% and 12%, binder ratios are 1, 2, 3 and 4 respectively.

Fixed carbon

The average values for the mean fixed carbon of the briquettes are presented in Appendix I3 and the result of the multiple linear regression analysis is presented in Table 4.9. Fitted model for fixed carbon is given in eqn. 4.3 and also shows that binder ratio has significant effect on fixed carbon. The relationship between binder ratio and fixed carbon content is graphically represented in Fig. 4.32.

Table 4.9. Fixed carbon model of briquette quality Model

			T	Sig.
	Coefficients	Std. Error		
Constant	.309	0.076	4.091	.000***
Size	.2.468E-005	0.000	0.495	0.695
Pressure	.003	0.003	0.762	0.452
Binder	-.006	0.002	-2.667	0.02*

FC = 0.309-0.006Br 4.3

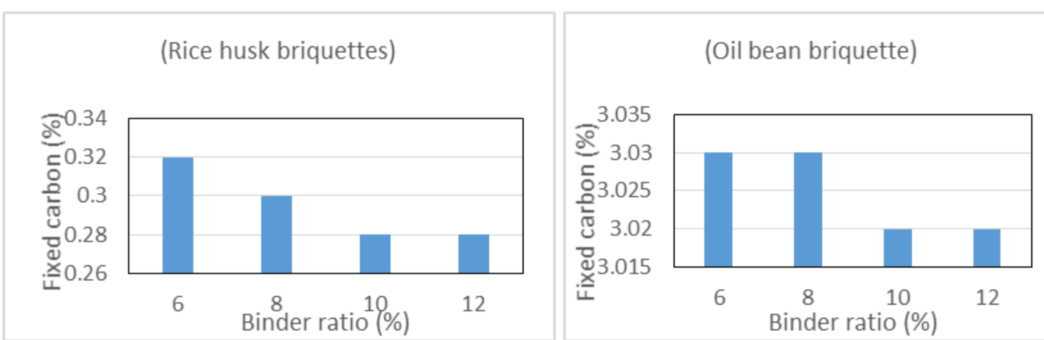

Fig. 4.33 Relationship between fixed carbon and binder ratio (Fixed carbon)

Unlike particle size and compaction pressure, binder ratio had significant effect on fixed carbon content at 5% significance level (p=0.02) as shown in Table 4.9

above and it explains 28.5% of the total variation in fixed carbon content. All the particles were obtained from the same char having uniform fixed carbon content which explains why variation of particle size could not cause any significant effect on fixed carbon content. Compaction pressure on the other hand does not alter the material composition of dry briquettes, hence its insignificant effect on fixed carbon content. Fixed carbon content of briquettes should be as high as possible because the heating value increases with increase in fixed carbon content. The fixed carbon content reduces with increase in cassava binder ratio which implies that the least binder ratio takes preference. The ranks for 6%, 8%, 10%, and 12% binder ratios are 1, 2, 3 and 4 respectively.

Calorific value

The average values for the mean calorific value of the briquettes are presented in Appendix I4 while the result of the multiple linear regression analysis is presented in Table 4.10. Fitted model for calorific value is given in eqn.4.4. The relationship between binder ratio, particle size and calorific value is graphically represented in Fig. 4.33.

Table 4.10 Calorific value model of briquette quality Model

Model			t	Sig.
	Coefficients	Std. Error		
Constant	23708.246	801.492	29.580	.000
Size	1.404	.529	2.656	.012
Pressure	23.107	36.157	.639	.527
Binder	-62.301	25.521	-2.441	.020

$$CV=237008.246+1.404Ps-62.301Br \qquad 4.4$$

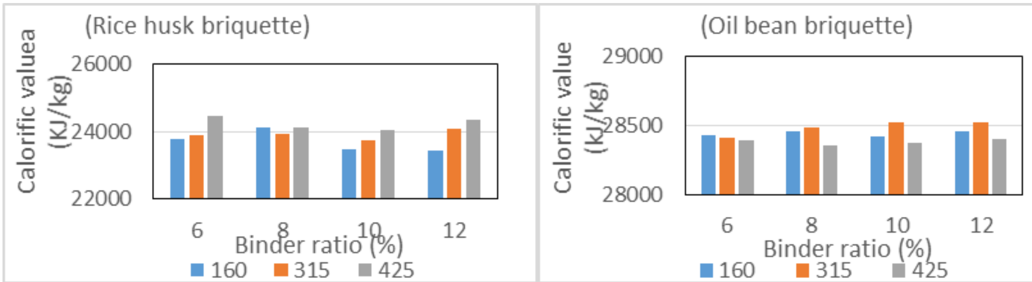

Fig. 4.33 Relationship between ash content, particle size and binder ratio

Heating value is the measure of the amount of heat per unit mass which is therefore required to be as high as possible for the briquettes. On the average, 160µm particles have less heating value than the rest of the particles which then makes it the least preference to 315 and 425µm particles. Ranks for 160, 315, and 425 particles are 3, 2, and 1 respectively. For, binder ratio, heating value reduces with increase in binder ratio, hence preference of the least binder ratio. Ranks for 6%, 8%, 10% and 12% binder ratios are 1, 2, 3 and 4 respectively.

Density

The average values for the mean fixed carbon of the briquettes are presented in Appendix I5. The result of the multiple linear regression analysis is presented in Table 4.11 and the fitted model is given in eqn. 4.5. The relationship between binder ratio, particle size and density is graphically represented in Fig. 4.34 and 4.35 for rice husk and oil bean respectively.

Table 4.11 Density of briquette quality Model

Model			t	Sig.
	Coefficients	Std. Error		
Constant	.435	.069	6.335	.000
Size	-.078	.002	-6.072	.000
Pressure	.021	.003	6.820	.000
Binder	.002	.002	1.002	.041

D =0.435-0.078Ps+0.021Pr+0.002Br 4.5

Where;

Ps = Particle size

Pr= pressure

Br = Binder ratio

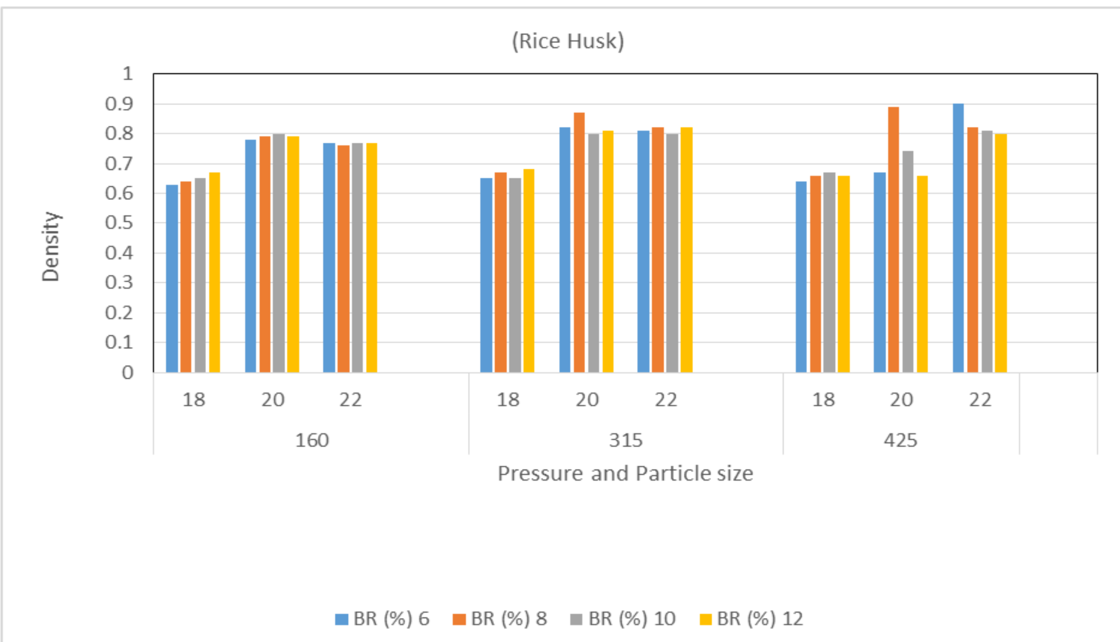

Fig. 4.34 Relationship between density, pressure, particle size and binder ratio (Rice husk briquette)

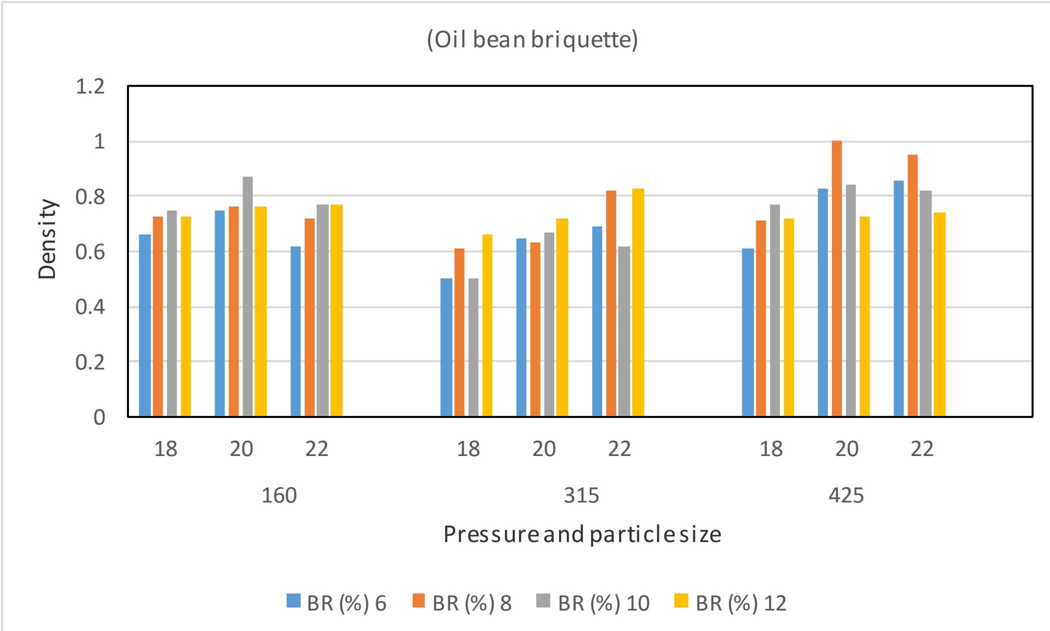

Fig. 4.35 Relationship between density, pressure, particle size and binder ratio (Oil bean briquette)

The model for briquette density is significant at 5% level of significance (p-value:< 000) and it accounts for 78.5% of the total variation. Compaction pressure, binder ratio and particle size had significant effect on briquette density at 5% significance level since their p-values are less than 0.05.

Large uncompacted particles had a density ranging between of 100-220kg/m^3. Medium and small particles had higher densities than large particles by 206kg/m^3 and 416 kg/m^3 respectively because reduction in particle size eases compaction and allows more mass of material for a given volume which increases briquette density.

This could be attributed to the displacement of excess binder from the particles at increasing pressure which results into increase in volume, hence decreasing density. However, the resultant effect of compaction pressure and binder ratio on briquette density was positive.

One percent increase in binder ratio changes briquette density by (0.01 - 0.03 kg/m^3) if all other conditions are kept constant. Increase in cassava binder ratio increases briquette density (Križan et al., 2011) because it fills the pores, hence increasing the mass of material in a given volume. A high density is required for briquettes because increase in density prolongs burning time, reduces space for storage and eases handling. Therefore, factor levels that increase density are given preference.

Particles Size: Fineness particles (160µm) have the highest density, followed by finer particles (315 µm), and then fine particles (425 µm). The ranks of 160µm, 315µm and 425µm particles are 1, 2 and 3 respectively.

Binder Ratio: Density increases with increase in binder ratio which then implies that the highest binder ratio is given preference to low binder ratios. The ranks of 6%, 8%, 10% and 12% binder ratios are 4, 3, 2, and 1 respectively.

Compaction Pressure: Density increases with increase in compaction pressure which means that the highest compaction pressures should be given preference to low compaction pressures. Ranks of 18bar, 20bar, and 22bar compaction pressures are 3, 2, and 1 respectively.

Average ranks of the factor levels

Particle size had significant effect on three of the dependent variables which therefore implies that the number of models having particle size as an explanatory variable are three. The average ranks for fineness, finer and fine particles are 2.333, 1.667, and 2 respectively.

Finer (315µm) particles have the least average rank which implies that their performance is the best among the particle sizes considered in the study

Binder ratio was significant in explaining four of the dependent variables and the average ranks for 6%, 78%, 10% and 12% binder ratios are 1.75, 2.25, 2.75, and 3.25 respectively.

The least average rank is 1.75 for 6% binder ratio which means that the optimal binder ratio for all the dependent variables considered is 6%.

Compaction pressure only had significant effect on density and therefore, the most preferred level was 22bar.

In summary, the optimal factor levels for each factor and their combination gives the optimal condition when putting into consideration all the dependent variables. Much as all treatments satisfied the minimum briquette quality requirements, the fitted linear regression models show that medium sized particles (315µm), 5% binder ratio and 22MPa compaction pressure of the hydraulic cylinder produced briquettes with superior quality (14.74 and 1.05% ash content, 76.06 and 81.84% volatile matter content, 0.34 and 3.03% fixed carbon content, 23559 and 28446 kJ/kg calorific value, and 0.805 and 0.96 kg/m^3 density) for rice husk and oil bean briquette respectively. These make up the optimal condition of the experiment.

4.5 Functional Group of the Optimized Briquettes

The fourier transform infrared (FTIR) spectra of the optimized samples of rice husk and oil bean briquettes are presented in Fig 4.36 and 4.37 respectively. The IR spectrum shows similarity in transmission mode of the two materials irrespective of the fact that their composition are not entirely the same. The comparison in caloric values for biomass waste material and their respective briquettes are presented in Fig. 4.38. Rice husk briquette has heating value of 23,147.01kJ/kg with 54% increase whereas oil bean briquette has 29,604.72kJ/kg with 4.2% increase in heating value.

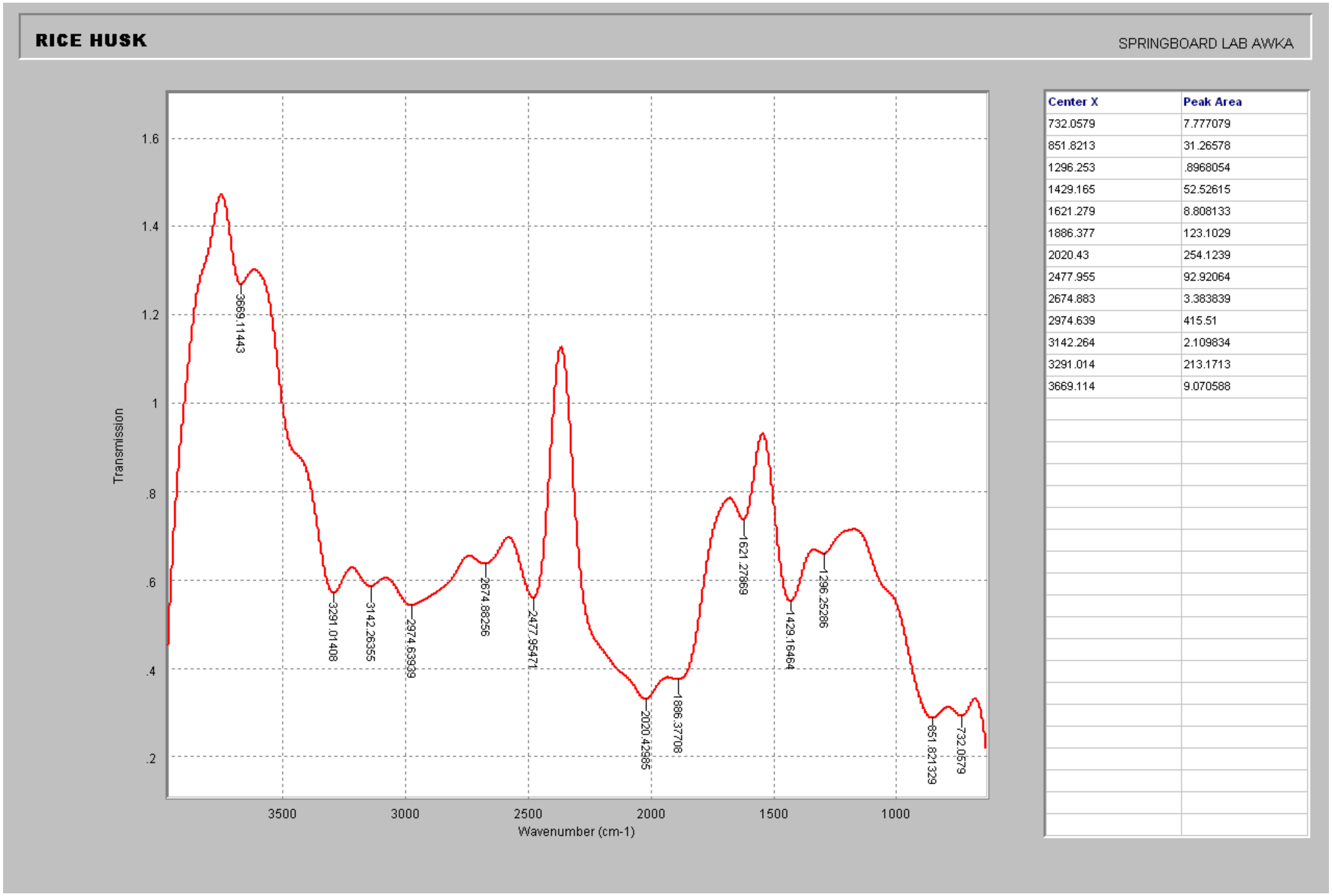

Fig. 4.36 FTIR spectroscopy of rice husk briquette

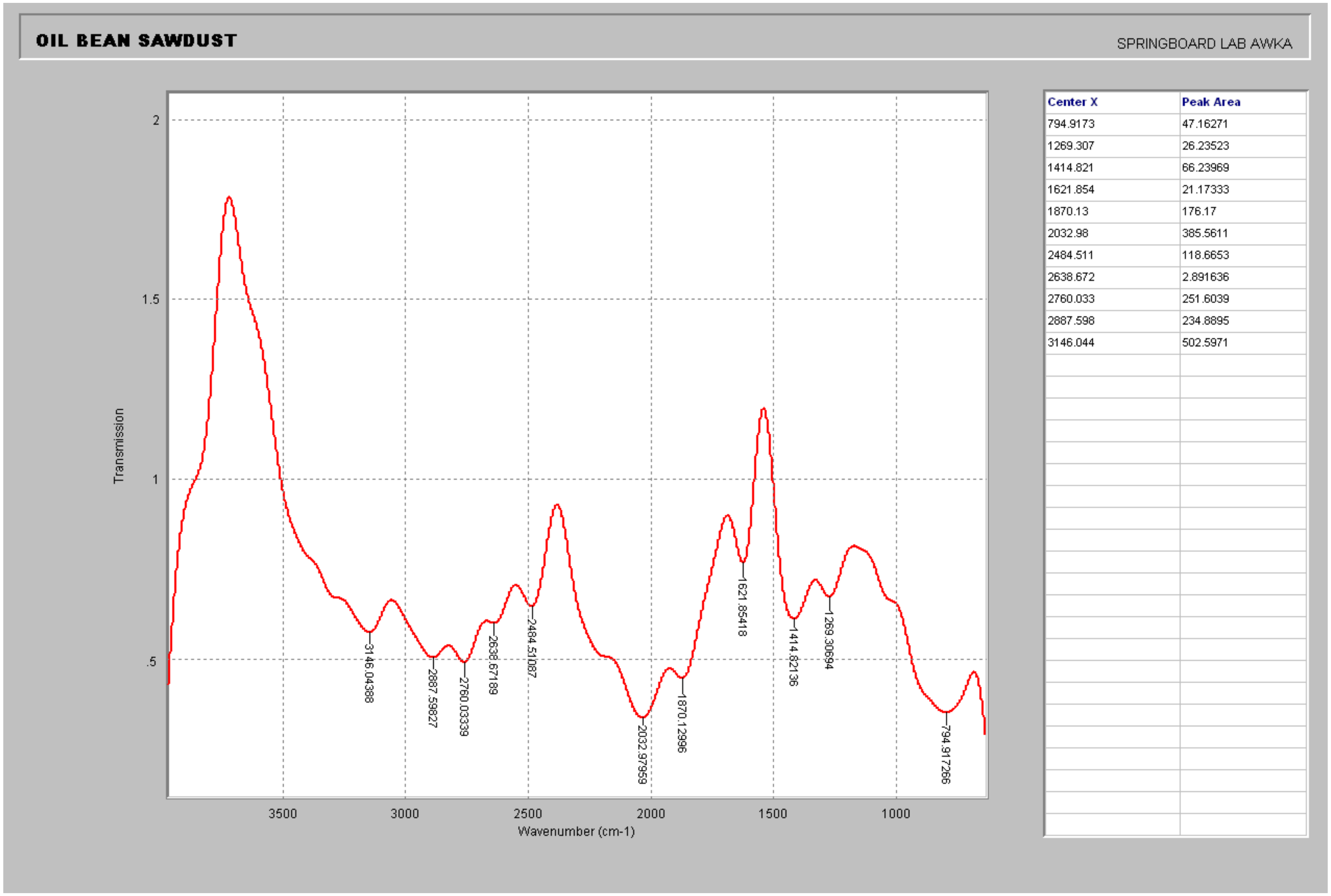

Fig. 4.37 FTIR spectroscopy of oil bean briquette

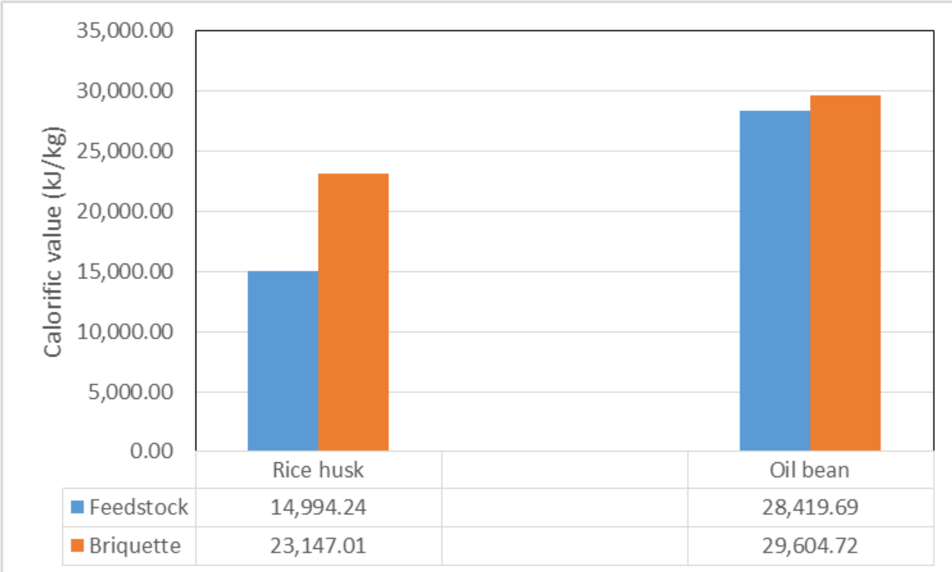

Fig. 4.38 Calorific values of the optimized briquettes

Weak broad bands characterized the infrared spectrum of both samples and showed predominant properties of carboxylic acid functional group Fig. 4.38 and 4.39. Carboxylic acid functional group combines the features of alcohol and ketones because it has both O-H bond and the C=O bond (Wade, 2006). The medium broad spectrum at 2674.883 and 2638.672 cm^{-1} for rice husk and oil bean sawdust briquette are clear and are the basis for the biological properties. At 2477 and 2484.511cm^{-1} of the two materials respectively, there is very broad band O-H acid that overlaps C- H stretch while N-H bend in the amides (1621cm^{-1}) is also present in the material. Amine functional group also combines the features of Amine and Ketones because it has both N-H bond and the C=O bound. These two functional groups of the briquettes confirms that the composition of the briquettes as made of biological materials and thus are renewable.

Heating values of the briquettes is an indication that the briquettes can be applied as energy source in variety of heat application systems. The similarity in the value as compared to the unprocessed material suggested that starch additives might have altered the energy combustion of the briquettes. While the heating value increased drastically almost twice for rice husk (54%), while that of oil bean briquette did not demonstrate much rise (3.5%). From discussion in material characterization (Table 4.1), rice husk had 15.11% ash content while oil bean saw dust had 1.26%. Because as ash content in biomass materials is one major reasons for the remarkable effect on their heating value, combustion characteristics and equipment design (Forero *et al.*, 2015), it is believed that the high ash content of rice husk affected it high rise of calorific value. However, lower porosity has been reported to be accountable for increase in heating value of materials (Abdulrasheed *et al.,* 2015). From the result, it appear that while low porosity might increase the calorific values of some materials, it might be detrimental to others. Oil bean sawdust has calorific value of 23,147 kJ/kg while oil bean husk energy combustion is high almost twice that of the wood sawdust (Madukas et al., 2016). Insignificant increase in calorific value could be attributed to high mechanical strength of the material (Table 3.1) which also is the reason for insignificant of particle size on bulk density (Table 4.6).

4.6 Summary of the findings

Results of the findings have identified biomass wastes materials as good source of energy that contain low amount of harmful elemental properties like sulphur, thus they are environmentally friendly. They can therefore be used as raw materials for briquetting and be energy source in various heat applications. This is indicated from the composition of the materials studied in this research. The materials have high heating value ranging from 14,000-30,000kJ/kg and low sulphur content of 0.04 – 0.1%. From the material composition, sawdust briquettes are more suitable for boilers because of their low ash content (<2%). From all indications, there lies great potentials for these waste materials to be used as energy resource and considering the magnitude of these waste generated in Nigeria, Nigeria could be counted among the countries of the world like Sweden, Finland, Austria, USA and other developed nations that derive a significant amount of their energy from biomass. However, this can only be achieved if the right technologies are in place in processing those biowaste materials from their natural forms to a more applicable form for various energy systems and heat applications.

Hydraulic press for briquette production has great potential in production of high quality briquettes. This is because of numerous advantages it has over other technologies of producing briquettes. Predictive models developed in this study can confidently be utilized in predicting performance of hydraulic briquetting machine. This is evident from the predicted results which highly correlated with those obtained experimentally. This comparative study established both the accuracy in performance and quality of briquettes produced. The models have also identified difference in the material composition in bulk density validation by the introduction of n-value which correlated with ash content of the materials. This however suggests the need for proper characterization of biomass waste materials in briquette production.

On effect of pressure and particle size of different biomass materials reveals significant difference on bulk density of the materials depending on the material composition. Reason for higher bulk density (0.648g/cm^3) for stool wood, (0.631g/cm^3) for Gmelina, (0.703g/cm^3) for Mahogany, (0.767g/cm^3) for oil bean and (0.803g/cm^3) for rice husk, all at 160μm is because particle size plays very important role in briquetting process. Its effect are significant irrespective of the composition of the biowaste material as reported by several researchers which also reported that densification would result in bulk densities in the range of 450 to 700kg/m^3 depending upon the material and densification conditions (Kaliyan et. al., 2009; Kaliyan and Morey, 2006; Colley et. al., 2006; Sokhansanj and Turhollow, 2004). Moreover, Forero-Nunez (2015) established that particle size affect compression ratio proportional. The report identified that the bigger particle, the greater the compression ratio. This however contradicting the finding of the present work but it is understandable to note that the disparity might be due to the limiting treatment levels in pressure the materials were subjected perhaps because the materials were maximally compressed.

Although pressure is another important factor that influences briquette quality, results of the analysis also indicated that its significant as obtained is also a function of the particle size and other characteristics of the materials before briquetting which include lignin, cellulosic and hemi cellulosic content of the material. This on the other hand determines the resistivity of the material to an applied force.

Optimization of briquette quality was achieved by various combinations of process variables to obtain variables for good quality briquettes multiple regression analysis. The quality of the briquette were measured from its calorific value, density, ash content, volatile matter content, etc (Sastry et al.,2013). Results obtained from the analysis revealed that briquette density of 0.8050 g/cm^3 was obtained at 6% binder, 315μm particle size and at 22bar. At this density, ash content, volatile matter, fixed carbon and calorific values of the briquettes are 1.05%, 81.84%, 0.31% and 23559kJ respectively. This result ensures safety in use of the briquettes for energy applications.

Finally, the role of bulk density in the efficiency of transportation and storage of briquettes is very vital as it influence the engineering design of transport equipment, storage and conversion process (Woodcock and Mason, 1987). As noted in Appendix C, bulk density of the materials ranged between 0.07 to 0.18 g/cm^3 whereas the briquettes bulk density varied between 0.365 to 0.806 g/cm^3. Similar result was obtained for sawdust as there is increase in density (0.12 to 0.22 g/cm^3) when decreasing the particle size from big to fine sizes (Forero-Nunez *et al.* 2015). Low density has characterized most lignocellulosic and fibrous materials such as sawdust thus they have a lot of void spaces throughout its structure that are filled up with air. After reducing the size of the particles, the fine particles releases the air inside and then increase density. Among the materials studied, Gmelina had the lowest whereas rice husk had the highest bulk density. However, bulk density of the materials used in this study was within the range reported for other biomass materials (Adapa et. al, 2010).

It is ultimately very important to study these characteristics of biomass materials for determination of the optimum performance of a briquetting machine.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Management of biomass wastes is one area of renewable energy generation that have received very little attention in Nigeria rather they are regarded as worthless material that amount to nothing so they need to be done away with possibly by burning them at point of production or are dispose inappropriately. This research work have broadened this area of waste management for energy applications. Direct burning of loose agro waste residues like wood sawdust, rice husk, palm kernel shells, and groundnut shells in a conventional manner is associated with very low thermal efficiency, loss of fuel and widespread air pollution. But when these wastes are made into briquettes, these problems are mitigated, transportation and storage cost are reduced and energy production by improving their net calorific values per unit is enhanced.

Briquette making from agricultural residue is one sure way of providing sustainable energy for developing countries. It can also help to create employment, sanitize the environment and help in fighting climate change because there will be less dependence on fossil fuel for energy. In this light, waste to energy conversion would be an economical and ecofriendly way for addressing both the issues of waste management and energy shortage. However, for briquettes to be used as fuel source, there is need to improve and promote its production technology in the area of machine design and operation. Due to the limited number of research works on hydraulic press, it has limited its adoption in briquette production as it regards it performance in producing good quality briquettes. Although its use as briquetting machine is not versatile in Nigeria because of this limitation, the present study has provided some helpful models needed in evaluating their performances. With the finding in the current study, adoption of C-frame hydraulic press for briquette production will provide wide range of benefits which are and not limited to; low production and operating cost, versatility, overload protection, large capacity etc. Apparently, this research was able to develop predictive mathematical models that can be used to evaluate the performance parameters of C-frame hydraulic briquetting machine. The performance models were verified with measured data from a C-frame hydraulic press It is obvious that emergence of these models will assist in better analysis of this type of hydraulic briquetting system as it relate to its application to biomass wastes. The quality of briquette obtained were optimized using compaction pressure, binder ratio and particle size.

It was also observed from the study that production of good quality briquettes from biomass waste briquettes is dependent on a number of factors whose influence were studied and found to be at very high significance depending on the material. Therefore from the foregoing intentions achieved in the course of the study, the following are the summary of findings:

1. Biomass waste are very good source of energy and can be produced into briquette forms in which they can be utilized as energy source in heat application systems. The study also observed biomass briquettes can help to reduce the environmental degradation and pollution associated with its indiscriminate disposal in unprocessed form.
2. Relevant parameters that are required for the performance of hydraulic press machine were identified as compaction pressure, machine geometry, moisture content, particle size, binder ratio, initial bulk density of the biomass material etc. and output capacity,

quantity of damaged briquettes, production efficiency and bulk density can be described with developed predictive mathematical models.

3. CAD model analysis was conducted on the key structural members of the machine to determine suitability of the machine to perform briquetting operation, it found that the stress, strain and displacement analysis was within the acceptable range for the machine. From the structural analysis of the frame and the cylinder hanger, the analysis maximized the stiffness, that is, removes material that contributes least to the stiffness of the structure under the given loading conditions. The stress concentration is at the point of attachment of the crucible cup and electric motor. At these point the maximum stress that is exerted is 13.3N/mm^2 and this is less than the yield stress (351.6N/mm^2) for mild steel therefore, the machine is safe and adequate to perform briquetting operation. It was observed also that yield displacement of the mild steel is at 0.067905mm but 0.05365mm was obtained for the press.
4. The predictive models developed in the research work will be used for predicting performance of hydraulic briquetting machine and can be applied in further analysis of the system in terms of fluid analysis and extensive structural analysis of the entire system.
5. All the developed models were compared with measured data from the machine and coefficient of correlation (R) value of 0.99, 0.96 and 0.92 for output capacity, damaged briquettes and production efficiency models respectively. Bulk density model for each of the material used also showed high R value of 0.99, 0.99, 0.96, 0.96 and 0.98 for stool wood, Gmelina, Mahogany, oil bean and Rice husk respectively.

6. On the effect of pressure and particle size on physical properties of the briquettes, it was observed that pressure increased bulk density at reduced particle size. This was attributed to low inter particle spaces that exist for fine particle sizes. Analysis of variance on the effect of particle size on bulk density shows there is significant at <0.1% probability for all the materials except Oil bean sawdust whereas at the levels of pressure studied there was also high significant difference at probability level of 1% for all the materials except Stool wood sawdust. These results indicates that response of biomass materials differ during compression process and this determine the characteristic of briquettes produced.
7. The optimization values were obtained at pressure of 22bar, 6% binder, and 315µm particle size. These values obtained can be utilized in producing good quality briquettes.

In conclusion, it can be deduced that the results of analysis in this research work can encourage developers of briquetting machine to venture more into using a C-frame hydraulic briquetting machine. This is based on the numerous advantages it has over other briquetting machines and based on CAD result on the suitability of the machine for briquette production, the frame and the cylinder hanger was found to be the main component that are subjected to failure during machine operation. However, the predictive mathematical models can be used in evaluating its performance at optimum design structure. The results obtained are quite important in design of hydraulic press.

5.2 Contribution to knowledge

The contribution of this work to knowledge are stated as follows;

1. The formulation of mathematical models for hydraulic briquetting machine for predicting output capacity, damaged briquettes, production efficiency and bulk density of biomass

briquettes and determination of model constants for various biomass materials as implemented in the models.

2. The quality optimization of process variables (binder, particle size and pressure) for maximization of briquette quality was obtained.
3. Evaluation of the significant effect of process variables (pressure and particle sizes) on bulk density and compression ratio of the briquettes was attained.

6.3 Recommendations

In view of the current research carried out, the following should be considered for further investigation:

1. There is need to determine model constants for other biomass materials that were not studied in the present study.
2. Other research work on comparison of these models with other models validation is very important.
3. Another study should be done to assess the strength of briquettes at optimal condition to ascertain whether they can withstand crumbling during handling and transportation.
4. The need to standardize briquette production conditions requires investigation of other raw materials since briquette quality is greatly influenced by its composition.

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