



ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CHEMICAL and BIO ENGINEERING
ENVIRONMENTAL ENGINEERING STREAM
Briquetting of Sawdust using Waste Paper as a Binder

A Thesis

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Declaration

I, the under signed, declare that this Thesis, entitled as, “Briquetting of Sawdust using waste paper as a Binder” is a result of my efforts and hard work. This thesis has never been presented for a degree at any University and that all the source of materials used for the thesis has been cited and duly acknowledged.

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Nomenclature

D_p	Average particle diameter of sawdust
d_1	Size of the upper sieve
d_2	Size of the lower sieve
A	Sawdust with average particle size of 0.5 mm
B	Sawdust with average particle size of 1.5 mm
C	Sawdust with average particle size of 3 mm
D	Sawdust with average particle size of 4.8 mm
E	Sawdust with average particle size of 6.8 mm
F	Raw sawdust (mixture)
1	25 %
2	30 %
3	35 %
4	40 %
5	45 %
wt	Weight
A_v	Briquettes bonded with avocado kernel flour
ρ_{br}	Density of briquette, g/cm^3
M_{br}	Mass of briquettes, kg/m^3
V_{br}	Volume of briquettes, cm^3
R	Radius of the briquette, cm,
H	Height of the briquette, cm,
Π	Mathematical constant i.e. 3.14
PI	Porosity index (%)
W_s	Dry weight of the sample briquette (g)
W_w	Wet weight of the sample briquette after immersed in water (g)

W_L	Weight loss percentage
S_R	Shatter resistance (%)
VM	Volatile matter (%)
AC	Ash content (%)
FC	Fixed carbon (%)
H_v	Heating value (MJ/kg)
ρ_{sd}	Density of sawdust (g/cm^3),
M_{sd}	Mass of sawdust (g)
V_{con}	Volume of the container (cm^3)
MC	Moisture content (%)

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Abstract

This study explored the possibility of producing sawdust briquettes that could be used for energy supply in small factories and for domestic cooking. A briquetting machine suitable for the production of sawdust briquettes on a small scale was constructed. A portion of sawdust was screened in to average diameter of: A (0.5mm), B (1.5mm), C (3mm), D (4.8mm), E (6.8mm) using standard sieves of 1mm, 2mm, 4mm, 5.6mm and 8mm mesh size. The raw sawdust was characterized for the following properties: moisture content (24.43%), density (91.34 kg/m³), volatile matter (94.92%) and ash content (2.6%). Briquettes were produced by mixing sawdust (both screened and raw) with waste paper in weight percentage ratios of 75:25, 70:30, 65:35, 60:40 and 55:45 respectively at three different die diameters. The computed density, porosity index, shatter resistance, volatile matter, ash content, fixed carbon and calorific value for all sawdust briquettes falls in the range of 218.24-322.62kg/m³, 33.97-312.4%, 98.88-99.95%, 70.24-90.56%, 2.33-7.26%, 6.7-24.26% and 14.5019-18.3832MJ/kg respectively. Further more from the results of the Analysis of Variance (ANOVA) carried out, there were no significant difference ($p>0.05$) in the quality of briquettes bonded with waste paper at different percentages except for percentage volatile matter, ash content and heating value . The effect of die diameter was found to be significant only on the physical properties of sawdust briquettes. A significant effect of average particle size of sawdust was recorded in density, porosity index and volatile matter of the briquettes. However, it was insignificant on shatter resistance, ash content and fixed carbon of the briquettes. The optimum blend of sawdust particle size - waste paper percentage and die diameter- waste paper percentage was assessed on the basis of the briquette properties: density, porosity index, volatile matter, ash content and gross calorific value. The combination of 0.5mm average particle size of sawdust and 30% waste paper gave the optimal density of 270.658kg/m³, porosity index of 29.782%, volatile matter of 86.496%, ash content of 2.829% and gross calorific values of 16.613 MJ/kg. The optimum blend of die diameter and waste paper was obtained at the combination of 6 cm and 25% with optimal values of density of 306.079 kg/m³, porosity index of 35.92%, volatile matter of 83.90%, ash content of 3.05% and gross calorific value of 17.134MJ/kg. It was concluded that the calorific values of briquettes obtained were sufficient to produce heat required for household cooking. Therefore sawdust briquettes can be a very good alternative source of energy for domestic cooking

CHAPTER ONE

1.0 Back ground of the study

The role and impact of natural resources in the functioning of an economic system can never be over-emphasized. In view of these, energy which, is usually obtained when all these natural resources are harnessed plays a vital role in the overall development planning of any nation. Energy has been the central cross-sectoral issue, which affects all human activities either directly or indirectly. It is a vital input to economic growth and development of any economy sector. Energy has been seen to be a crucial input in the process of economic, social and industrial development. Apart from the other three classical factors i.e. land, capital and labor, the role of energy cannot be underestimated when it comes to development [1].

Energy resources are generally classified into two namely renewable and non-renewable. The renewable are thought to be a better option since the non-renewable has a capability not to be replenished and could be exhausted. Renewable energy sources are more environmentally friendly and are thus better candidates for use in achieving some measures of technological development under a sustainable environment both in the developed and developing nations. [2].

It is in view of this that much attention is being given to the search for alternative energy sources that will be renewable. This renewable energy includes solar energy in its direct form, wind, geothermal, water and biomass. Out of all these types of renewable energy, Biomass which is the generic name given to all dry plant materials and organic waste has found more recognition. This is because its development always results in a cleaner environment and at the same time can provide the means to recycle wastes to some valuable product. Another advantage of biomass over other sources of renewable energy is its ready availability and energy conversion that is not so expensive [1].

Wood from commercial forest land is the largest potential source of biomass when compared to others. Most of this potential lies in wood processing by-products otherwise known as wood wastes such as sawdust, spent paper pulping liquor, forest management by products such as thinning and logging residues. Out of all the various kinds of wood wastes, sawdust is of high

importance. Sawdust is always obtained from forest wastes or manufacturing wastes. As a result of growing worldwide concern regarding environmental impacts particularly climate change from the use of fossil fuels coupled with the volatile fossil fuel market and, the need for an independent energy supply to sustain economic development, there is currently a great deal of interest in renewable energy in general and biomass energy in particular[1].

Among the several kinds of biomass resources, agricultural residues - sawdust, rice husk, cotton stalk, groundnut husk etc - have become one of the most promising choices as cooking fuels due to its availability in substantial quantities as waste annually. However, the utilization of these biomass residues in their natural form as fuel is difficult because of their very low bulk density, low heat release and the excessive amounts of smoke they generate. All of these characteristics make them difficult to handle, store, transport, and utilize in their raw form. One of the ways of improving the thermal value of such biomass is the application of briquetting technology. This involves the densification of loose biomass to produce fuel briquette which has better handling characteristics and enhanced volumetric calorific value [1].

Briquetting involves the collection of combustible materials that are not usable as such because of their low density, and compressing them into a solid fuel product of any convenient shape that can be burned like wood or charcoal. Briquettes are easier to package and store, cheaper to transport, more convenient to use, and their burning characteristics are better than those of the original organic waste material [3].

Presently, the major source of energy to the rural community is fuel woods because other sources of energy (electricity, gas and kerosene) are either not available or grossly inadequate where available and they are beyond the reach of the masses. Fuel wood collection has grave consequence on forest conservation and sustainable forest resources management. One of the popular biomass briquettes emerging in developed and developing countries is the sawdust briquettes. This involving compressing and extruding sawdust to make a reconstituted log that can replace firewood. It saves trees that can prevent soil erosion and desertification by providing an alternative to burning wood for domestic and industrial heating and cooking. Also, it substitutes sawmilling waste for a valuable resource [5].

1.1 Statement of problem

Two of the major energy issues today are that of energy security and environmental implication of fossil fuel consumption. The population of Ethiopia depends on biomass for everyday energy needs. Fuel wood accounts for around 78% of the total energy demand in Ethiopia. Forest resources in Ethiopia have experienced so much pressure due to increasing need for wood and wood products. Nearly half the world's population, almost all in developing countries, like Ethiopia, cooks using biomass solid fuels, predominantly wood. Heavy reliance on wood for domestic cooking leads to deforestation or desertification resulting in further scarcity of this resource. With deforestation becoming a major problem in many parts of the developing world, there is increased scarcity of wood for household cooking. With the increase in the rate of tree felling for furniture making and charcoal production as well as for firewood, the forest ecosystem has been greatly disturbed and altered thus leading to a high rate of deforestation and environmental pollution.

Sawdust is waste material from all types of primary and secondary wood processing. Sawdust accumulation and disposal at the various sawmills have always created an environmental problem. Sawdust is bulky, and is therefore expensive to store and transport. Apart from the problems of transportation, storage, and handling, the direct burning of loose saw dust biomass is associated with very low thermal efficiency and widespread air pollution.

Starch is one of the popular binders used in briquetting. As good as starch has been, it has to be replaced because, it is the most common carbohydrate in the human diet and is contained in large amounts in such staple foods as potatoes, wheat, maize, rice and cassava. This gives the reason why waste paper was employed in this work. With successful production of briquettes from sawdust, fuel wood users especially rural dwellers can have an alternative to fuel wood as sources of energy at lower cost. This is due to the fact that sawdust is readily available in large quantities as wastes in majority of the wood processing industries.

Natural resources and primary energy sources are becoming scarce. Supply of new and alternative energy sources has become a necessity in order to provide better outcome from energy cost and efficiency. In this regard, briquetting of sawdust using waste paper as a binder provides an excellent energy source and an environmental friendly combustible fuel.

1.2 Objectives

1.2.1 General objective

The General Objective of this research was to produce sawdust briquette using waste paper as a binder.

1.2.2 Specific objectives

The specific objectives were to:

- 1 Determine physical and combustion properties of raw sawdust;
- 2 Determine the physical and combustion properties of the sawdust briquettes; and
- 3 Investigate the effect of average particle size of sawdust, waste paper percentage and die diameter on the quality of sawdust briquettes.

CHAPTER TWO

2.0 Literature Review

2.1 Sawdust Briquettes

Sawdust is a kind of by-product from cutting, grinding, drilling, sanding or pulverizing wood with a saw or other tools. Sawdust is readily available in large quantities as wastes in majority of the wood processing industries. Sawdust constitutes a major source of residues of small particles of wood waste, which takes a long time to decompose, available in sawmill industries, wood processing and pulp plants. High concentration of sawdust in one area is considered an environmental problem. Sawdust is easily available at almost free of charge from saw mills as well as from individual carpenters within many societies. Sawdust contains a lot of energy and is therefore ideal for making inexpensive fuel briquettes. The good thing about sawdust is that we can utilize its lignin to bind the briquettes instead of using starch binder which is the most expensive component in briquettes. It has been observed that the forestry and wood based industries are usually characterized by the production of large volumes of residues without any economic utilization. In the past, these residues were left in the field to be wastefully burnt away. However, in recent years, burning of wood residues in the open has been discouraged because of environmental problems associated with it [3].

There is a potential for utilizing forestry and wood residues especially sawdust for energy. The most significant role of sawdust is played as fuel by processed into pellets. It is an emerging and promising career to make wood pellets from sawdust. Nowadays, hundreds of countries all over the world have built their factories of making wood pellets from sawdust. Compared to agricultural raw material, sawdust has a lower ash content, lower risk of corrosion and dirtying and also requires no additives or thickeners to increase production costs since humidity and the actual wood lignin work as natural adhesive. One of the popular biomass briquettes emerging in developed and developing countries is the sawdust briquettes. The sawdust wastes having been briquetted can be utilized as a high grade solid fuel by improving the calorific value and ensuring a clean and bluish smoke free flame suitable for cooking. This could be a way of turning wood waste to wealth. The calorific value of sawdust briquettes is comparable to that of lower quality

class coal. When sawdust is briquetted, chemical pollutants are eliminated and with enough supply of oxygen complete combustion of the fuel is guaranteed [1].

It has been proposed that the conversion of sawdust wastes through briquetting process will go along way reducing waste disposal problems in majority of the wood processing industries. Furthermore deforestation which promotes pollution will be drastically reduced if the use of sawdust waste is enhanced. The production of briquettes from sawdust exemplifies the potential of appropriate technology for wood waste utilization. It saves trees that can prevent soil erosion and desertification by providing an alternative to burning wood for domestic and industrial heating and cooking. Also, it substitutes sawmilling waste for a valuable resource. It improves health by providing a cleaner burning fuel and also provides a better alternative to firewood (40% more efficient, longer burning and better) as well as helping to protect the environment by reducing the number of trees cut for firewood. In addition, briquetting engenders many micro enterprise opportunities that include the production of the presses from locally available materials, using materials like agricultural waste and sawdust, briquette production enterprise, packaging and selling of the Briquette [5].

If produced at low cost and made conveniently accessible to consumers, sawdust briquettes could serve as complement to firewood and charcoal for domestic cooking and agro-industrial operations. Besides, briquettes have advantages over fuel wood in terms of greater heat intensity, cleanliness, convenience in use, and relatively smaller space requirement. An important advantage of the sawdust briquettes over the rest of materials used is the sulphur content, which is 0% in order to avoid contaminating the environment with sulphur dioxide emissions during combustion [1].

2.2 Fundamental aspects of briquetting

Briquetting is the process of densification of biomass to produce homogeneous, uniformly sized solid pieces of high bulk density which can be conveniently used as a fuel. It is important to mention that biomass densification is simply a physical transformation that does not change the chemical composition of biomass. Thus, the calorific value of biomass is not affected by densification. Nevertheless, since non-densified products exhibit lower bulk density than pellets

and briquettes, fluffy materials (e.g. chips, sawdust, etc.) have lower energy density than densified products. The process offers the following advantages:

- The net calorific value per unit volume is increased,
- Easier handling,
- Lower transportation cost
- The fuel produced is uniform in size and quality,
- Disposal of residue is facilitated, and
- Environmental friendly fuels

It can be regarded as a waste control measure in the case of production of briquettes from agricultural wastes. However, depending on the material of interest, briquetting can be used to provide fuel source as a preventive measure to many ecological problems. During the briquetting process, fine material is compacted into regular shape and size which does not separate during transportation, storage or combustion. The briquetting of biomass is one sure way of fighting climate change and ensure sustainable development due to the fact that it reduces dependence on fossil fuel, use waste products, as well as it reduces pollution which may have resulted in case of dumping [4].

There are a number of ways which have been developed to solve the problem of how to put the huge volume of wastes from agriculture and agro-processing to some useful purpose. Briquettes made from materials that cost little or no money to obtain, such as old newspaper or partially decomposed plant waste, can be an alternate fuel to charcoal, firewood or coal, and may cost less. Depending on materials used to make the briquettes, they may burn cleaner than coal. Finally, turning “throw-away” materials into a fuel source is attractive because it is a sustainable process. Many different methods and technologies exist for pressing briquettes. Briquettes can be used as an alternative to fuel-wood as the demand for the latter, especially in the developing countries continue to rise as a result of increasing population. Also the problem of agricultural and municipal waste disposal (i.e. sawdust, rice husk, office and household waste, etc.) is posing challenge to the farmer and the general public as these wastes constitute a nuisance to the environment. Also, more than two billion people globally use biomass for cooking food. Smoke from burning biomass is one of the fourth leading causes of death and disease in the world’s poorest countries [6].

Briquetting can be regarded as an attempt to link up two large and complex worlds: that of agriculture and that of fuel supply and use. Briquetting will never the impact of a major new fuel such as oil, which can change entire patterns of consumer behavior in the energy world. This means that technology of briquetting must fit with the existing agricultural context rather than the other way round [7]. Among the notable advantages of briquetting process are increment in bulk density of biomass residues, lowering moisture content and making briquettes of uniform size and shape for easy handling, transport and storage. It also helps in uniform burning when used as fuel [8]. On the basis of compaction, the briquetting technologies can be divided into:

- ➡ High pressure compaction
- ➡ Medium pressure compaction with a heating device
- ➡ Low pressure compaction with a binder.

In all these compaction techniques, solid particles are the starting materials. The individual particles are still identifiable to some extent in the final product. Briquetting and extrusion both represent compaction i.e., the pressing together of particles in a confined volume. If fine materials which deform under high pressure are pressed, no binders are required. The strength of such compacts is caused by van der Waals' forces, valence forces, or interlocking. Natural components of the material may be activated by the prevailing high pressure forces to become binders. Some of the materials need binders even under high pressure conditions [9].

In order to understand the suitability of biomass for briquetting, it is essential to know the physical and chemical properties of biomass which also influence its behavior as a fuel. Physical properties of interest include moisture content, bulk density, void volume and thermal properties. Chemical characteristics of importance include the proximate and ultimate analysis, and higher heating value. The physical properties are most important in any description of the binding mechanisms of biomass densification [7]. Densification of biomass under high pressure brings about mechanical interlocking and increased adhesion between the particles, forming intermolecular bonds in the contact area. In the case of biomass the binding mechanisms under high pressure can be divided into adhesion and cohesion forces, attractive forces between solid particles, and interlocking bonds. High viscous bonding media, such as tar and other molecular weight organic liquids can form bonds very similar to solid bridges. Adhesion forces at the solid-

fluid interface and cohesion forces within the solid are used fully for binding. Lignin of biomass/wood can also be assumed to help in binding in this way. Finely divided solids easily attract free atoms or molecules from the surrounding atmosphere. The thin adsorption layers thus formed are not freely movable. However, they can contact or penetrate each other. The application of external force such as pressure may increase the contact area causing the molecular forces to transmit high enough which increases the strength of the bond between the adhering partners. Another important binding mechanism is van der Waals' forces. They are prominent at extremely short distances between the adhesion partners. This type of adhesion possibility is much higher for powders. Fibers or bulky particles can interlock or fold about each other as a result forming interlocking or form-closed bonds. To obtain this type of bond, compression and shear forces must always act on the system. The strength of the resulting agglomerate depends only on the type of interaction and the material characteristics [9].

2.3 Briquetting system variables

2.3.1 Feedstock variables

Feedstock/material variables are those factors which are characteristic of a particular biomass feedstock. Feedstock variables include moisture content, particle size, shape, and distribution. These variables are feedstock dependent and have a great effect on pellet quality and in selecting proper process conditions.

Moisture content: Moisture present in the biomass facilitates starch gelatinization, protein denaturation, and fiber solubilization processes during extrusion, pelleting, or briquetting. The percentage of moisture in the feed biomass to extruder machine is a very critical factor. In general, it has been found that when the feed moisture content is 8-10 %, the briquettes will have 6-8% moisture. At this moisture content, the briquettes are strong and free of cracks and the briquetting process is smooth. But when the moisture content is more than 10%, the briquettes are poor and weak and the briquetting operation is erratic. Excess steam is produced at higher moisture content leading to the blockage of incoming feed from the hopper, and sometimes it shoots out the briquettes from the die. Therefore, it is necessary to maintain optimum moisture content. In the briquetting process water also acts as a film type binder by strengthening the bonding in briquettes. In the case of organic and cellular products, water helps in promoting

bonding by van der Waals' forces by increasing the true area of contact of the particles. In fact, the surface effects of water are so pronounced that the success or failure of the compaction process solely depends solely upon the moisture content of the material. The right amount of moisture develops self-bonding properties in lignocelluloses substances at elevated temperatures and pressures prevalent in briquetting machines [10].

Particle Size, Shape, and Distribution: Particle size and shape are of great importance for densification. It is generally agreed that biomass material of 6-8 mm size with 10-20% powdery component (< 4 mesh) gives the best results. Although the screw extruder which employs high pressure (1000 - 1500 bar), is capable of briquetting material of oversized particles, the briquetting will not be smooth and clogging might take place at the entrance of the die resulting in jamming of the machine. The larger particles which are not conveyed through the screw start accumulating at the entry point and the steam produced due to high temperature (due to rotation of screw, heat conducted from the die and also if the material is preheated) inside the barrel of the machine starts condensing on fresh cold feed resulting in the formation of lumps and leads to jamming. That is why the processing conditions should be changed to suit the requirements of each particular biomass. Therefore, it is desirable to crush larger particles to get a random distribution of particle size so that an adequate amount of sufficiently small particles is present for embedding into the larger particles. The presence of different size particles improves the packing dynamics and also contributes to high static strength. Only fine and powdered particles of size less than 1 mm are not suitable for a screw extruder because they are less dense, more cohesive, non-free flowing entities [10].

2.3.2 Process variables

Process variables such as temperature, pressure, retention time, and die geometry and speed plays an important role in reaching the desired product quality of densified biomass in terms of durability, density, and calorific value [10].

Temperature: Quality attributes like durability and bulk density are significantly influenced by barrel temperature. The pressure required to obtain a certain density is reduced by the addition of heat in the die. High temperature conditioning of the raw materials will increase the briquette durability [10].

Pressure: Pressure plays an important role in the quality of pellets from agricultural biomass. Briquetting pressure should be selected at an optimum value that influences the mechanical strength by the increasing plastic deformation. However, above an optimal briquetting pressure, fractures may occur in the briquette due to a sudden dilation. Application of high pressure and temperature during densification may develop solid bridges by diffusion of molecules from one particle to another at the point of contact, which increases the density [10].

Die diameter: The dimensions significantly affect both the amount of materials that can be pelleted and the energy required for compression and influences the product properties like moisture content, bulk density, and durability. The length to diameter ratio can be a good measure for degree of compression during briquetting. The increase in pelletizing pressure increases the length of the pellet, where as the increase in diameter of the pellet decreases the pelleting pressure. Hence, the dimensions of the die and press channels in the matrix have a strong influence on deciding the pressure needed to press the pellets through the matrix [10].

2.4 Briquetting technologies

Biomass densification represents a set of technologies for the conversion of biomass residues into a convenient fuel. The technology is also known as briquetting or agglomeration. Depending on the types of equipment used, it could be categorized into five main types:

- Piston press densification
- Screw press densification
- Roll press densification
- Pelletizing
- Low pressure or manual presses [11]

2.4.1 Piston press densification

High compaction technology or binderless technology consists of the piston press and the screw press. The piston press acts in a discontinuous fashion with materials being fed into a cylinder which is then compressed by a piston in to slightly-tapering die. The compressed material is heated by frictional forces as it is pushed through the die. The diameter of the briquette is closely

related to the output of the machine [10]. There are two types of piston press 1) the die and punch technology; and 2) hydraulic press. In the former, which is also known as ram and die technology, biomass is punched in to a die by a reciprocating ram with a very high pressure there by compressing the mass to obtain a compacted product. The hydraulic press process consists of first compacting the biomass in the vertical direction and then again in the horizontal direction [2].

The merits and demerits of this technology are:

- There is less relative motion between the ram and the biomass hence, the wear of the ram is considerably reduced.
- Some operational experience has now been gained using different types of biomass.
- The moisture content of the raw material should be less than 12% for the best results.
- The quality of the briquette goes down with an increase in production for the same power.
- Briquettes are somewhat brittle [9].

2.4.2 Screw press densification

In the screw process, material is fed continuously into a screw which forces the material into a cylindrical die; this die is often heated to raise the temperature the point where lignin flow occurred. Pressure builds up smoothly along the screw rather than discontinuously under the impact of piston [7].

The compaction ratio of screw presses ranges from 2.5: to 6:1 or even more. Due to the application of high pressures, the temperature rises fluidizing the lignin present in the biomass which acts as a binder. The outer surface of the briquettes obtained through this process is carbonized and has a hole in the center which promotes better combustion [12].

2.4.3 Role press densification

In a briquetting roller press, the feedstock falls in between two rollers, rotating in opposite directions and is compacted into pillow –shaped briquettes. Briquetting biomass usually requires a binder. This type of is used for briquetting carbonized biomass to produce charcoal briquettes [11].

2.4.4 Pelletizes

Pelletizing is closely related to briquetting except that it uses smaller dies (approximately 30 mm) so that the smaller products are called pellets. The pelletizer has a number of dies arranged as holes bored on a thick steel or ring and the material is forced into the dies by means of two or three rollers. The two main types of pellet presses are: flat/disk and ring types. Other types of pelletizing machines include the punch press and the Cog-Wheel pelletizer. Pelletizers produce cylindrical briquettes between 5mm and 30mm in diameter and of variable length. They have good mechanical strength and combustion characteristics. Pellets are suitable as a fuel for industrial applications where automatic feeding is required. Typically pelletizers produce up to 1000kg of pellets per hour but initially require high capital investment and have high energy input requirement [9].

2.4.5 Low pressure or manual presses

There are different types of manual presses used for briquetting biomass feed stocks. They are specifically designed for the purpose or adapted from existing implements used for other purposes. Manually clay brick making presses are a good example. They are used both for raw biomass feedstock or charcoal. Although it is time consuming, it is good alternative for small scale operators who cannot afford an expensive briquetting unit. The main advantages of low-pressure briquetting are low capital costs, low operating costs and low level of skill required to operate the technology. Low-pressure techniques are particularly suitable for briquetting green plant waste such as bagasse (sugar cane residues) and sawdust. The wet material shaped under low pressure in simple block presses or extrusion presses. The resulting briquette has a higher density than the original material but still requires drying before it can be used. The dried briquette has little mechanical strength and crumbles easily. The use of a binder is imperative [11].

2.5 Common binders used in biomass densification

Binders are substances, organic or inorganic, natural or synthetic, that can hold (bind) two things or something together. Two types are combustible and non-combustible binders. Combustible binders are binders that support combustion and can burn. Examples are starch, petroleum residues, molasses, cottonseed oil etc. Non-combustible binders are binders that cannot support combustion examples are clay, cement, limestone, etc. Starches have proved very satisfactory as binders. Binders improve the binding characteristics of the biomass and produce a more durable product. Binders also help reduce wear in production equipment and increase abrasion resistance the fuel [6].

In pellet production, binders are usually allowed, but must be specified on the final product. Binders are needed when the pressure produced by the compacting equipment is too low for 'self-bonding' or when materials are compacted that does not self-bond such as straw, rice husk and charcoal. Alternative uses of the binder must be weighed against the value of the final product as an energy source. Commonly used binding agents include starches from corn, wheat, cassava (manioc), sugar cane molasses, tars, pitch, resins, glues, fiber, fish waste and certain plants like algae. The effect of adding a bonding agent is to enhance cohesion and reduce pressure requirements. A binder holds components by both mechanical and chemical adhesion, and occurs when the binder molecules adhere to specific points in the molecular structure of the adherent. Cassava, a tropical root crop often used as a binding agent, is quite robust and can be grown in infertile soil. It also has unique properties such as its high viscosity and resistance to freezing. The binder plays an important role in the final quality of the briquettes. Each binder has a steady effect on [13]:

- Briquette solidity (important in case of transportation)
- Sensitivity to moistness (important in case of long storing)
- Mineral matter content
- Market price

All this aspects also have a relative impact depending on the percentage of binder in the final product. Chemical binders are seen as standard practice in commercial briquetting where conforming specific physical properties is considered essential. Binders which produce an objectionable odor or smoke on burning are not acceptable for the domestic market. The binding

agent also needs to be fairly resistant to fermentation and bacterial attack during storage to meet market fluctuations. All these considerations tend to favor starch as the best all-round binder. In fact, because cost is such a critical factor, the natural binders inherent within the feed stock alone are often relied upon [3]. The most common natural binders found in biomass feed stocks are water soluble carbohydrates, lignin, protein, starch and fat. These binders will more commonly form bridge type binding mechanisms. Steam conditioning or pre-heating is nearly always needed to activate the inherent or added binders in a briquette. There are various binding agents in use which can be divided into two main groups: organic and inorganic binders [13]. The most important binders are shown in table 2.1

Table 2.1: Classification of the most important binders

Organic binders	Inorganic binders
Molasses	Clay
Coal tar	Cement
Bitumen	Lime
Starch	Sulfite liquor

Many binders have been proposed and used to produce fuel briquettes. The properties required of a binder are [13]:-

- ✓ Produces a strong briquette.
- ✓ Produces a waterproof briquette.
- ✓ Does not detract from the quality of the coal.
- ✓ Does not interfere with the use of the coal.
- ✓ Is environmentally acceptable and economically viable.

2.6 Characteristics of briquettes

The main purpose of briquetting material is to reduce the volume and thereby increasing the energy density. When densification takes place, there are two quality aspects that need to be considered, firstly, the briquette has to remain in solid form until it has served its purpose (handling characteristics). Secondly, the briquette has to perform well as a fuel (fuel characteristics). The first aspect, that the product should not crumble and disintegrate when handled, stored and transported, is mainly a function of the quality of the densification process for a given raw material. The second aspect is mainly related to the properties of the raw material

and the shape and density of the individual briquette. The distinction is not always clear and sometimes they interfere with each other. For example, improving the handling characteristics by making a denser briquette often has a detrimental effect on its combustion behavior. The energy characteristics are other important issues when describing and comparing briquettes with other fuels. The energy characteristics describe how the briquette act and what it produces when burned. The calorific value of briquettes is an important measure of the amount of energy released from every briquette when burned. Briquettes are normally priced by weight, but still, the calorific value is the most important factor in determining the competitiveness of the fuel. The calorific value varies with ash content and moisture content. Different ash and moisture contents in briquettes result in different calorific values [14].

2.6.1 Physical characteristics

Density: Most processes are capable of producing briquettes with densities above 1000 kg/m³, i.e. the individual briquettes will sink in water. The upper limit for the density is set by the physical density of each raw material which, for ligneous material, is about 1500 kg/m³. The density of individual pieces is termed apparent density. High pressure processes such as mechanical piston presses, pellet presses and some screw extruders, make briquettes in the 1200 -1400 kg/m³ density range [14].

Hydraulic piston presses make less dense briquettes, sometimes below 1000 kg/m³. In briquetting, the resulting density is affected to a significant degree by the particle size of the raw material. Finely ground material, for example sanding dust from wood plants, will make very dense briquettes but requires high pressures and temperatures to agglomerate without a binder. The density of the product is also affected by the moisture content. Water in the raw material will prevent the compression of the briquettes and the steam that evaporates from the material due to the high temperatures will leave voids which decrease the apparent density. If the briquettes later pick up humidity from the air, the result is a swelling of the material which also decreases the density. This process can lead to the total disintegration of the briquettes [14].

Friability: This factor is a measurement of the briquette's resistance to mechanical action that will affect them when handled and transported. Tests can be done either in a rotating drum or by repeatedly dropping samples from a specified height. In both methods, the samples are screened

(20 mm sieve) and the fraction retained is used as an index of a briquette's friability. It is difficult to give a figure for an acceptable friability index as the relationship between test results and reality has never been studied. When the briquettes score higher in tests, say between 0.5 and 1.0, such results are more difficult to interpret. They do have a function though when comparing several processes in order to find the most suitable for a given material. General observation at a number of operating plants suggests that briquettes produced by mechanical piston-presses and screw-presses are hard enough to be transported by lorry for considerable distances without degradation. No plants using such machines complained about losses due to product disintegration. One or two plants using hydraulic presses did find that the product was too soft for transportation [10].

Resistance to humidity: Inherent binders (lignin) and most externally added binders are water soluble. This results in one of the weakest points in briquette quality, which is that briquettes must not be subjected to water or humid air. Briquettes and pellets have to be stored under cover and they do have a limited lifetime under humid conditions. The latter problem appears to be only minor even in tropical countries. The dense, hard-surfaced briquettes produced in mechanical piston presses and screw presses with heated dies have enough resistance to humidity to withstand the rainy season. Although resistance to humidity may not be such a crucial factor when storing briquettes, provided they are shielded from direct rain, this factor may be of importance in the combustion and, especially, gasification of briquettes [14].

2.6.2 Combustion characteristics

Calorific/heating value: One of the most important characteristics of a fuel is its calorific value, that is the amount of energy per kg it gives off when burned. Heating value can be determined laboratorial experiment using oxygen bomb calorimeter. Although briquettes, as with most solid fuels, are priced by weight or volume, market forces will eventually set the price of each fuel according to its energy content. However, the production cost of briquettes is independent of their calorific value as are the transportation and handling costs. The calorific value can thus be used to calculate the competitiveness of a processed fuel in a given market situation. There is a range of other factors, such as ease of handling, burning characteristics etc., which also influence the market value but calorific value is probably the most important factor [14].

CHAPTER THREE

3.0 Materials and Experimental Methods

3.1 Materials and equipments

3.1.1 Materials

Sawdust of *Cupressus Lusitanica*, waste paper and water were the materials used in this work.

3.1.2 Equipments

Oven/ incubator (dual-purpose), electrical furnace (nambertherm, more than heat 30-3000 °C), analytical balance (sensitive to 0.0001g), sieves (1mm, 2mm, 4mm.5.6mm and 8mm mesh size), cutter and mixer (robot @ coupe, R23), homemade briquetting press , digital balance(0.5g-16 kg), stop watch, crucibles, meter, desiccators, plastic basin, stove, 3dm³ cylindrical container and oxygen bomb calorimeter (Parr 6200) were the equipments used to characterize sawdust and the briquettes.

3.2 Experimental Methods

3.2.1 Study area

The experimental process of characterization of the raw sawdust and briquettes, except gross calorific value which was determined in laboratory of Alternative Energy development and Promotion Directorate laboratory under Ministry of Water Irrigation and Electricity, Addis Ababa, were carried out in Bahir Dar Institute of Technology, Faculty of Chemical and Food Engineering, Chemical Research grade Laboratory, Bahir Dar. Waste paper (any available paper such as old news paper, used up exercise book etc.), avocado kernel and sawdust of *Cupressus Lusitanica* were collected for the production of briquettes. The sawdust was sun dried and of which parts was screened to the average particle size of 0.5mm, 1.5mm, 3mm, 4.8mm and 6.8mm. Both sieved and raw sawdust were sampled, labeled and stored for briquetting purpose. Waste paper and avocado kernel flour were used as a binder during briquetting of sawdust in different proportions separately. Five percentages notably 25%, 30%, 35%, 40% and 45% of the

weight of the mixture was used to determine the effect of binder concentration on the quality of briquettes produced from sawdust of *Cupressus Lusitanica*.

3.2.2 Experimental frame work of the study

The studies of all the experiments were planned according to the following frame work (fig 3.1). The frame work of this study was categorized into three groups: binder preparation, characterization of sawdust and, production and characterization of briquettes. Initially waste paper, avocado kernel and sawdust of *Cupressus Lusitanica* were collected. Physical and combustion properties of a portion of sawdust were determined. The remaining sawdust was sampled and mixed with binder. Soaked waste paper and gelatinized avocado kernel flour were used as a binder during production of sawdust briquettes. Finally analysis of physical and combustion properties of sawdust briquettes was done.

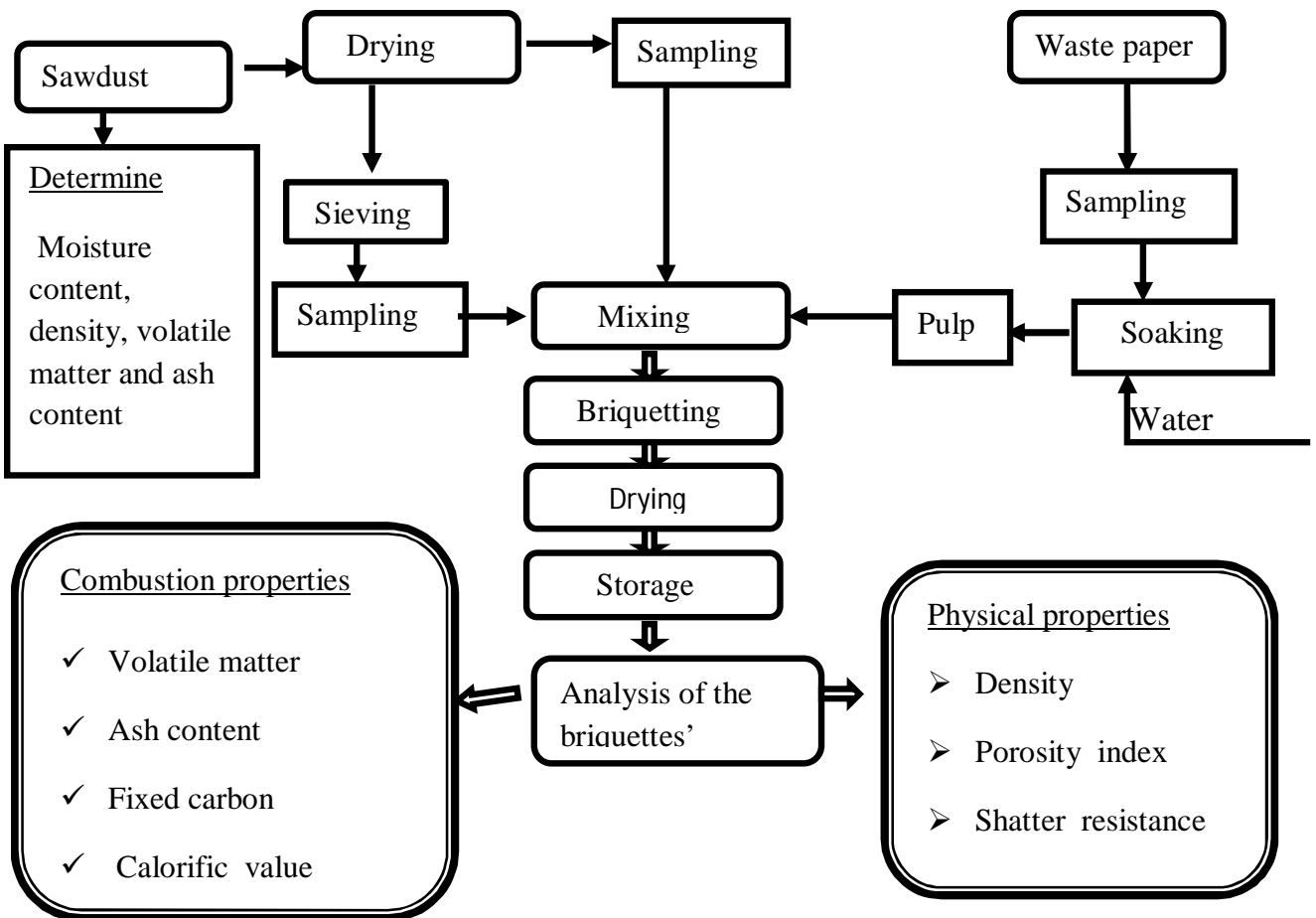


Fig 3.1: General frame work of the experiment

3.2.3 Preparation of materials

Sawdust: The feedstock (sawdust) was collected, sun dried for two days to reduce the moisture content. The raw sawdust was characterized in terms of moisture content, density, volatile matter and ash content. The dried sawdust was used to produce sawdust briquettes. A portion of the dried sawdust was screened by standard mesh sizes of 1mm, 2mm, 4mm, 5.6mm and 8mm which were arranged vertically starting from the smallest to the widest sieve size and mounted in an electrical sieve shaker. The sieves were shaken for 10 minutes using the shaker. The sawdust was labeled as: A (passed through 1mm); B (retained on 1mm); C (retained on 2mm); D (retained on 4mm) and E (retained on 5.6mm). The raw (non-screened) sawdust was labeled as F. All types of sawdust size (A-F) were considered for briquetting purpose to see the effect of particle size on the quality of briquettes. The average particle size of the screened sawdust for each sieved sample was determined using the relation given;

$$D_p = 0.5*(d_1+d_2) \quad 3.1$$

Where, D_p represents average particle diameter of sawdust, d_1 represents size of the upper sieve and d_2 represents size of the lower sieve. The average particle sizes of sawdust were tabulated in table 3.1. Both the screened (A, B, C, D and E) and raw sawdust (F) were presented in figure 3.2.

Table 3.1: Average particle size of screened sawdust labeled as A, B, C, D and E.

Sawdust	d_1 (mm)	d_2 (mm)	D_p (mm)
A	1	0 (pan)	0.5
B	2	1	1.5
C	4	2	3
D	5.6	4	4.8
E	8	5.6	6.8

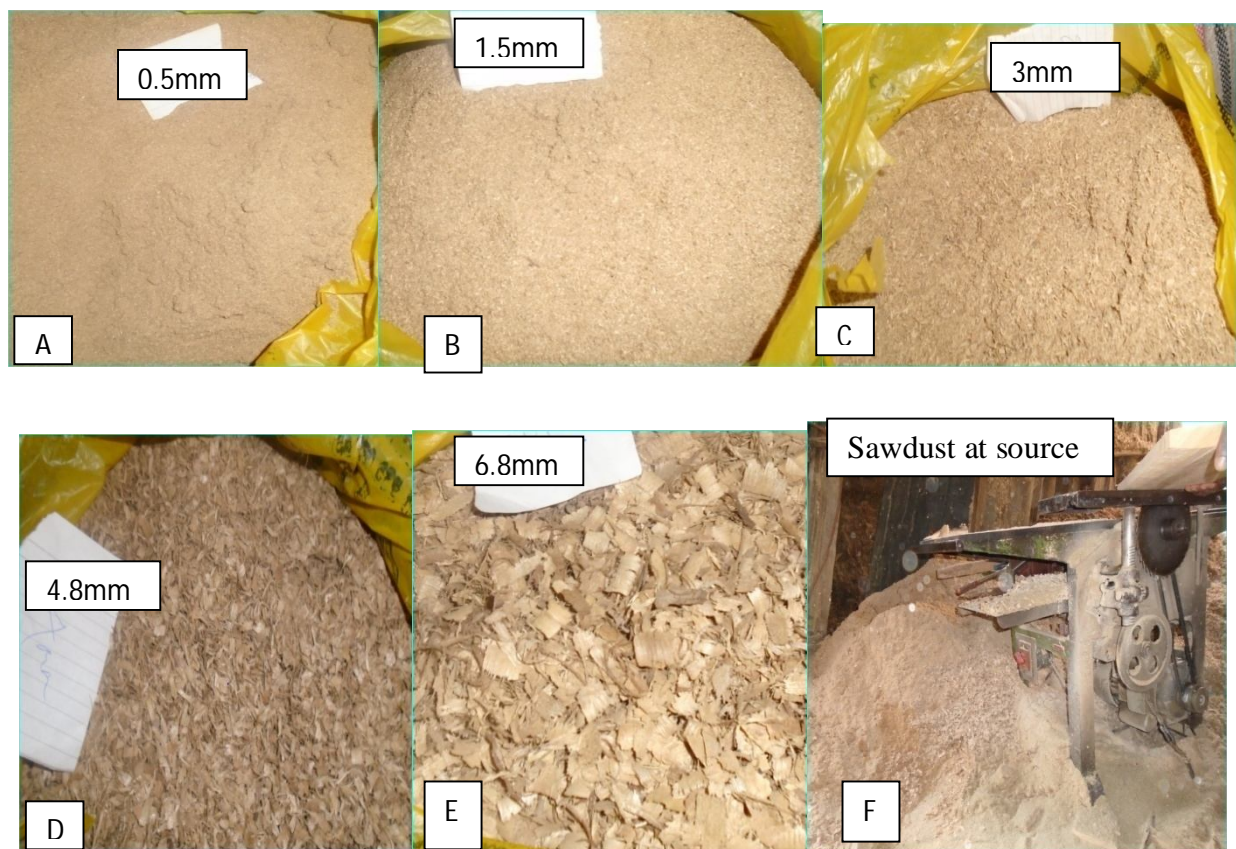


Fig 3.2: A; sawdust that passed through 1mm, B; sawdust that retained on 1mm, C ;sawdust retained on 2mm, D; sawdust retained on 4mm, E; sawdust retained on 5.6 mm, F; raw sawdust at the source .

Binder: Briquetting of saw dust with rurally available cheap binding material will be best for power generation. If the binder itself is a biomass; it will be more useful. The problem constituting by waste paper is enormous. How to dispose this waste is becoming worrisome and it is generated every day. Mixing waste paper with sawdust briquettes could lead to better briquette performance and cost-effectiveness making this fuel more attractive to both producers and consumers. Kraft paper, newsprint, used paper could be utilized to bind coal dust or other particulate combustible wastes together to make a strong briquette, using processes similar to paper making technology. This will reduce the burning of waste papers and atmospheric pollution as a result of paper burning. The waste papers generated in companies and house hold level is enormous. So instead of burning this waste it can be used as additive to solid briquettes. Five levels of weight percentages, 25%, 30%, 35%, 40% and 45% on dry weight basis, of each

were considered. The waste paper was collected, cut, sampled and soaked with water until it looks like porridge.

3.2.4 Determination of physical and combustion properties of sawdust

In this work, sawdust of *Cupressus Lusitanica* was characterized in terms of density, moisture content, percentage volatile matter and percentage ash content.

Density: The density of the sawdust sample was determined by weighing an empty cylindrical container of known volume (0.003m^3) and then carefully filled with the sawdust sample. After filling, the container with the sample was weighed. Then the mass of the containing sample was determined by subtracting the weight of container from weight of sample and container.

$$\rho_{sd} = \frac{M_{sd}}{V_{con}} \quad 3.2$$

Where ρ_{sd} is density of sawdust (g/cm^3), M_{sd} is mass of sawdust (g) and V_{con} is volume of the container (cm^3).

Percentage moisture content: It was determined by weighing a portion of a sample and oven drying it at $105\text{ }^\circ\text{C}$ for until mass of the sample was constant. The change in weight was then used to determine the sample's moisture content using the following relation.

$$\text{MC (\%)} = \text{B/A} * 100 \quad 3.3$$

Where MC is moisture content, A is the mass of sample before drying, g and B is the change in weight of sample before and after drying in oven.

Percentage volatile matter: volatile matter is defined as those products, exclusive of moisture, given off by a material as gas or vapor. The high volatile matter content of a biomass material indicates that during combustion, most of it will volatilize and burn as gas in the cook stove [18]. The percentage volatile matter of sawdust was determined by placing the sample in an oven until a constant weight was obtained. The sawdust was then kept in a furnace at a temperature of $550\text{ }^\circ\text{C}$ for 10 minutes and weighing after cooling in desiccators to obtain the change in weight. The percentage volatile matter was computed using equation 3.4

$$\text{VM (\%)} = (\text{W}_3/\text{W}_2)*100 \quad 3.4$$

Where, VM (%) = percentage volatile matter of sawdust, W_2 =oven dried sample weight of sawdust, g and W_3 =change in weight of oven dried sawdust before and after transferred to muffle furnace, g

Percentage ash content: Ash is the non-combustible inorganic residue that remains after a complete combustion [19]. A sample of the sawdust was placed in an oven until a constant weight was obtained. The oven dried sample was then transferred in to the furnace set at a temperature of 900 °C and left for about 30 minutes. Then after, the crucible and its contents were transferred to desiccators and then crucible and its contents were reweighed to obtain the weight of ash. The percentage ash content was calculated as the ratio of weight of ash to that of weight of dry sample and was determined using equation 3.5.

$$AC (\%) = (W_2/W_1) *100 \quad 3.5$$

Where, W_1 = Initial weight of oven dried sample (g), W_2 = weight of ash (g) and

AC (%) = percentage ash content

3.2.5 Construction of homemade briquetting press machine

A homemade briquetting machine was constructed (figure 3.4). A Multi view drawing of the briquetting press machine was presented in figure 3.5. It was constructed mainly from wood while some parts of it were made from metal. It was used to produce sawdust briquettes using waste paper as a binder at different proportions. It has five different parts which includes the main body/stand that supports the rest, four cylinders/moulds connected each other by nails with supporting base, a plate base which covers the opening of the cylinders while pressing, the presser having four equal legs which are assembled with circular woods at their bottom ends to press down the well mixed sample during briquette production and press arm, which is assembled on one side of the stand, to push down ward the presser by applying pressure on it.

The stand, supports the rest parts having a press arm, is made from wood which is milled in size of 4cm width, 5cm length and height of 61 cm on one side and 76 cm on other side. The two sides, 100 cm far from each other, are connected by wood using nails. There are two stages, having 2cm width and height, on the stand to support and allow the movement of the base and cylinder supporter base to both ends of the briquetting machine. The press arm, which is used to push down the presser and having a dimension of 4cm*5cm*120cm, is assembled at a height of

51cm from the base. The cylinders, 10 cm in diameter and 20 cm in height, are made from metal sheet and are connected in a square arrangement. They are 2cm far from each other and positioned vertically over the supporting base. They are drilled all around so that the water can escape when the feedstock is pressed. A flat wood base/ plate which was placed on the first stage of the stand and which was free to move to both ends, was used to cover the open ends of the moulds/ cylinders during compaction and moved to one of the end of the stand during ejection of the briquettes. The base and supporting base with the four cylinders are free to move to both sides of the stand on their own stage provided. The presser, its legs have square arrangement, is made from pieces of metals. It is constructed in such a way that its legs with assembled circular wood can freely move up and down inside the cylinders during briquette production and ejection.

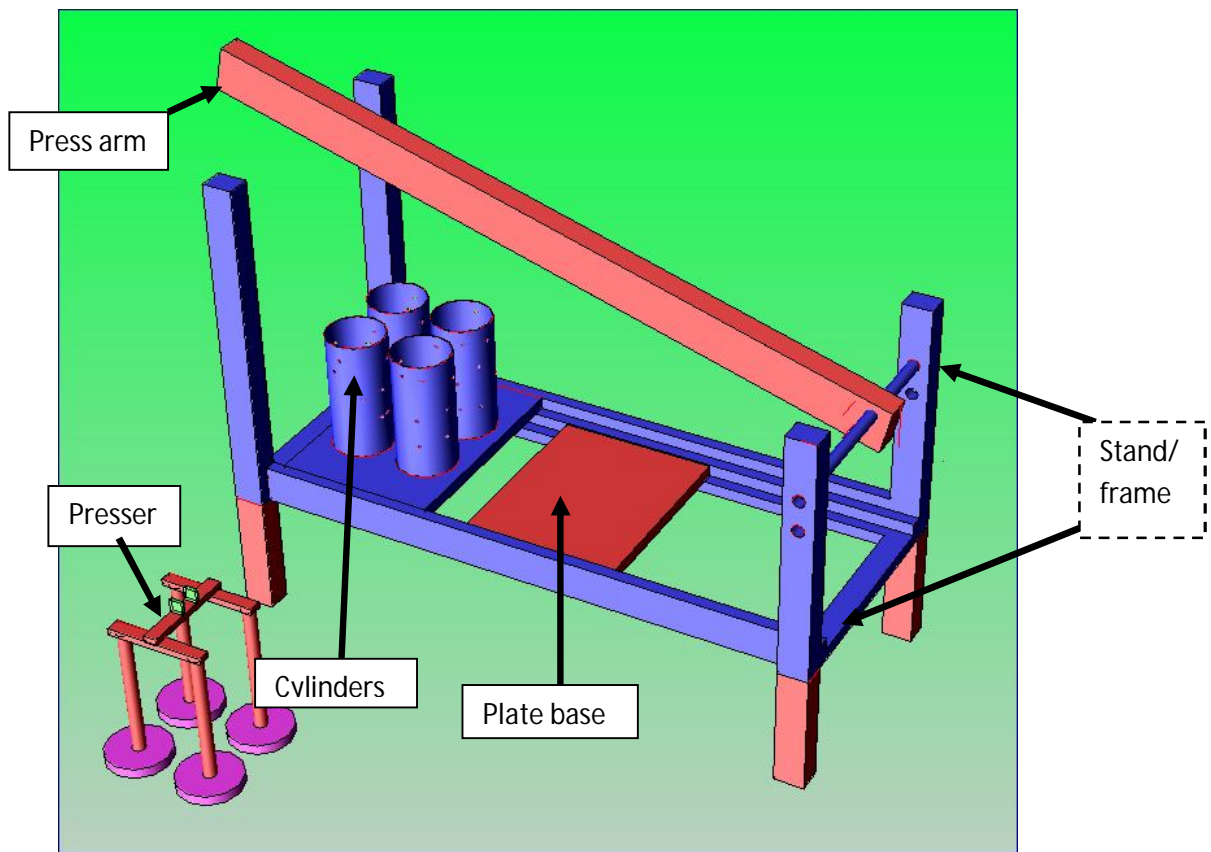


Figure 3.3: Cad drawing of briquetting machine

Pressing is achieved through a simple lever mechanism. The briquetting press machine is medium in size and all its five parts are not assembled permanently so it is easy to transport however, it requires two persons to run it efficiently. During briquette production, all the parts

are joined together temporarily but during the ejection of briquette, the base will be moved towards either of the two ends and the openings of the cylinders become free. Hence the briquettes will be free to leave out from the cylinders.

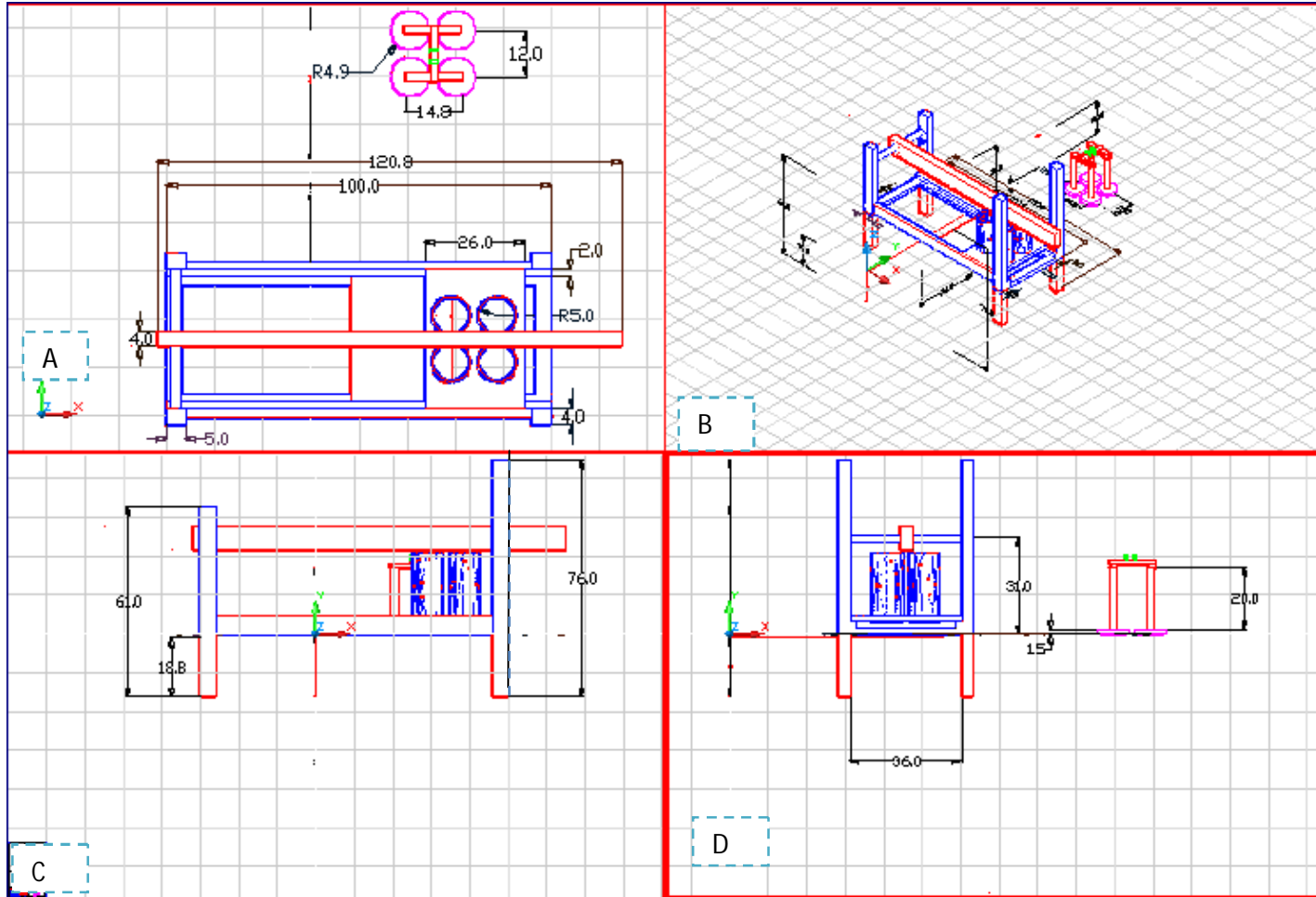


Figure 3.4: Multi view drawing of the briquetting machine, A-top view, B-3Dview, C-front view, D- right view. Dimenstions in cm.

The briquetting press machine was constructed in such a way that first the main body/stand is constructed using different wood assembled each other permanently. Secondly four cylinders were constructed and assembled to a wood base which has four holes to insert and support the cylinders. Thirdly four lids were constructed in such a way that they can move freely inside the cylinders while pushing the briquette down ward. Finally the presser is constructed which enables to press the feedstock inside the four cylinders simultaneously. All motions such as

vertical motion of presser in and out of the cylinders, horizontal motion of base and supporting base with cylinders: up and down movement of arm press and the ejection of the briquettes was effected through manual operation. The briquetting press machine enables to produce four briquettes at a time. The average time consumed in one batch operation(2 minutes for filling the cylinders, 10 minutes for densification and 3 minutes for ejection of briquettes) is approximately 15 minutes. So the average capacity of the presser is: $[4 \text{ briquette} * 60 \text{ minute/hr}] / 15 \text{ minutes}$. Therefore the presser can produce 16 briquettes/hr at an average. Even if the press is designed for briquetting of sawdust for the case of this work, it can be used for any types of feedstock available in the given environment however; there must be binder because the pressure is lower.

3.2.6 Experimental setup and description

The briquettes were produced using a simple lever system hand press machine with four cylindrical moulds. Waste paper was used as a binder for the briquetting of sawdust. The experiment was designed to evaluate the effect of binder percentage (wt/wt %), average particle size of the sawdust and die diameter on the quality of sawdust briquettes. In this work, Design-Expert Software, general factorial, 2FI model, was used to analyze the effect of such operating factors on the quality of sawdust briquettes. So there were three factors i.e. binder percentages (wt/wt %), average particle size of the sawdust (mm) and die diameter (cm). The first two factors have five levels while the third has three levels respectively.

A specific quantity of sawdust and binder were weighed using a digital balance. The sampled sawdust was then wetted with water so as to enhance uniform mixing with the binding agent. For each batch of briquette, sampled wetted sawdust was mixed thoroughly with soaked waste paper in the proper binder-mix ratio, until a uniform mixture was obtained and then the sawdust-binder mixture was hand-fed in to the cylinders. The mixture was pressed down inside the cylinders by applying a pressure on the presser using the arm press which was used to multiply force. The water was left out during briquetting process through the holes of the cylinders which are found all around the cylinders. The mixture was pressed down until a sufficient pressure is applied, and then the base was removed to enhance the ejection of densified mixture. After the base was removed, the mixture was pressed down again to eject the final product i.e. briquettes. Then the briquettes were sun dried and stored. Figure 3.6 shows the set up of the experiment.

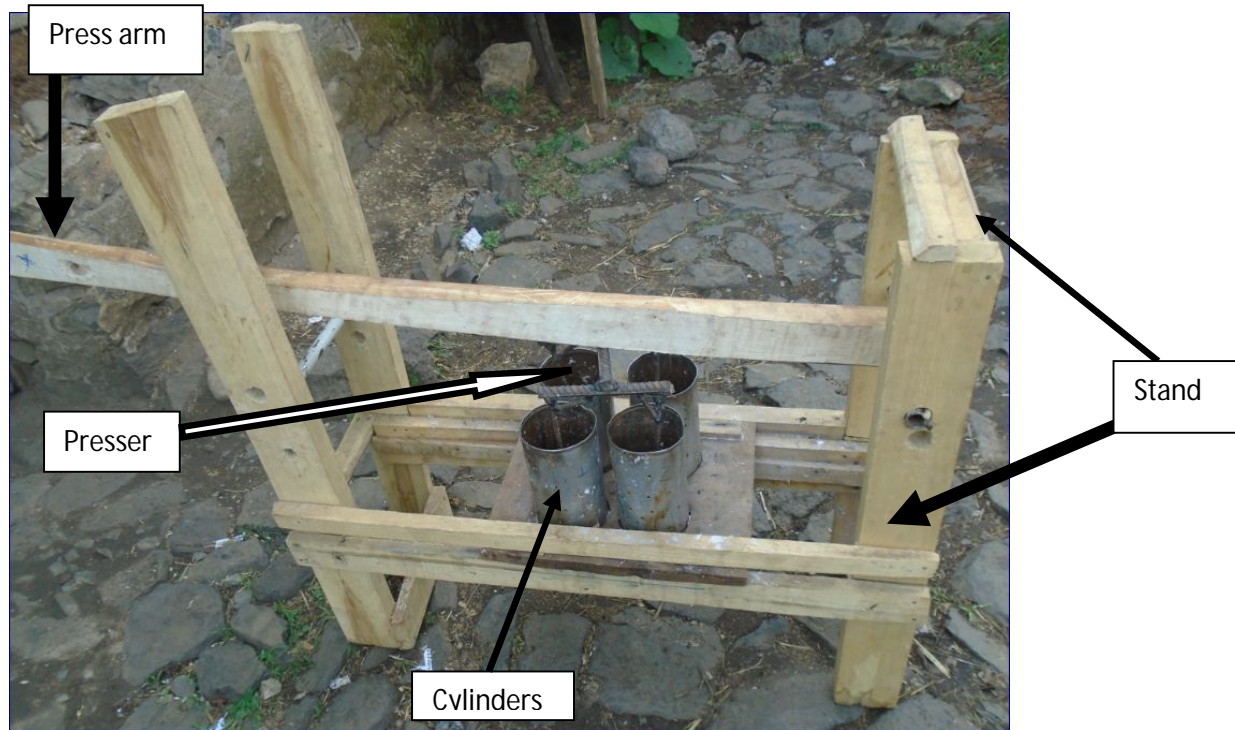


Figure 3.5: Experimental set up for briquetting of sawdust

3.2.6.1 Production of sawdust briquettes

Sieved and raw sawdust were used for briquette production. The sieved sawdust was sampled in to five types based on their average particle size (A, B, C,D, and E) as shown in fig 3.2. The three factors in these experiments were size of sawdust, dry weight percentage of waste paper and die geometry.

Briquetting of raw sawdust: The effect of die diameter (6cm, 8cm and 10cm) was applied for non-screened sawdust (raw sawdust) and the waste paper percentage (wt/wt %) was varied i.e. (25%, 30%, 35%, 40%, and 45%). The briquettes were named as: $F_{M,N}$ and presented in table 3.2;

Where, F represents non screened sawdust i.e. raw sawdust as shown in figure 3.2.

M stands for the die geometry and has values of 6, 8 and 10 cm.

N stands for weight percentage of waste paper to raw sawdust (wt/wt %) and has values of 1(25%), 2(30%), 3(35%), 4(40%) and 5(45%).

Table 3.2 Names of briquettes with the corresponding waste paper percentage and die geometry

Die diameter	Name of briquettes				
6 cm	F _{6,1}	F _{6,2}	F _{6,3}	F _{6,4}	F _{6,5}
8 cm	F _{8,1}	F _{8,2}	F _{8,3}	F _{8,4}	F _{8,5}
10 cm	F _{10,1}	F _{10,2}	F _{10,3}	F _{10,4}	F _{10,5}

Briquetting of screened sawdust: Five weight percentages of waste paper (25%, 30%, 35%, 40% and 45%) were used for the sieved sawdust (A, B, C,D, and E) at constant die diameter of 10 cm. The names of briquettes, average particle size of sawdust and corresponding waste paper percentages were presented in table 3.3. The briquettes were named based on the size of sawdust and weight percentage of waste paper as; M_N; Where

M represents for the size of sawdust and varies from A-E as mentioned in section 3.3.1 and

N represents the percentage of waste paper (wt/wt % dry basis) with values of 1(25%), 2(30%), 3(35%), 4(40%) and 5(45%).

Table 3.3: Name of briquettes with different particle size of sawdust and waste paper percentage

Particle size	Name of briquettes (M _N)				
0.5 mm	A ₁	A ₂	A ₃	A ₄	A ₅
1.5 mm	B ₁	B ₂	B ₃	B ₄	B ₅
3 mm	C ₁	C ₂	C ₃	C ₄	C ₅
4.8 mm	D ₁	D ₂	D ₃	D ₄	D ₅
6.8 mm	E ₁	E ₂	E ₃	E ₄	E ₅

3.2.7 Determination of physical and combustion properties of sawdust briquettes

Density, porosity index, shatter resistance, percentage volatile matter, percentage ash content, percentage fixed carbon and gross calorific value of the sawdust briquettes were determined.

Density: One of the major indices for assessing the combustion and handling characteristics and ignition behavior of briquettes is density. It is defined as structural packing of the molecules of the substance in a given volume [8]. The weights of briquettes were determined in the laboratory using digital balance. Volumes of briquettes were determined by a simple calculations based on the direct measurement of height and diameter of the briquettes since briquettes were cylindrical in shape. The volume was evaluated using.

$$\rho_{br} = \frac{M_{br}}{V_{br}} \quad 3.6$$

$$V_{br} = \pi R^2 H \quad 3.7$$

Where, R=radius of the briquette, cm, H=height of the briquette, cm, M_{br} = mass of briquettes, kg, V_{br} =volume of briquettes, cm^3 , π = mathematical constant i.e. 3.14 and ρ_{br} =density of briquette, g/cm^3

Porosity index: The porosity of briquettes was determined based on the amount of water each sample absorbs. A pre weighed briquette was immersed in water for 30 seconds. Then the briquette was taken out of water and reweighed to obtain the wet weight of briquette. The weight of water absorbed was determined by subtracting dry weight of the briquette from wet weight of the briquette. The porosity index was calculated as the ratio of the mass of water absorbed to the mass of the sample briquette immersed in water [16]. Similarly another batch was introduced and the same process was repeated until the completion of the samples. It was calculated using;

$$PI (\%) = (W_w - W_s) / W_s *100 \quad 3.8$$

Where, PI= porosity index, W_s =dry weight of the sample briquette (g) and W_w =wet weight of the sample briquette after immersed in water (g).

Shatter resistance: The durability of the briquettes was determined in accordance with Aina, O.M., Adetogun, A.C. And Iyiola, K.A [18]. Each briquette sample was allowed to drop from a height of 2m onto a concrete floor five times. The durability (%) can be calculated as the ratio of the final weight of the briquette retained after five drops to the initial weight of the briquette. The fraction of the briquette that remained unshattered was used as an index of briquette durability. The percentage weight loss of briquettes was expressed as a percentage of the initial mass of the

material remaining on the solid base, while the shatter resistance was obtained by subtracting the percentage weight loss from 100 as presented by equation 3.10.

$$W_L (\%) = (W_1 - W_2) / W_1 * 100 \quad 3.9$$

$$S_R (\%) = 100 - W_L \quad 3.10$$

Where $W_L (\%)$ = weight loss percentage, W_1 = weight of briquette before shattering (g), W_2 = weight of briquette after shattering (g) and $S_R (\%)$ = shatter resistance percentage.

Percentage volatile matter: Volatile matter refers to the part of a biomass material that is released as volatile gases. It is defined as those products, exclusive of moisture, given off by a material as gas or vapor. Biomass generally has high volatile matter content of around 70% to 86% and low char content. The high volatile matter content of a biomass material indicates that during combustion, most of it will volatilize and burn as gas in the cook stove. The percentage volatile matter of the briquettes was determined in accordance with, Aina, O.M., Adetogun, A.C. And Iyiola, K.A, [18].

A portion of a briquette was kept in an oven until a constant weight of the sample is obtained. The oven dried sample was kept in the muffle furnace at a temperature of 550 °C for 10 minutes. After which the volatile matter in it have escaped, the crucible and its contents retrieved and cooled in a desiccators and weighed after cooling to obtain weight of volatile part of the sample i.e. the change in weight of the sample before and after transferred to furnace . The analytical balance was used to weigh the weight of sample. The percentage volatile matter is the ratio of weight of volatile matter to weight of oven dried sample. Percentage of volatile matter of the briquette was computed using the relation presented in equation 3.7. Finally another batch was introduced and the same process was repeated until the completion of the samples.

$$VM (\%) = (W_2 - W_3) / W_2 * 100 \quad 3.11$$

Where, $VM (\%)$ = percentage volatile matter, W_2 = oven dried sample weight, g and W_3 = weight of oven dried sample after heating in furnace, g

Ash content: All chemical breakdown of a biomass fuel produce a solid residue, which in cases can be called ash. Ash is the non-combustible inorganic residue that retains after a complete

combustion. The ash can cause problems for thermo-chemical conversion process, and particularly for combustion because some chemical compounds in the ash can react to form slag. The amount of ash is an important data when biomass is used as fuel in boilers, because at high temperatures can melt and cause fouling of equipment. The residual ash is undesirable, so the lower level is the best fuel quality. Ash is expected to have values for commercial fuels from 0.6% to 9.8%, energy crops from 1% to 9.6%, cereals from 1.8% to 4.8% and industrial waste from 0.4% to 22.6%. General values may appear in a range from levels below 5–20% [19].

A portion of a sample of the briquette was placed in an oven until it is free of moisture content. The oven dried sample was then placed in a pre weighed crucible. This was transferred in to the furnace set at a temperature of 900 °C and left for about 30 minutes. During this time the sample was turned to white ash. Then after, the crucible and its contents were transferred to desiccators and cooled. After cooling the crucible and its contents were reweighed to obtain the weight of ash. The same process was repeated until the completion of the samples. The percentage ash content was calculated as the ratio of weight of ash to that of weight of dry sample and was determined by:-

$$\text{PAC} = (\text{W}_2/\text{W}_1) * 100 \quad 3.12$$

Where, W_1 = weight of oven dried sample (g), W_2 = weight of oven dried sample after complete combustion in furnace i.e. weight of ash (g) and PAC= percentage ash content

Fixed carbon percentage: Carbon content refers to the percentage of carbon present in a particular sample. Essentially, the fixed carbon of a fuel is the percentage of carbon available for combustion. This is not equal to the total amount of carbon in the fuel (the ultimate carbon) because there is also a significant amount that will be released as hydrocarbons in the volatiles. Fixed carbon gives an indication of the proportion of char that remains after the devolatilization phase. The percentage fixed carbon of briquettes was calculated by subtracting the sum of PVM and PAC from 100 [20]. The same process was repeated until the completion of the samples.

$$\text{FC} (\%) = 100 - (\text{PAC} + \text{PVM}) \quad 3.13$$

Where, FC (%) = fixed carbon percentage, PAC=Percentage ash content and PVM= percentage volatile matter.

Calorific value: Calorific value determines the energy content of a fuel. It is the property of biomass fuel that depends on its chemical composition and moisture content. The most important fuel property is its calorific or heat value [17]. The gross calorific values of sawdust briquettes were determined using a standard Oxygen Bomb calorimeter (Parr 6200). The bomb was closed and charged in with oxygen up to 30 bars. The bomb was fired up by depressing the ignite switch to burn the sample in an excess of oxygen. A predetermined mass of each sample was burnt in the bomb calorimeter until complete combustion was obtained. The temperature rise and mass of sample were used to compute the gross calorific values of the biomass briquettes as presented in equation 3.14. The 6200 calorimeter will automatically make all of the calculations necessary to produce a gross heat of combustion for the sample. However, it is important that the user understand these calculations to ensure the instrument is set up so the calculations match the procedures and the units are consistent throughout the process. Analytical balance, oven, furnace and 6200 calorimeter used in the experiment are presented in figure 3.9.

$$H_c = (WT - e_1 - e_2 - e_3) / m \quad 3.14$$

Where, H_c = Gross heat of combustion, T = Observed temperature rise, W = Energy equivalent of the calorimeter being used, e_1 = Heat produced by burning the nitrogen portion of the air trapped in the bomb to form nitric acid, e_2 = Heat produced by the formation of sulfuric acid from the reaction of sulfur dioxide, water and oxygen, e_3 = Heat produced by the heating wire and cotton thread and m = mass of the sample.



Figure 3.6: A; oven, B; furnace, C; Analytical balance, D; Oxygen bomb calorimeter

3.2.8 Investigation of the effect of different factors on the quality of sawdust briquettes

3.2.8.1 Effect of average particle size of sawdust

The size of the input fraction has an important effect on the densification process because larger input fractions increase the energy needed for densification. However, briquettes formed from large input fractions have lower homogeneity and strength. On the other hand, a large portion of fine particles allows for better material densification. The resulting briquette is uniform, of high quality, and reaches higher volumetric density. With increasing particle size, the bond strength between particles decreases, causing them to crumble. In order to investigate the effect of average particle size of sawdust on the physical and combustion properties of briquettes, the raw sawdust was screened to A (0.5mm), B (1.5mm), C (3mm), D (4.8mm) and E (6.8mm). Five levels of waste paper percentages (25, 30, 35, 40 and 45%) were combined to each size of sawdust during production of sawdust briquettes at constant die diameter of 10 cm.

3.2.8.2 Effect of weight percentage of waste paper

The waste paper was used as a binding agent. As the weight percentage of waste paper varies, the bond will also vary. This was the reason why variation of waste paper percentage was considered. The effect of waste paper percentage was considered for screened sawdust of sizes 0.5, 1.5, 3, 4.8 and 6.8mm at constant die diameter of 10 cm. Five waste paper percentages notably 25%, 30%, 35%, 40% and 45% of the weight of mixture was used to determine the effect of binder (waste paper) concentration on physical and combustion characteristics of sawdust briquettes.

3.2.8.3 Effect of die diameter

Pressure plays an important role in the quality of briquette. According to P.D. Grover & S.K. Mishra [10], application of high pressure during densification may develop solid bridges by diffusion of molecules from one particle to another. The variation of die diameter with three levels (6, 8 and 10 cm) was applied for the raw sawdust at five weight percentages of waste paper as a binder (25, 30, 35, 40 and 45%).

CHAPTER FOUR

4.0 Results and Discussion

The physical and combustion characteristics of the raw sawdust and briquettes produced from sawdust were studied. Density, moisture content, volatile matter and ash content of raw sawdust were determined. The qualities of sawdust briquettes were evaluated by using different operating factors such as binder percentage, die-geometry and average particle size of sawdust. The physical and combustion properties of the sawdust briquettes examined in this work were limited to density, porosity index, shatter resistance, percentage volatile matter, percentage ash content, fixed carbon percentage and gross calorific value.

4.1 Physical and combustion properties of sawdust

4.1.1 Physical properties of sawdust

Moisture content: Moisture content of a sample is expressed as the quantity of water per unit mass of sample in wet base. Moisture content has strong influence on density, durability, and storage. The moisture content in bio-briquettes should be as low as possible, generally in the range of 10-15 percent. If the feed moisture content is around 8-10% and the resulting briquettes after compaction process will have 6-8% moisture content [22]. The moisture content of raw sawdust was determined by weighing 27.21 gram of the sample and oven drying it at 105 °C for until mass of a sample was constant (20.56g). The change in weight was then used to determine the sample's moisture content. The moisture content was determined using equation 3.12. The moisture content of sawdust was found to be higher (24.43%). This is too high to prepare briquettes directly from raw sawdust hence drying is needed to lower to the standard moisture content of biomass for briquetting application which is in the range of 10-15%. This implies it will cause problem in direct burning and excessive energy will be needed for drying of briquettes if it was directly densified. Therefore, it is important to dry the sawdust before briquetting to some extent in order to reduce the moisture content of bio briquettes to 10-15%.

Density: The density of sawdust was determined by dividing the mass of the sample contained in a 0.003m^3 container to the volume of the container. The average mass of the sample contained in a 0.003m^3 was found to be 362.8 g. However, 24.43% of the sawdust was found to be moisture, hence the exact mass of the sampled sawdust will be: $362.8 * (1 - 0.2443)$ which gives 274.2 g. The density of raw sawdust was determined using equation 3.1. The density of sawdust, 2.4 times less than the least density of sawdust briquettes, obtained was found to be 91.34 kg/m^3 . This implies, it has low energy density, difficult to store and transport, and has less burning time. Therefore, it is better to densify instead of directly using sawdust as fuel.

4.1.2 Combustion properties of sawdust

Percentage Volatile matter: The percentage volatile matter of sawdust was determined by placing the sample in an oven until a constant weight was obtained. The sawdust was then kept in a furnace at a temperature of $550 \text{ }^\circ\text{C}$ for 10 minutes and weighing after cooling in desiccators to obtain the change in weight. The percentage volatile matter was computed using equation 3.4 and the average value of 94.92% was recorded. This is high and signifies easy ignition of the sawdust and proportionate increase in flame length. The percentage volatile matter of the raw sawdust was higher than that of volatile matter of sawdust briquettes. This could be resulted from either the waste paper has lower volatile matter than sawdust or the mass transfer rate was reduced due to the bond formed between sawdust and binder.

Percentage Ash content: A sample of the sawdust was placed in an oven until a constant weight was obtained. The oven dried sample was then transferred in to the furnace set at a temperature of $900 \text{ }^\circ\text{C}$ and left for about 30 minutes. Then after, the crucible and its contents were transferred to desiccators and then crucible and its contents were reweighed to obtain the weight of ash. The percentage ash content was calculated as the ratio of weight of ash to that of weight of dry sample and was determined using equation 3.5 and the average result obtained was 2.6%. The average ash content of raw sawdust was lower than that of all types of corresponding raw sawdust briquettes bonded with waste paper as a binder. This could be due to the variation in mass transfer rate due to the bond formed between sawdust particles and the waste paper. In the raw sawdust, the particles are not bonded to each other so allowing adequate flow of oxygen, there will be complete combustion. However, in briquettes, the particles are bonded and there are additives (waste paper) which may result higher ash content than the raw sawdust.

4.2 Physical and Combustion properties of sawdust briquettes

4.2.1 Physical properties of sawdust briquettes

The quality of the briquettes assessed on the basis of their physical condition revealed that their external surface was relatively smooth and cylindrical in shape. The physical characteristics of the sawdust briquettes evaluated were limited to density, porosity index and shatter resistance. The raw data was presented in appendix A.

4.2.1.1 Density

One very important parameter in briquette production is the density. Density is a physical property of briquettes. It is defined as structural packing of the molecules of the substance in a given volume. The density of biomass material plays an important role in the determination of its fuel value. Denser briquettes contain more heat per unit volume than the other in that, all things being constant; they tend to burn for longer periods of time. Hence, high-density products are desirable in terms of transportation, storage and handling. The density of biomass briquettes depends on the density of the original biomass, the briquetting pressure and, to a certain extent, on the briquetting temperature and time [21].

The experimental results of effect of average particle size, waste paper percentage, binder type and die geometry on the density of briquettes obtained were evaluated. Obi, O. F., Akubuo, C. O., Okonkwo, W. I, [18], reported that sawdust briquettes bonded with starch give a density of 546 kg/m³. The maximum density obtained in this work was 322.62 kg/m³ which were lower than the value reported. This could be to the type of binder, applied pressure used and species of the wood in the two studies is different. In this work, the binder used were waste paper and avocado kernel and the presser is manual hence the applied pressure is low.

Effect of average particle size of sawdust: It is generally accepted that raw material particle size influence the density of produced pellets, e.g. small particles gives a higher density of single pellet. This is true at least at low and medium densification pressures [23].

Five levels of average particle size of sawdust (0.5, 1.5, and 3, 4.8 and 6.8 mm) were used. For each particle size, five waste paper percentages (25, 30, 35, 40 and 45%) were combined for each at constant die-geometry of 10cm. Figure 4.1 shows the effect of average particle size of sawdust on density of briquettes briquetted at die geometry of 10 cm.

The highest density (280.78kg/m^3) was obtained from the sawdust of average particle size of 0.5mm and the least density (218.24kg/m^3) was observed in the sawdust of average particle size of 4.8mm. As can be seen from the figure, density of briquettes was decreased when the average particle size of sawdust increased for each waste paper percentage combinations. The smaller particle size is compact easily leading to small number of pore space while the greater particles have large number of pore spaces. As the number of pores increased, the void space within the briquette increases, the density will be decreased. That is why the density of briquettes was decreased when the average particle of sawdust was increased.

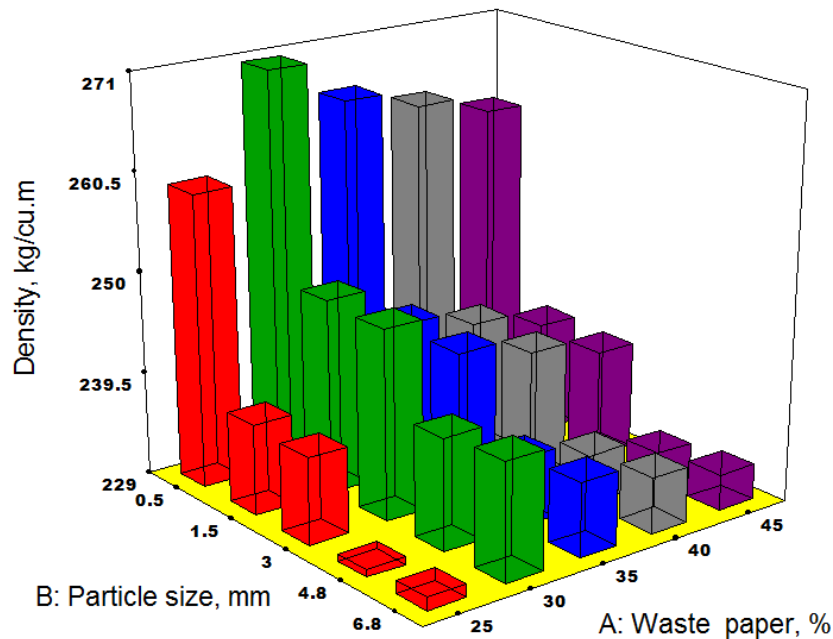


Figure 4.1: Effect of average particle size of sawdust on density of briquettes

According to Mac Bail (1966) and Payne (1978), medium or fine materials are desirable in briquetting and the results obtained in this work were corroborated their findings. The optimum average particle size of sawdust on the basis of density of briquettes was attained at 0.5mm.

Effect of waste paper percentage: Different levels of waste paper percentages were combined for each of sawdust of size of 0.5mm, 1.5mm, 3mm, 4.8mm and 6.8mm at constant die diameter of 10 cm. Figure 4.2 shows the difference in density of briquettes according to waste paper percentage. Although the effect of waste paper percentage on density of briquettes was found to be insignificant ($p>0.05$), as the percentage by weight of waste paper was increased, the density was increased. However, it was noted that as the waste paper percentage exceeded 30%, there was a decrease in the density of briquettes. This implies the effect of waste paper percentage was

not a significant factor; however, it has to be at the optimum percentage of 30% on the basis of density of briquettes since it could bring a change on density of briquettes.

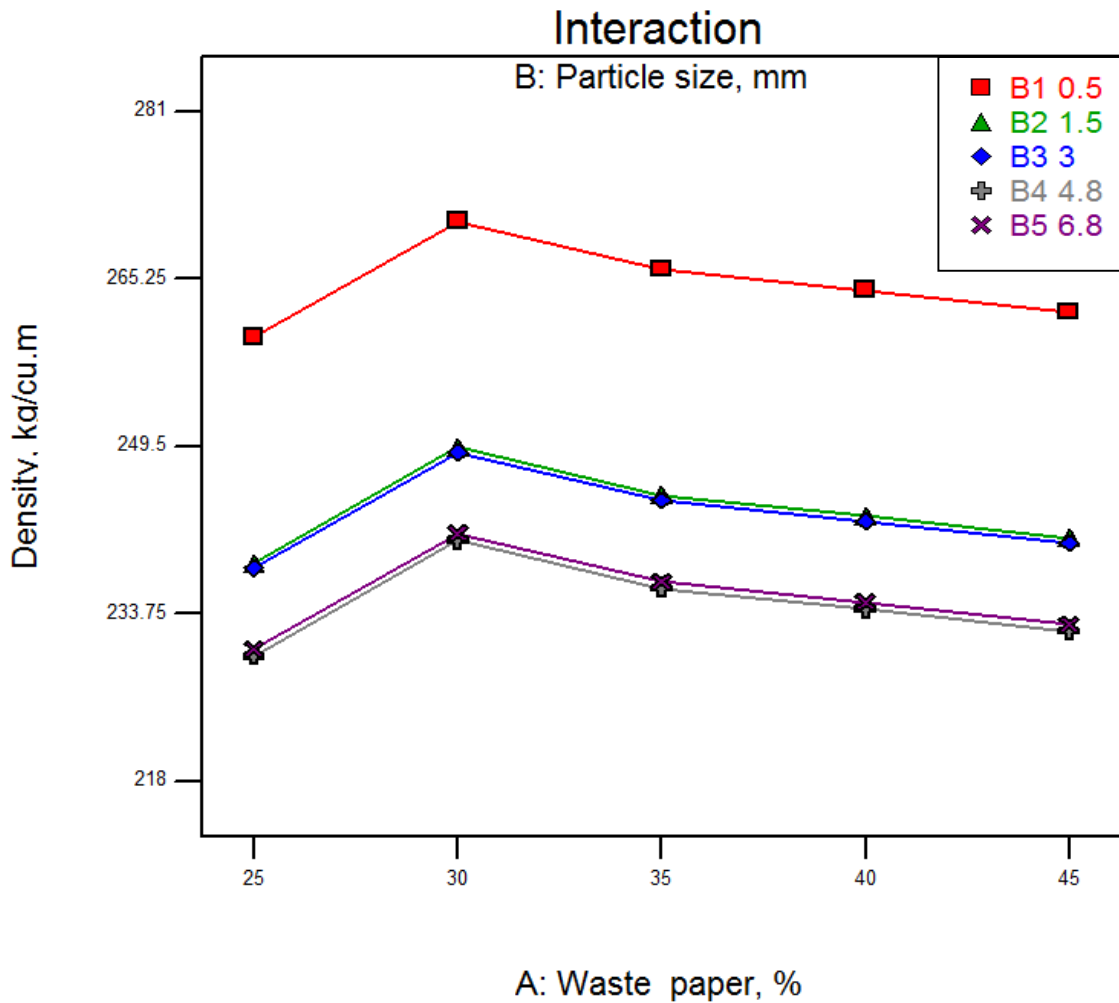


Figure 4.2: Effect of waste paper percentage on density of briquette

Effect of die diameter: Densities of briquettes at the different die geometries are presented in figure 4.3. The effect of pressure was considered by varying the diameter of the cylinders/moulds. The raw sawdust was sampled and combined with waste paper in different weight percentages. The same combination of sawdust and waste paper were briquetted using the three die geometries. As can be seen from the figure, the maximum density (322.62 kg/m^3) was obtained for the die geometry of 6 cm and the least density (246.27 kg/m^3) from die geometry of 10 cm. As it can also be seen from the figure, the density was decreased when the die geometry was increased. As the die geometry increase the contact area will also increase. Hence the applied pressure will be smaller and smaller because pressure and area have inverse relations.

Lower pressure allows large number of pores hence the density will be lower. From result obtained, it can be concluded that the die geometry was the basic factor for briquetting and the optimum die geometry on the basis of density was attained at smaller die geometry of 6 cm.

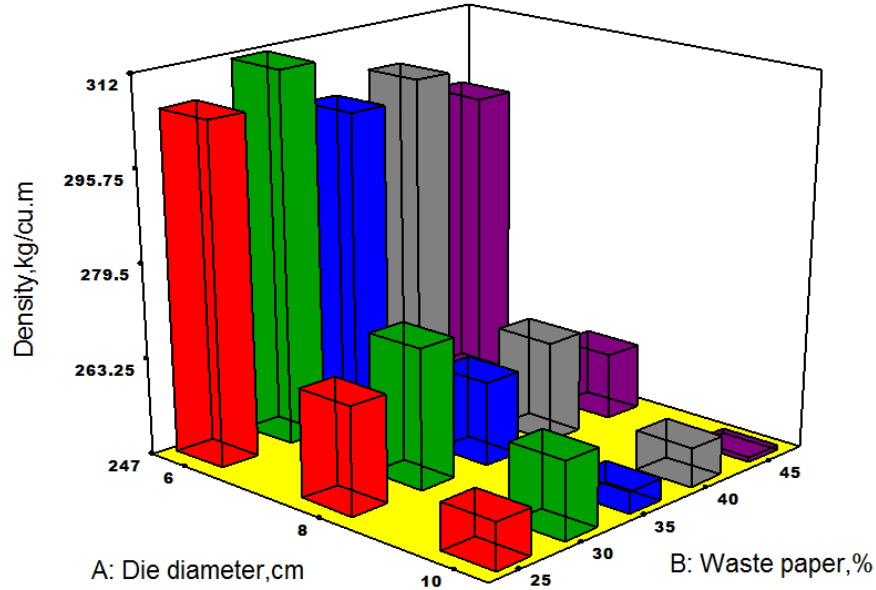


Figure 4.3: Effect of die diameter on density of sawdust briquettes

4.2.1.2 Porosity index (weight, %)

Porosity is a measure of the void spaces in a material and is a fraction of the volume of voids over the total volume; it generally lies between 0-1. Porosity index is the ratio of weight of water absorbed to dry weight of sample briquette when immersed to water. The lower the porosity index of the briquettes the higher the density of the briquettes produced. A briquette with higher porosity index has lower water resistance capacity. Hence, briquettes having low porosity index are desirable to storage and water resistance.

Effect of average particle size: Figure 4.4 shows the effect of average particle size on the porosity index of sawdust briquettes. Each size of sawdust was mixed with soaked waste paper at five different percentages (25, 30, 35, 40 and 45%). When the level of average particle size of sawdust was varied, the least porosity index (33.97%) was obtained from 0.5mm particle size of sawdust while the highest (312.24%) was from sawdust of average particle size of 6.8mm.

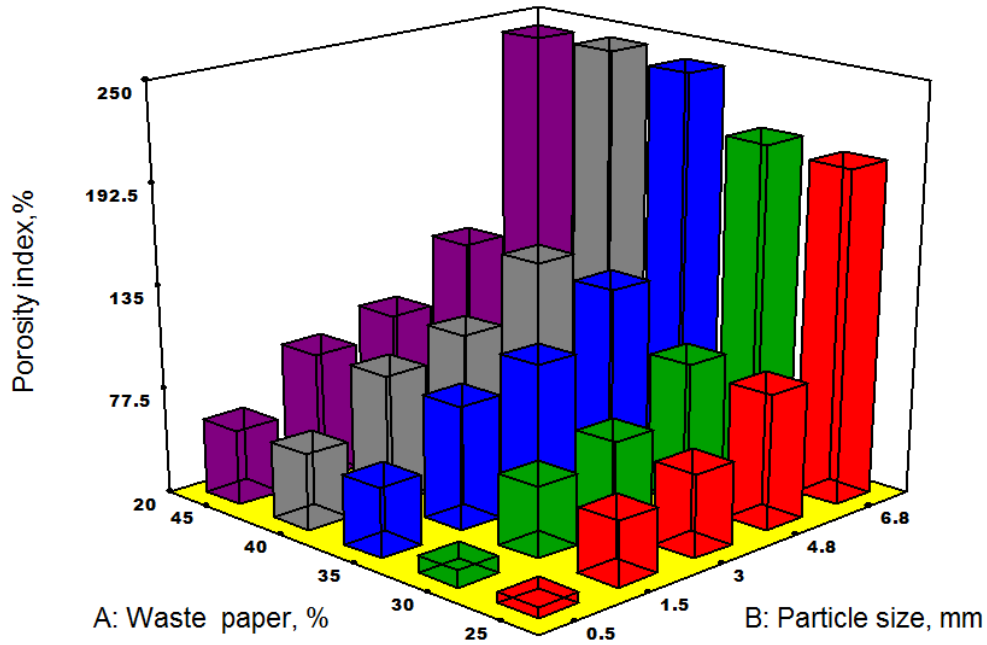


Figure 4.4: Effect particle size of sawdust on porosity index of briquettes

Generally, as can be seen from the figure porosity index was increased as the average particle size was increased from the smallest to highest for all operating conditions (constant die geometry and waste paper percentages). This is due to increasing the average particle size introduces the number of pore space within the briquette by reducing the surface area thereby enhancing the penetration of water into the briquettes. The lower porosity index the higher resistant to water. If briquettes have higher porosity index, it will absorb more water and will be disintegrated easily and also lowers the calorific value. As can be also seen from the figure, sawdust at lower average particle size has lower porosity index. Hence desirable briquettes can be produced with relatively smaller particle size of sawdust.

Effect of waste paper percentage: In order to investigate the effect of waste paper percentage on the porosity index (%) of briquettes, five levels of waste paper percentages were combined to each of sawdust with average particle size of 0.5, 1.5, 3, 4.8 and 6.8mm. Porosity index of briquettes at different waste paper percentages are presented in figure 4.5. As can be seen from the figure, the porosity index (%) was increased as waste paper percentage was increased. However, the change was not significant ($p > 0.05$). As the percentage waste paper increased, the amount of water absorbed also increased. This is due to that paper has higher water holding

capacity than sawdust. Therefore, it is better to use lower waste paper percentage and smaller average particle size of sawdust to produce a desirable briquettes.

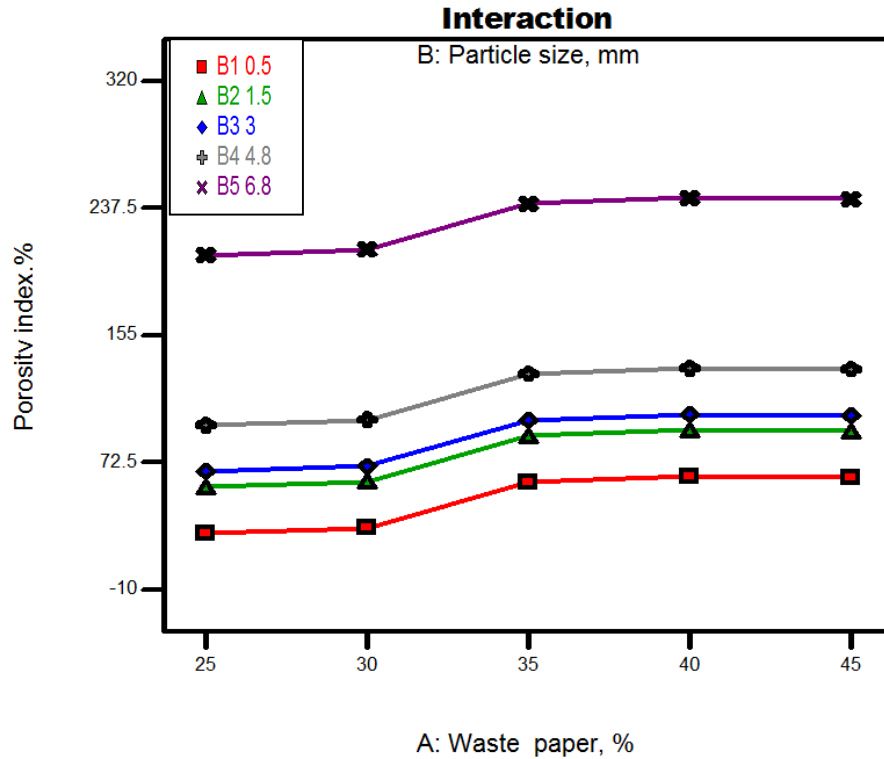


Figure 4.5: Effect of waste paper percentage on porosity index of briquettes

Effect of die diameter: The effect of die geometry on the porosity index of briquettes was presented in figure 4.6. Results from the figure shows that for increasing die geometry there was corresponding increase in porosity index of briquettes. This was resulted from the variation of the pressure because pressure and die geometry have inverse relationship. When the die geometry gets smaller and smaller, the pressure will become higher leading to less number of pores within the briquettes. Hence, the amount of water absorbed will be lower. This implies die geometry has a marked effect on porosity index of briquettes. Therefore, briquettes with good quality can be produced at lower die geometry of cylinders than higher other things being constant.

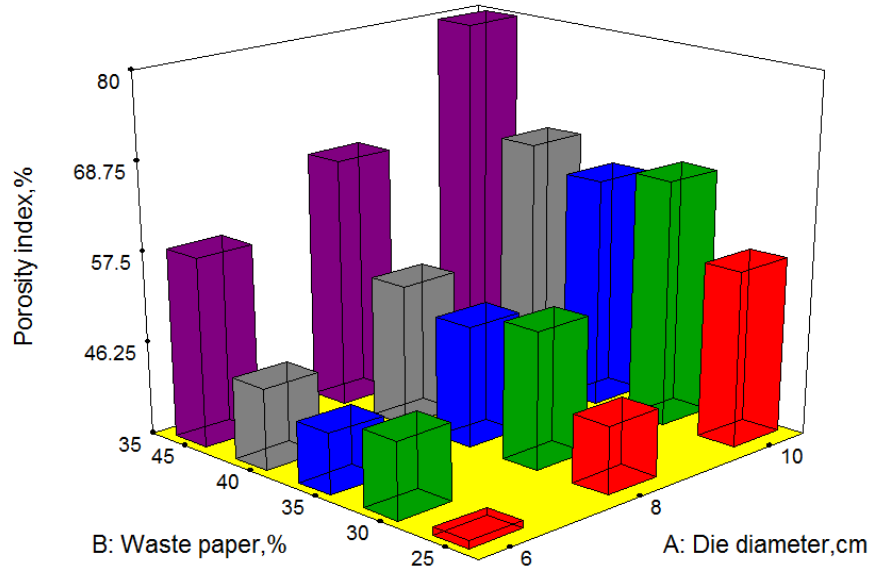


Figure 4.6: Effect of die diameter on porosity index of briquettes

At constant die diameter and waste paper percentage, the porosity index of briquettes of raw sawdust obtained was less than that of briquettes of sawdust with average particle size of 1.5mm. This was the interlocking of particles due to the presence of different particle sizes. It can be concluded that, it is better to use the raw sawdust instead of using very fine particle size of sawdust because it avoids the task of sieving.

4.2.1.3 Shatter resistance (weight, %)

Durability represents the measure of shear and impact forces a briquette could withstand during handling, storage and transportation processes. The durability rating of the briquette was expressed as a percentage of the initial mass of the material remaining on the metal plate and this gave an indication of the ability of the briquette to withstand mechanical handling. Higher shatter resistance implies a lower weight loss and high stability and resistance to handling stress [23].

Effect of average particle size of sawdust: Figure 4.7 shows the effect of average particle size of sawdust on shatter resistance briquettes. Generally as can be seen from the figure, the shatter resistance of briquettes was increased when the average particle size of sawdust was increased. When the average particle size increases, the density of briquettes will be decreases. The reaction force of denser briquettes is greater than that of less denser briquettes when they are allowed to fall on the same height towards a concrete floor. This leads denser briquettes to loss more parts of it. Hence, as particle size increases the density decrease so the shatter resistance increases.

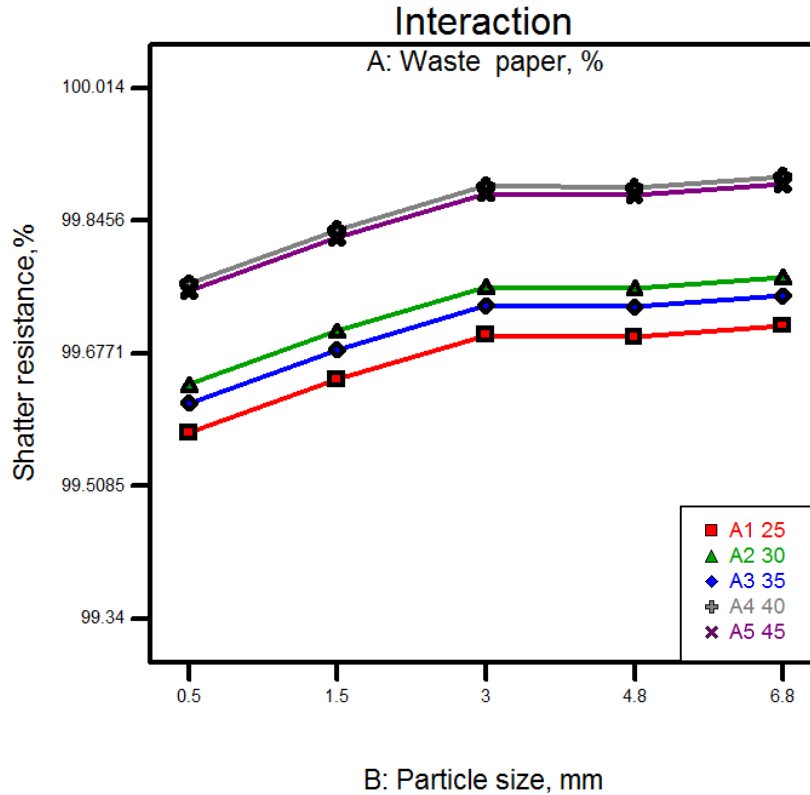


Figure 4.7: Effect of average particle size of sawdust on shatter resistance of briquettes

Effect of die diameter: The effect of die geometry on shatter resistance of briquettes was presented in figure 4.8. As can be seen from the figure, the shatter resistance of briquettes was increased when the die geometry increased. This may be due to as the die geometry increase, the density decreases. Hence the force exerted on the floor, by the briquettes when they are allowed to drop at a specific height, will be decrease. The lowest and highest shatter resistance obtained was 98.88 and 99.88% respectively. Therefore, sawdust can be converted into good quality, highly storable and durable high-grade solid fuel briquettes that will be suitable for both domestic and industrial energy production for heat generation.

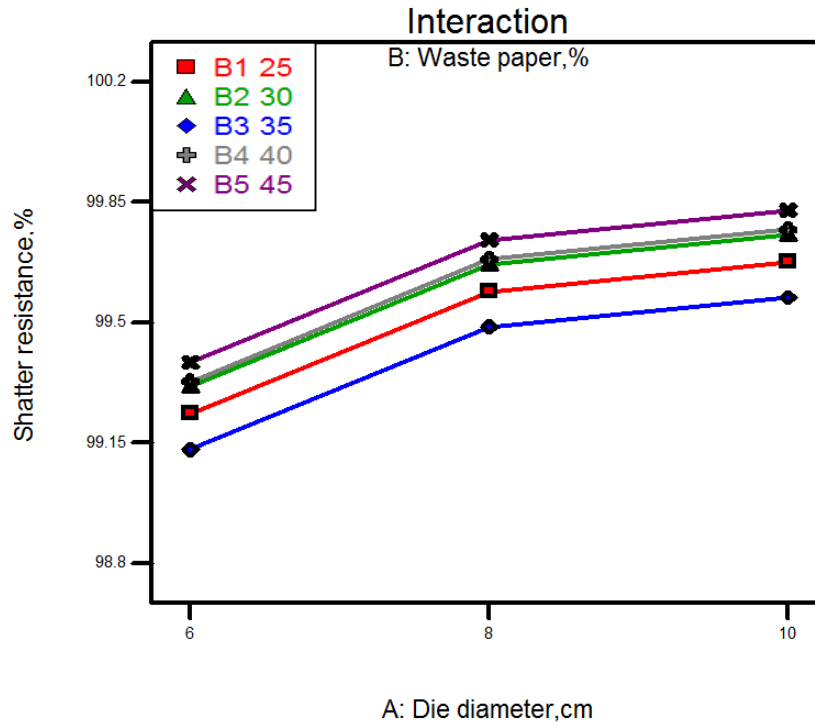


Figure 4.8: Effect of die diameter on shatter resistance of briquettes

Effect of waste paper percentage: The effect of percentage waste paper on shatter resistance of briquettes was presented in figure 4.9. Although the change was not significant ($p > 0.05$), it was observed that the shatter resistance of briquettes was increased when the percentage waste paper was increased. As the percentage waste paper increase, the bond within the sawdust particles also increases. And when the bond increases, the rate of disintegration of particles from briquette will be reduced. And also as the percentage of waste paper increases, the weight of the briquette decreases since paper has less dense than that of sawdust. That is why the shatter resistance of briquettes was increased when the waste paper percentage was increased.

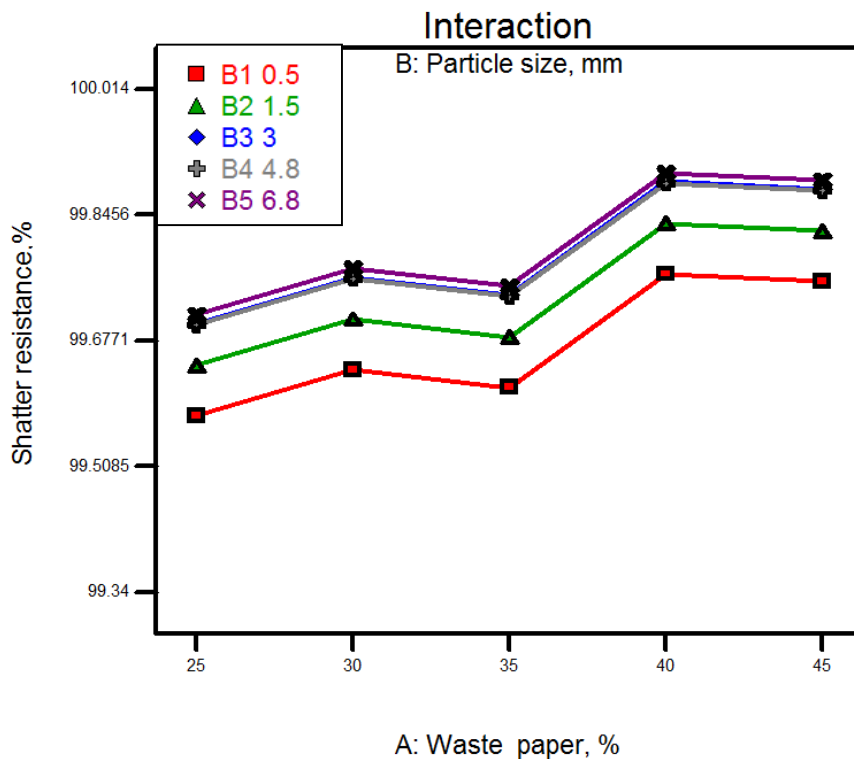


Figure 4.9: Effect of percentage waste paper on shatter resistance of briquettes

4.2.2 Combustion properties of sawdust briquettes

The quality of the briquettes assessed on the basis of their combustion properties of sawdust briquettes were limited to volatile matter, ash content, fixed carbon and gross calorific value. The effect of average particle size of sawdust, waste paper percentage, binder type and die geometry were investigated and the raw data was presented in appendix B

4.2.2.1 Volatile matter

Volatile matter represents the components of carbon, hydrogen and oxygen present in the biomass that when heated turn to vapor, usually a mixture of short and long chain hydrocarbons. Volatile content has been shown to influence the thermal behavior of solid fuels, but this is also influenced by the structure and bonding within the fuel. Biomass generally has a volatile content of around 70-86% of the weight of the dry biomass which makes biomass a more reactive fuel giving a much faster combustion rate during the devolatilisation phase than other fuels such as coal. A briquette with low volatile content tends to incomplete combustion which leads to significant amount of smoke and release of toxic gas [24].

The effects of particle size, die-geometry, and binder percentage and binder type on volatile matter of briquettes was investigated. All factors, but die geometry, were found to be significant ($p < 0.05$) on volatile matter of briquettes. From the experimental results obtained, the volatile matter of the briquettes varies in the range of 70.24% to 92.13%. This value, is higher, gives an idea of the flame length during the combustion process and the ease of ignition. These values were comparable with the values recommended in the literature [24]. From the result obtained, briquettes bonded with avocado kernel flour have higher volatile matter than others. So it will be highly reactive fuel than other types of briquettes which have lower volatile matter than it.

Effect of average particle size of sawdust: Figure 4.10 shows the effect of average particle size of sawdust on volatile matter of briquettes. As can be seen from the figure, the highest and lowest volatile matter obtained were 90.56% and 70.46% respectively. As can be also observed from the figure, the volatile matter was generally increased as the average particle size was increased from 0.5mm to 3mm. This could be the result of fine particles would be compacted easily compared to larger particles, other things being constant. If particles compacted well, the density will be higher leading to low rate of mass transfer during volatilizing phase hence the amount of volatile matter released will be reduced.

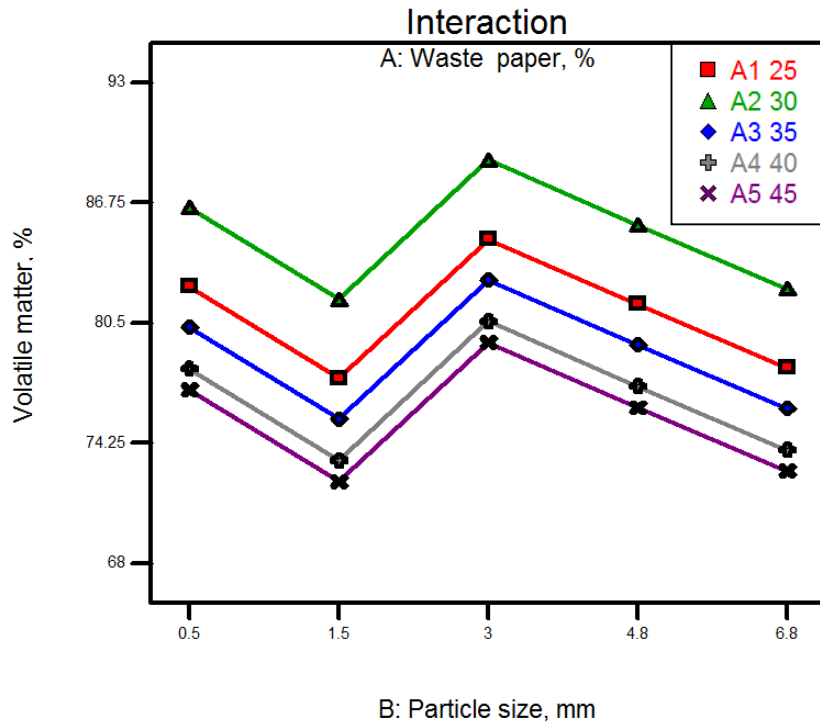


Figure 4.10 : Effect of average particle size of sawdust on volatile matter of briquettes

However, volatile matter of briquettes was found to be decreased as the average particle size of sawdust exceeded 3mm. This can be resulted from the size of individual particles of sawdust. As the average particle size of sawdust increase, the amount of volatile matter within it increases but the mass transfer rate within the particle itself is weak since the contact area is lower. The maximum value of volatile matter (90.56%) was obtained in average particle size of sawdust of 3mm. The result shows that briquetting of sawdust can give a better performance based on high volatile matter at 3mm average particle size of sawdust.

Effect of die diameter: The raw sawdust was sampled and then bonded with soaked waste paper in five weight percentages (25, 30, 35, 40 and 45%) at three die geometries. Volatile matter of sawdust briquettes at different die geometries are presented in figure 4.11. As can be seen from the figure, generally the volatile matter of the briquettes was found to be the same in the three die geometries. The recorded result show that the effect of die geometry has insignificant ($p=0.3568$) effect on volatile matter of sawdust briquettes.

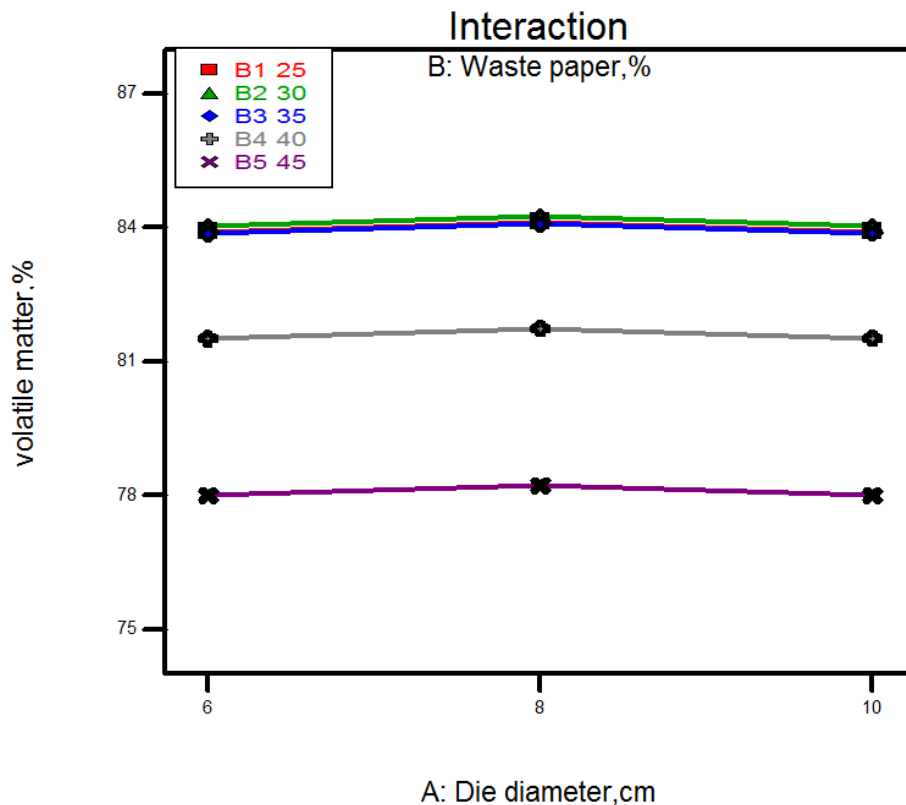


Figure 4.11: Effect of die diameter on percentage volatile matter of briquettes

Effect of waste paper percentage : Figure 4.12 shows the effect of waste paper percentage on the volatile matter of briquettes bonded from waste paper and sawdust at different proportions.

Five waste paper weight percentages were combined for each of sawdust samples of particle size of 0.5, 1.5, 3, 4.8 and 6.8mm at constant die geometry of 10 cm. Generally, as can be seen from the figure, volatile matter of briquettes was increased when waste paper percentage was increased from 25% to 30% but when waste paper percentage was exceeded 30%, the volatile matter of briquettes was decreased. This could be either the waste paper has lower volatile matter than sawdust or when the weight percentage of waste paper increases, the bond also increases. As a result the mass transfer rate will be decreased i.e. the rate of volatalization will be hindered. That is why the volatile matter of the briquettes decreases when the weight percentage of waste paper increases. Hence for optimal performance waste paper at 30% could be added to sawdust briquettes. This shows that waste paper with sawdust, 30% weight percentage of waste paper, could lead to better briquettes performance and cost effectiveness making this fuel more attractive. It can be concluded that the effect of waste paper percentage has a significant ($p < 0.05$) effect on the combustion quality of briquettes.

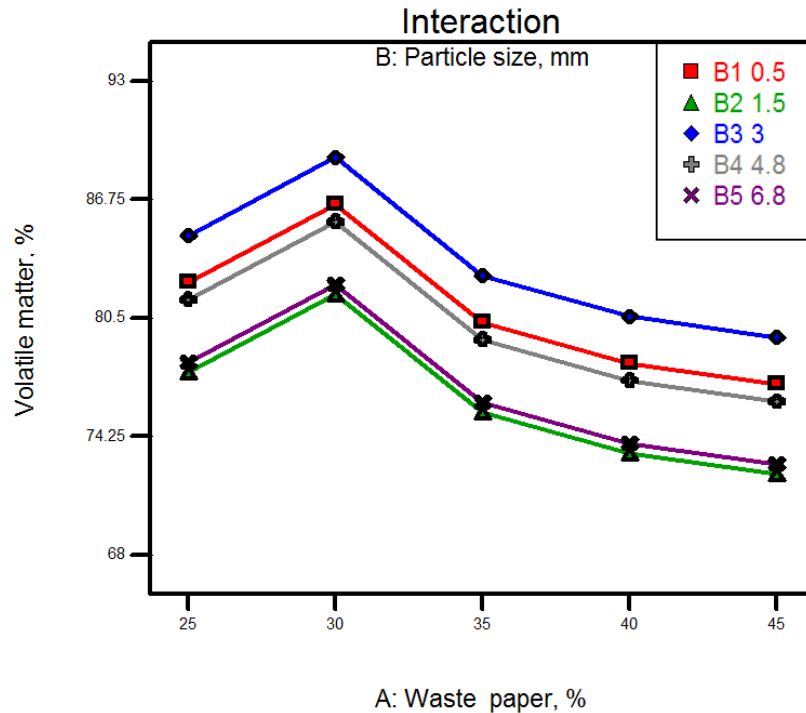


Figure 4.12: Effect of waste paper percentage on volatile matter of briquettes

4.2.2.2 Ash content

Ash is the non-combustible inorganic residue that remains after complete combustion. Ash has a significant influence on the heat transfer to the surface of the fuel as well as the diffusion of

oxygen to the fuel surface during combustion. The higher the fuel's ash content, the lower its calorific value. As ash is an impurity that will not burn, fuels with low ash content are better suited for thermal utilization than fuels with high ash content. Higher ash content in a fuel usually leads to higher dust emission and affects the combustion volume and efficiency [24].

Ash content in briquettes normally causes increase in the combustion remnant in form of ash which lowers the heating effect of the briquettes [16]. The ash content of different types of biomass is an indicator of slagging behavior of the biomass. Generally, the greater the ash content the greater the slagging behavior. But this does not mean that biomass with lower ash content will not show any slagging behaviour. The temperature of operation, the mineral compositions of ash and their percentage combined, determine the slagging behaviour. Minerals like SiO_2 , Na_2O and K_2O are more troublesome. Usually slagging takes place with biomass fuels containing more than 4% ash and non-slagging fuels with ash content less than 4% [25].

Effect of average particle size of sawdust: In order to determine the effect of average particle size of sawdust on ash content of briquettes, five levels of particle size were used for this work. Each size of sawdust samples was bonded with waste paper using die geometry of 10 cm. Figure 4.13 shows the variation in percentage ash content according to the average particle size of sawdust. The highest percentage ash content (7.26%) was observed in the sawdust of average particle size of 6.8mm while the least (2.33%) was from sawdust of average particle size of 3mm. Generally as can be seen from the figure, the percentage ash content of briquettes was decreased when the average particle size of sawdust was increased. This could be resulted from the presense of different pore sapces within the briquette.

As the particle size increase, the number of pore space within the briquette will be higher. The smaller particles are less course ,compacted easily, small number of pore space leading to incomplet combustion. As the size of particles increases, the number of pore sapce within the sample will be greater allowing oxygen to flow easily within the sample. Hence, allowing adequateflow of oxygen and so a combustion was complete resulting in a less ash amount Therfor, briquettes with larger particle will be burn completely and the ash content will be smaller. Therefore, optimum average particle size was found to be 3mm on the basis of percentage ash content of briquettes.

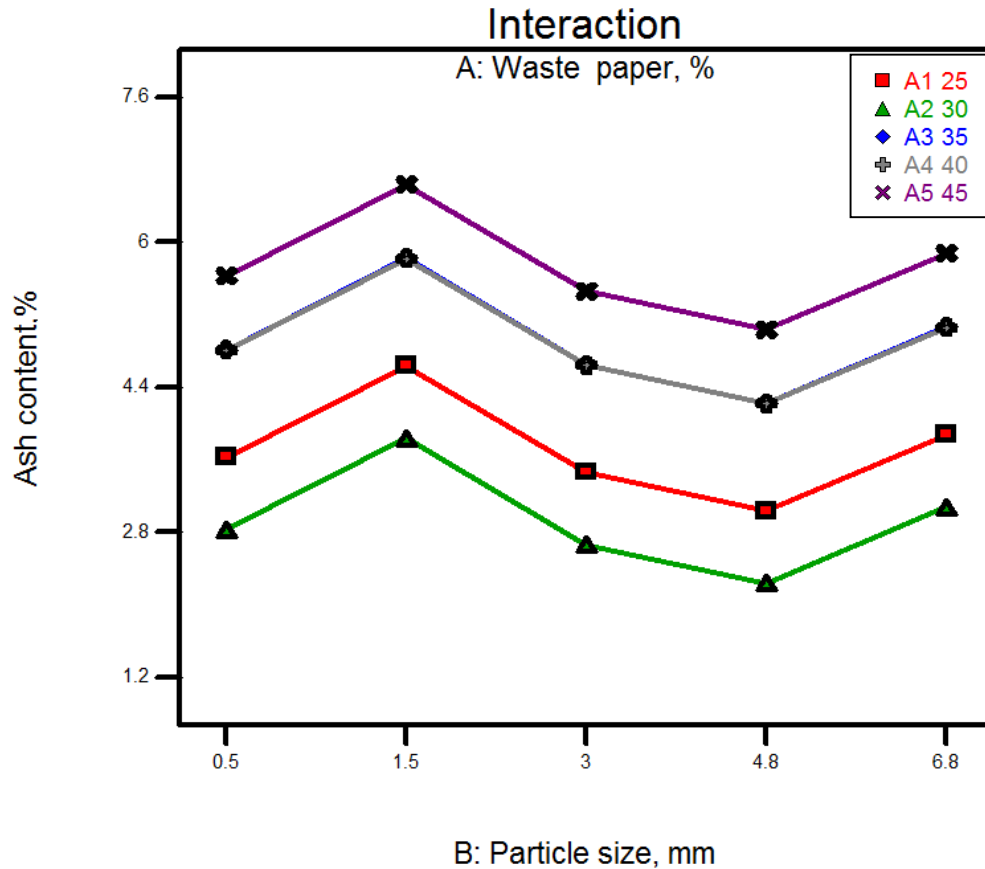


Figure 4.13: Effect of average particle size on ash content of briquettes

Effect of percentage of waste paper: Waste paper was used as a binder in five levels during briquetting of sawdust. The highest percentage ash content (7.26%) was observed in 40% of weight percentage of waste paper while the least value (2.33%) was from 30% waste paper. Figure 4.14 shows the variation in percentage ash content of briquettes according to weight percentage of waste paper. From the figure, it can be observed that the percentage ash content of the briquettes was decreased when percentage of waste paper was increased from 25% to 30%. However, it was increased when the percentage of waste paper was exceeded 30%. Hence for optimal performance waste paper at 30% could be added to sawdust briquettes. The increase in percentage ash content with increase in percentage waste paper might be attributed to higher content of the waste paper in the mixture. This could be either waste paper has higher ash content than sawdust or as the percentage waste paper increase, the interparticle bond increases which can reduce the mass transfer rate within the briquette which can hinder the flow of oxygen. Therefore, it is better to use waste paper as binder at the optimum weight percentage to produce briquettes with low ash content.

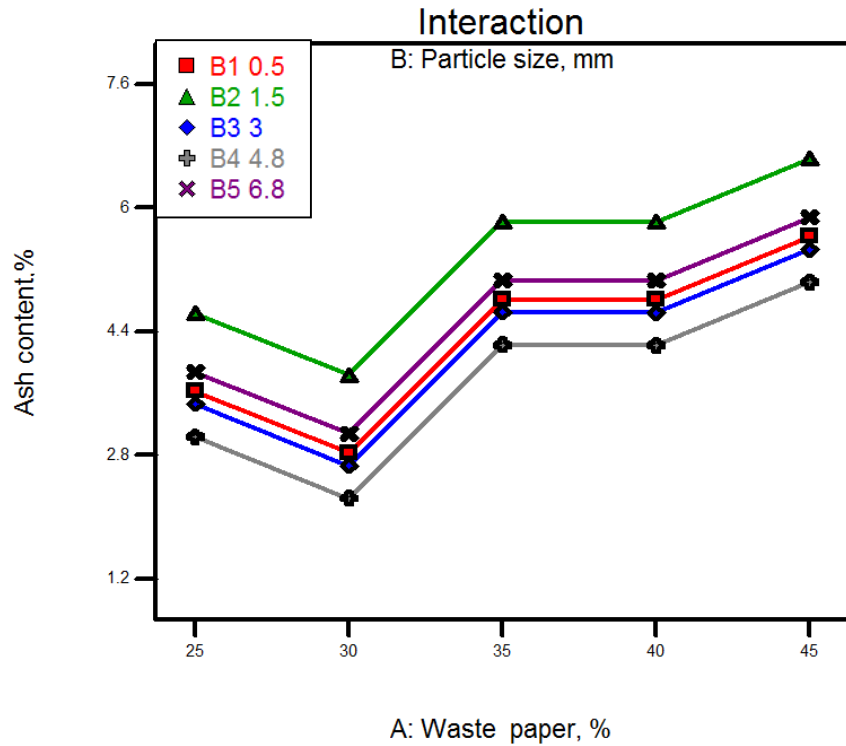


Figure 4.14 : Effect of percentage of waste paper on the ash content of briquettes

Effect of die diameter: The briquettes were produced from the raw sawdust using three different die diameters at constant weight percentage of waste paper. The effect of die diameter on the ash content of briquettes was presented figure 4.15. From the figure, it can be observed that the percentage ash content of briquettes produced at different die geometries show almost similar values. From this result, it can be concluded that the effect of die geometry on ash content of sawdust briquettes has insignificant ($p > 0.05$) effect.

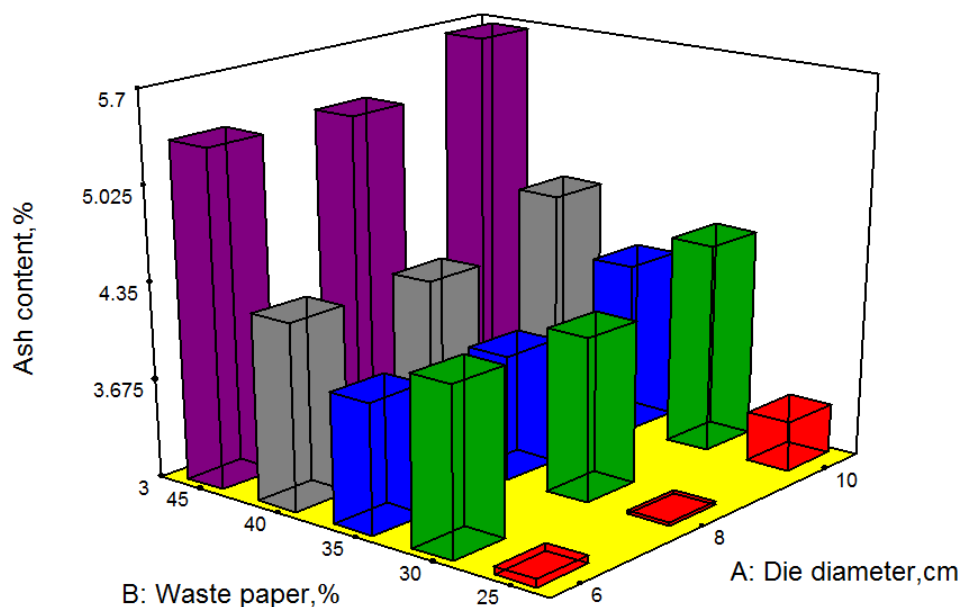


Figure 4.15: Effect of die diameter on percentage ash content of briquettes

4.2.2.3 Percentage fixed carbon

The fixed carbon of the briquette is a percentage of carbon (solid fuel) available for char combustion. This is not equal to the total amount of carbon in the fuel (the ultimate carbon) since a significant amount is released as hydrocarbons in the volatiles. Fixed carbon positively correlated with carbon monoxide, with less fixed carbon contained in the briquettes gave less carbon monoxide and prolong cooking time by its low heat release. A lower fixed carbon, a better result during combustion and a lesser probability of CO₂ generation. Briquettes having high volatile matter have lower fixed carbon, which low fixed carbon tends to be harder, heavier, stronger and easier to ignite than briquettes containing high fixed carbon [24]. The fixed carbon of the briquette, which is the percentage of carbon (solid fuel) available for char combustion after volatile matter is distilled off, gives a rough estimate of the heating value of a fuel [17]. The value of fixed carbon of briquettes obtained was ranged between 6.63% and 24.26%. The highest fixed carbon was observed in briquettes formed from sawdust of average particle size of 1.5mm and waste paper percentage of 35% while the least was from briquettes of raw sawdust and avocado kernel flour percentage of 45%. Generally the least average fixed carbon was obtained for briquettes bonded with avocado kernel.

Effect of average particle size of sawdust: Figure 4.16 shows the variation of fixed carbon of briquettes according to the variation of average particle size of sawdust. From the figure, it can be observed that generally the fixed carbon of briquettes was increased when the average particle size was increased except when the average particle was increased from 1.5mm to 3mm.

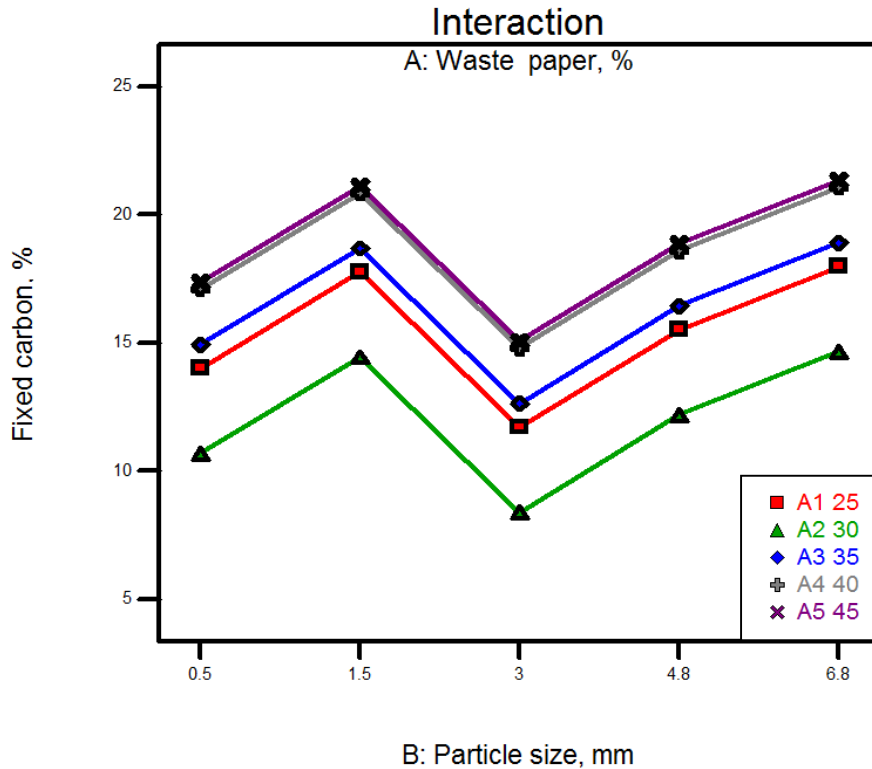


Figure 4.16: Effect average particle size of sawdust on percentage fixed carbon of briquettes

However, the change was not significant ($p > 0.05$). Percentage fixed carbon of briquettes was determined by subtracting the sum of volatile matter and ash content from 100. However, the ash content of briquettes obtained was lower and has negligible effect on fixed carbon when compared with that of volatile matter. Hence fixed carbon of briquettes was found to be dependent on volatile matter of the briquette. A briquette with high volatile matter was found to have a lower fixed carbon. Due to this fact the graph of volatile matter and fixed carbon, effect of average particle size of sawdust, were found to be inverse of each other. The least fixed carbon percentage of briquettes obtained was at 3mm average particle size of sawdust. Therefore, on the basis of percentage fixed carbon of briquettes, it is better to use sawdust of average particle size of 3mm.

Effect of waste paper percentage: The effect of waste paper percentage on fixed carbon percentage of briquettes was presented in figure 4.17. Generally, though there was not significant change, as can be seen from the figure, the fixed carbon percentage of briquettes was increased when the percentage waste paper was increased. In section 4.3.1, it was recored that waste paper percentage and percentage volatile matter show inverse relations. If the volatile matter of the briquette is lower, the fixed carbon will be higher. So as waste paper percentage increases, the fixed carbon percentage also increases.

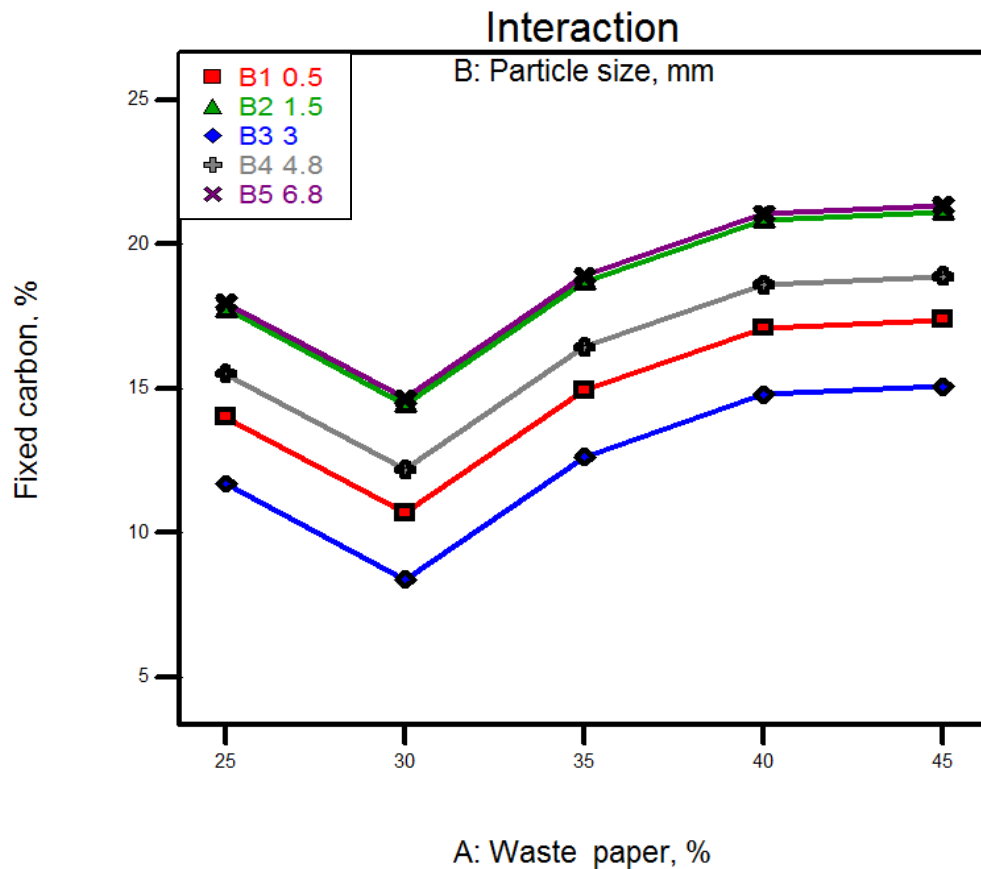


Figure 4.17: Effect of percentage waste paper on fixed carbon of briquettes

Effect of die diameter: The result of the effect of die diameter on the percentage fixed carbon of briquettes was presented in figure 4.18. The effect of die geometry was found to be insignificant ($p>0.05$) on volatile matter and ash content of briquettes. Almost the same values, for each of them, were recorded for all types of briquettes briquetted at different die geometries. The effect of die geometry on fixed carbon of briquettes was insignificant ($p>0.05$). Therefore, die geometry

has not a significant effect on combustion properties of briquettes based on the results obtained in this work.

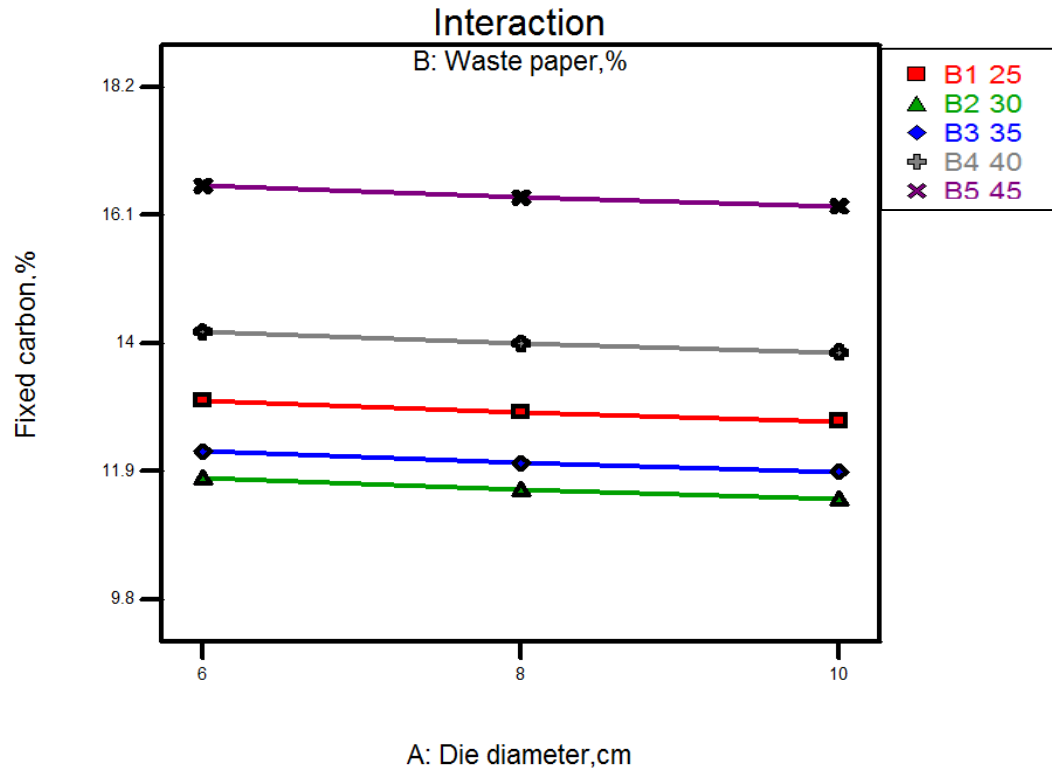


Figure 4.18: Effect of die diameter on percentage fixed carbon of briquettes

4.2.2.4 Calorific value

Calorific value is the most important combustion property for determining the suitability of a material as fuel. It gives the indication of the quantity of fuel required to generate a specific amount of energy. The calorific value is the standard measure of the energy content of a fuel. It is defined as the amount of heat evolved when a unit weight of fuel is completely burnt and the combustion products are cooled to 298k. Calorific value determines the energy content of a fuel. The higher calorific value denotes the high quality of briquettes. The calorific value is the most important combustion property for determining the suitability of a material as fuel. It gives the indication of the quantity of fuel required to generate a specific amount of energy [26]. The calorific values of the briquettes were determined at different factors such as average particle size of sawdust, waste paper percentage, die geometry of the mould and binder type, and the values were computed using oxygen bomb calorimeter (Parr 6200).

Effect of average particle size of sawdust: Figure 4.19 shows the difference in energy content of sawdust briquettes according to the average particle size of sawdust.

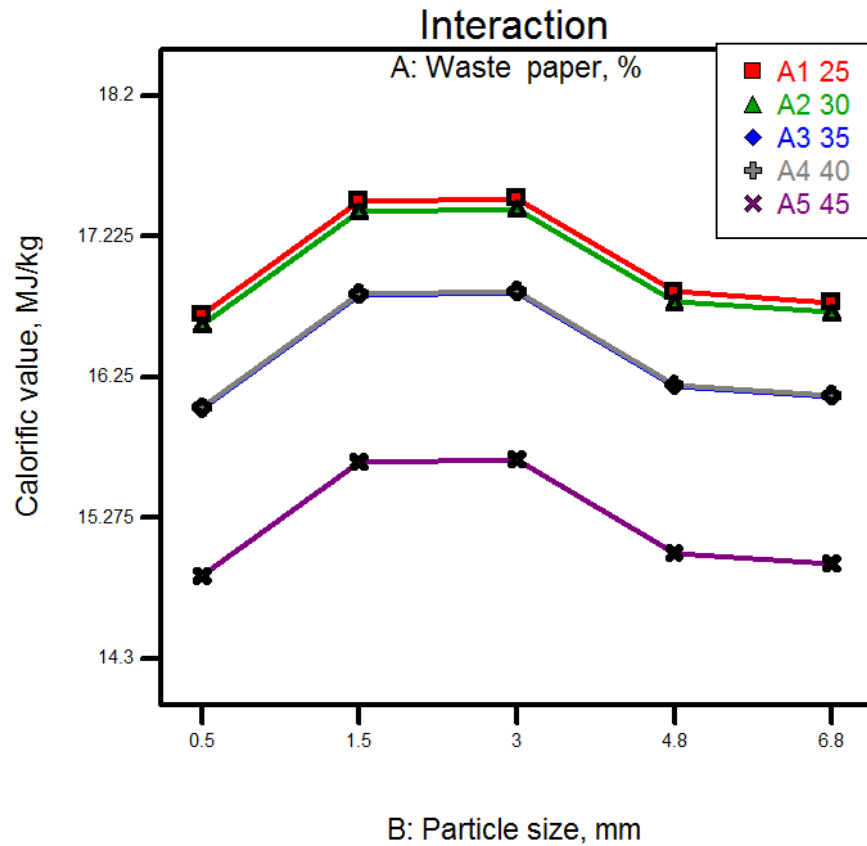


Figure 4.19: Effect of average particle size on calorific value of sawdust briquettes

It was discovered that average particle size has little or insignificant ($p > 0.05$) effect on the calorific value of the briquettes. It can then be concluded that particle size of feedstock has not a marked effect on calorific value of briquettes. As can be also seen from the figure, the computed calorific value for all sawdust briquettes, produced from different average particle size, falls in the range of 14.5019 MJ/kg to 18.1332MJ/kg. This energy value can produce enough heat for house hold and small scale industrial application. The results of the calorific value of the sawdust briquettes compare well with the results of the heating value of sawdust charcoal briquette obtained by [13] and most biomass briquettes including almond shell briquette (19,490 kJ/kg), corn cob briquette (20,890 kJ/kg) [19].

Effect of waste paper percentage: Figure 4.20 shows the variation in calorific value of briquettes according to the waste paper percentage. As can be observed from the figure, for increasing waste paper percentage, there was corresponding decrease in calorific value of

briquettes. This shows that, waste paper has to be added as small as possible to get briquettes with high calorific value. It was discovered that the calorific value of briquettes was significantly affected by waste paper percentage. Briquettes with low waste paper percentage produce higher calorific value than briquettes with high waste paper percentages. It can be concluded that waste paper percentage is a significant factor in briquette production and the increase of waste paper percentage has reduced the calorific value of the briquettes. Hence, it has to be at its optimum level of 25% based on the results obtained in this work.

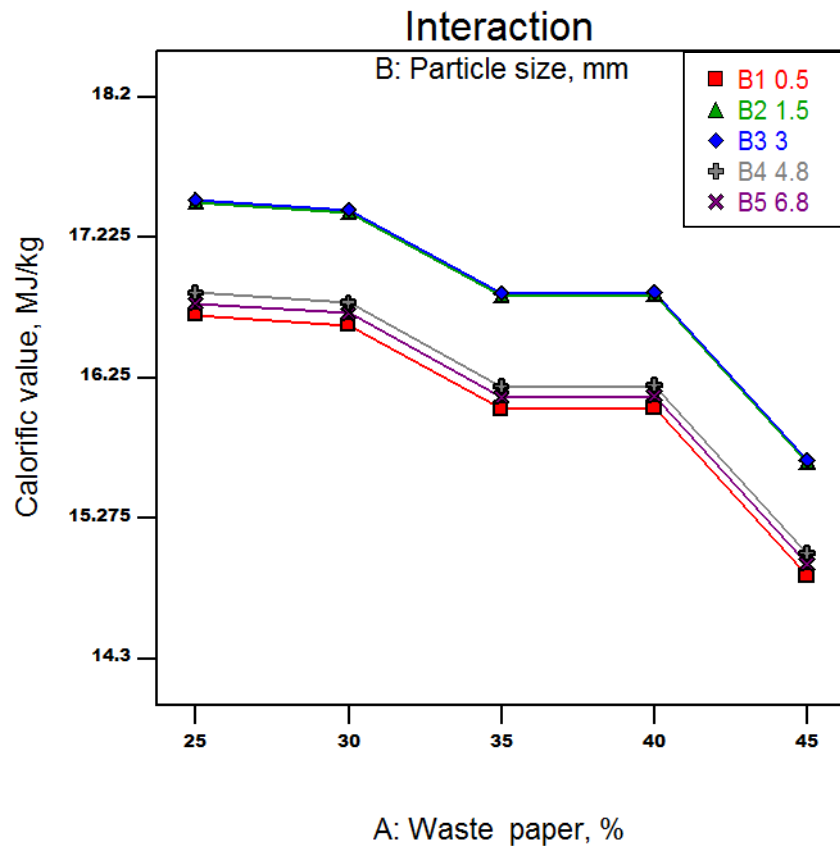


Figure 4.20: Effect of waste paper percentage on calorific value of briquettes.

Effect of die diameter: Figure 4.21 shows the difference in calorific value of sawdust briquettes according to die diameter of the mould. The highest and the least calorific value of briquettes produced by using the three die geometries were 18.5832 MJ/kg and 15.1165MJ/kg. It was discovered that die geometry of mould has a little or insignificant ($p>0.05$) effect on the calorific value of sawdust briquettes. As indicated in the figure, the calorific values of briquettes produced in different die geometries were almost constant. It can be concluded that die geometry is not a significant factor on the calorific value of briquettes.

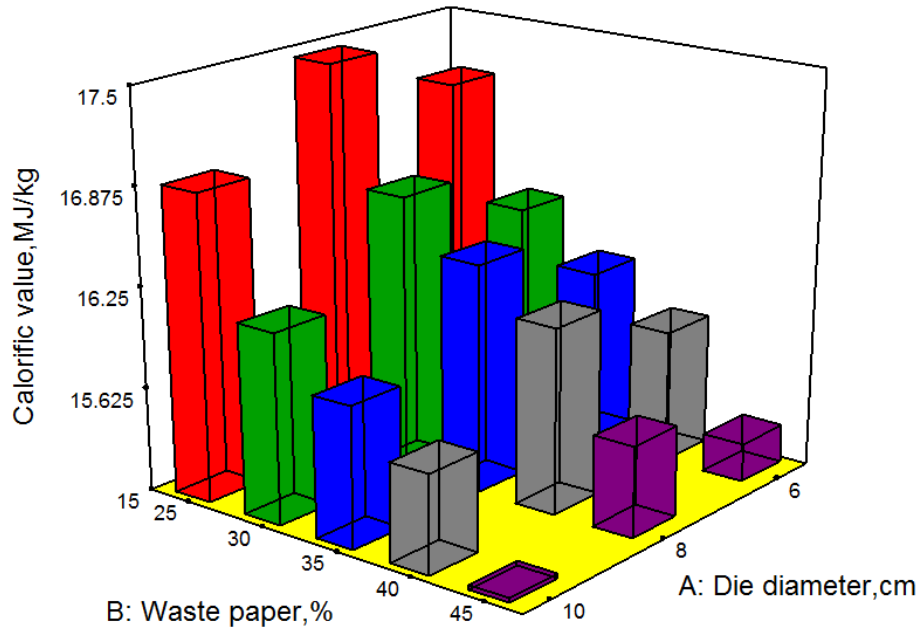


Figure 4.21: Effect of die diameter on the calorific value of sawdust briquettes

Summary: The effect of average particle size of sawdust, waste paper percentage and die diameter on the physical and combustion properties of sawdust briquettes investigated in this research was summarized. Table 4.2 shows the results of the analysis of variance (ANOVA) for comparing the presence of significant difference in briquette properties according to the average particle size of sawdust, waste paper percentage and die diameter.

Table 4.1: ANOVA table for physical and combustion properties of sawdust briquettes.

Parameters	Source of variance	SS	df	MS	F	P-value	Comment
Density	Particle size	3101.52	4	775.38	3.22	0.0407	<i>S</i>
	Paper percentage	505.75	4	126.44	0.52	0.7194	<i>Ns</i>
	Die diameter	6069.66	2	3034.83	15.65	0.0017	<i>S</i>
Porosity index	Particle size	97367.49	4	24341.87	24.85	<0.0001	<i>S</i>
	Paper percentage	6931.99	4	1733	1.77	0.1843	<i>Ns</i>
	Die diameter	1134.60	2	567.3	8.03	0.0122	<i>S</i>
Shatter resistance	Particle size	0.17	4	0.042	0.95	0.4592	<i>Ns</i>
	Paper percentage	0.4	4	0.1	2.28	0.1056	<i>Ns</i>
	Die diameter	0.55	2	0.27	3.96	0.0639	<i>Ns</i>
Volatile matter	Particle size	206.53	4	51.63	3.33	0.0363	<i>S</i>
	Paper percentage	237.29	4	59.32	3.83	0.0228	<i>S</i>
	Die diameter	14.95	2	7.47	1.18	0.3568	<i>Ns</i>
Ash content	Particle size	7.19	4	1.8	1.6	0.2228	<i>Ns</i>
	Paper percentage	25.10	4	6.27	5.58	0.0052	<i>S</i>
	Die diameter	0.52	2	0.26	0.29	0.7586	<i>Ns</i>
Fixed carbon	Particle size	172.32	4	43.08	2.82	0.0604	<i>Ns</i>
	Paper percentage	174.02	4	43.08	2.85	0.0588	<i>Ns</i>
	Die diameter	0.58	2	0.29	0.055	0.9467	<i>Ns</i>
Calorific value	Particle size	3.13	4	0.78	2.26	0.1075	<i>Ns</i>
	Paper percentage	10.52	4	2.63	7.6	0.0012	<i>S</i>
	Die diameter	1.28	2	0.64	2.22	0.1716	<i>Ns</i>

* Note: *S* = significant, *Ns* = not significant, SS is sum of squares and MS is mean of squares

As can be observed from table 4.2, there were no significant difference ($p > 0.05$) in the quality of briquettes bonded with waste paper at different percentages except for percentage volatile matter, ash content and heating value. From the table it can be also seen that the effect of average particle size of sawdust was significant ($p < 0.05$) on density, porosity index and percentage volatile matter of briquettes however, it was insignificant ($p > 0.05$) on shatter resistance, ash content, fixed carbon percentage and calorific value of briquettes. The effect of die geometry was found to be insignificant ($p < 0.05$) on the quality of sawdust briquettes except for porosity index and density of briquettes. The effect of binder type was significant in all properties of sawdust

briquettes evaluated in this work, density, porosity index, shatter resistance, volatile matter, ash content, fixed carbon and calorific value of briquettes. None of the densification variables except binder type had significant effect ($p > 0.05$) on the fixed carbon (%) of the briquettes.

4.3 Optimization

The optimum blend of sawdust particle size-waste paper percentage and die diameter- waste paper percentage was assessed in this work on the basis of the briquette properties: density, porosity index, percentage volatile matter, percentage ash content and gross calorific value. However, higher importance (+++), was given to density and calorific value because they are two of the major indices for assessing the combustion, handling characteristics and ignition behavior of briquettes. Numerical optimization was used in this work. The optimization was done to maximize density, volatile matter and calorific value, and to minimize porosity index and ash content of the briquettes.

Optimum sawdust particle size –waste paper percentage blend: Five levels of average particle size of sawdust (0.5, 1.5, 3, 4.8 and 6.8mm) were mixed with different waste paper percentages (25, 30, 35, 40 and 45%, wt/wt) and then briquetted at constant die diameter of 10 cm. as can be seen from the figure 4.22, a combined desirability of 0.758 was obtained.

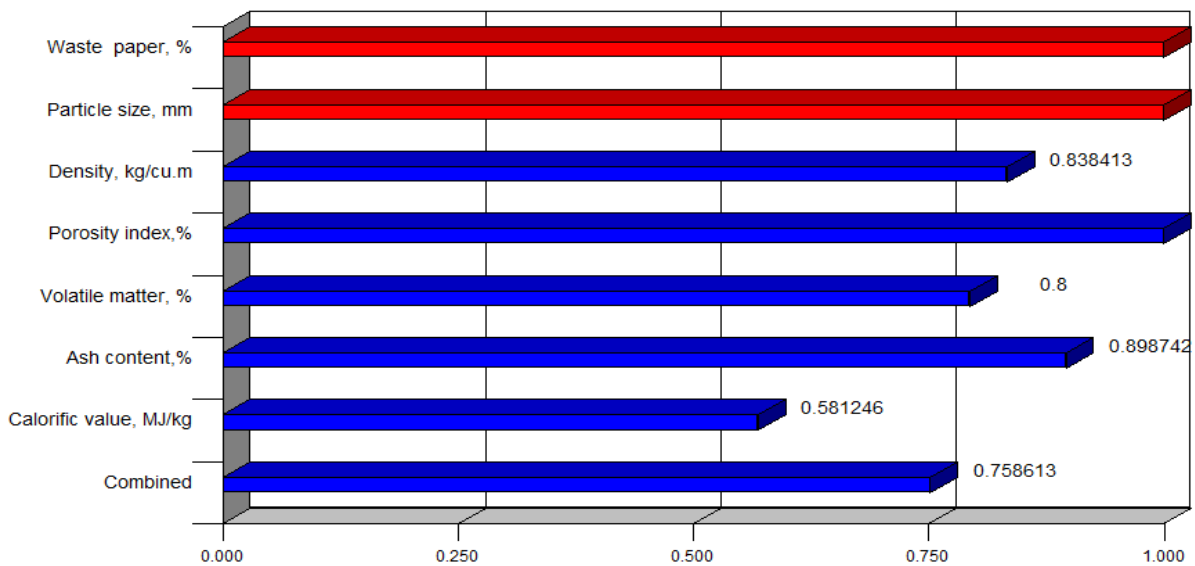


Figure 4.22: Desirability graph for optimum blend of sawdust particle size and waste paper percentage

The briquettes' physical and combustion properties were determined. Among several combinations of sawdust average particle size and waste paper percentage, a blend of sawdust of average particle size of 0.5mm and waste paper percentage of 30% gave the optimum density of 270.658 kg/m³, porosity index of 29.782%, volatile matter of 86.496%, ash content of 2.829% and calorific value of 16.613MJ/kg..

Optimum die diameter –waste paper percentage blend: Raw sawdust was mixed with waste paper in weight percentage ratios of 75:25, 70:30, 65:35, 60:40 and 55:45 respectively. Briquettes were produced by using three different die geometries (6, 8 and 10cm). Physical and combustion properties of the briquettes were determined. A blend of die diameter of 6cm and waste paper percentage of 25% gave the optimum density of 306.079 kg/m³, porosity index of 35.92%, volatile matter of 83.905%, ash content of 3.053 % and calorific value of 17.134 MJ/kg. The desirability graph is presented in figure 4.23.

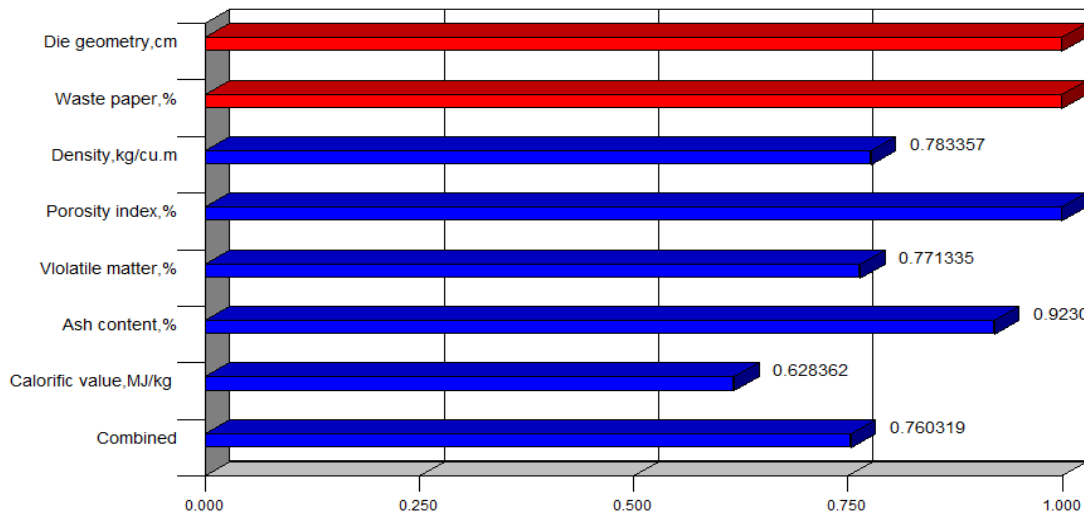


Figure 4.23: Desirability graph for optimum blend of die geometry and waste paper percentage

Higher optimum density and calorific value were obtained in the optimum blend of die geometry and waste paper than that of sawdust particle size and waste paper percentage. Therefore it can be concluded that die geometry is more important factor than that of particle size of feedstock in briquettes production.

CHAPTER FIVE

5.0 Conclusion and Recommendation

5.1 Conclusion

This study assessed the physical and combustion properties of briquettes produced from sawdust of *Cupressus Lusitanica* using waste paper as a binder. From the experiment carried out, it was generally found out that the characteristics of sawdust briquettes produced were satisfactory. The computed density, porosity index, shatter resistance, volatile matter, ash content, fixed carbon and calorific value for all sawdust briquettes falls in the range of 218.24-322.62kg/m³, 33.97-312.4%, 98.88-99.95%, 70.24-90.56%, 2.33-7.26%, 6.7-24.26% and 14.5019-18.3832MJ/kg respectively. The ANOVA result shows that only density and porosity index of the briquette was significantly affected by the die diameter. Similarly, the effect of waste paper percentage has insignificant effect on the quality of briquettes except for volatile matter, ash content and calorific value. A significant effect of average particle size of sawdust (feedstock) was resulted on density, porosity index and volatile matter of the briquettes.

The combination of 0.5mm average particle size of sawdust and 30% waste paper gave the optimal density of 270.658kg/m³, porosity index of 29.782%, volatile matter of 86.496%, ash content of 2.829% and gross calorific values of 16.613 MJ/kg. The optimum blend of die diameter and waste paper was obtained at the combination of 6 cm and 25% with optimal values of density of 306.079 kg/m³, porosity index of 35.92%, volatile matter of 83.90%, ash content of 3.05% and gross calorific value of 17.134MJ/kg.

Using waste paper as a binder resulted several interesting findings that could be used to develop sawdust briquettes where this waste product is readily available especially in urban areas where there are a number of wood processing industries. Capability of production of sawdust briquettes with good quality using only waste paper as a binder is an encouraging fact. These sawdust briquettes produced by using waste paper as a binder would make good substitutes as well as good supplements to firewood, can be easily transported, stored and used in a simple manner. With these alternative use of, sawdust briquettes, produced at house hold level, there will be reduction on the number of trees cut per year for firewood thus mitigating the occurrences of climate changes. The results of physical and combustion property testing showed that sawdust

briquettes can be manufactured and used in place of wood or charcoal without significantly affecting one's ability to cook.

5.2 Recommendations

Based on the study made on briquetting of sawdust of *Cupressus Lusitanica* the following recommendations were given.

- ➡ Development of briquetting technology will be lead to increase job opportunities and establish entrepreneurs. An appropriate assistance of government, nongovernmental organization and professional persons has to be performed. Also further research on the design and construction of the briquetting technologies had to be done.
- ➡ The use of sawdust briquettes is an important alternative fuel that should be further developed as it allows for the revaluation of sawdust. So a wide publicity of the use of sawdust briquettes has to be given.
- ➡ Moreover, design and construction of carbonizer and appropriate stove for briquettes, carbonization and characterization of briquettes, scaling up of the briquetting machine and its economic viability are an open area of study for this work.

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Appendices

A: Determination of physical properties of sawdust briquettes

1. Density: it was determined using the relation described in equation:

$$\rho_{br} = M_{br}/V_{br} \text{ and, } V_{br} = \pi R^2 H$$

Where, R=radius of the briquette, cm, H=height of the briquette, cm, π = mathematical constant i.e. 3.14 and ρ_{br} =density of briquette, kg/m³

Exp. No	Names	R (cm)	H (cm)	V (cm ³)	M (gm)	ρ_s (kg/m ³)
1	F _{6,2}	3	3.5	98.91	30.1	304.32
2	F _{8,3}	4	3.75	188.40	52.2	277.07
3	F _{6,5}	3	5	141.30	43.3	306.44
4	A ₁	5	9	683.61	171.7	251.17
5	F _{10,5}	5	6	455.74	114.2	250.58
6	D ₄	5	10	759.57	177.7	233.95
7	C ₂	5	7.3	554.48	135.0	243.47
8	F _{10,4}	5	4.6	349.40	100.4	287.35
9	C ₄	5	10.5	797.54	192.3	241.11
10	B ₅	5	8.5	645.63	151.8	235.12
11	C ₃	5	8.5	645.63	156.2	241.93
12	B ₄	5	11.4	865.90	203.9	235.48
13	A ₄	5	4.6	303.83	105.0	290.78

14	B ₂	5	9.5	721.59	183.0	253.61
15	D ₂	5	9	683.61	171.2	250.44
16	F _{8,2}	4	3	150.72	42.0	278.66
17	F _{6,3}	3	3.5	98.91	28.5	288.14
18	A ₃	5	7.5	569.67	150.1	263.48
19	F _{6,1}	3	4.2	118.69	35.8	301.63
20	D ₃	5	9	683.64	149.2	218.24
21	F _{6,4}	3	2	56.52	18.8	332.62
22	A ₅	5	8.5	645.63	162.7	252.00
23	F _{8,4}	4	4	200.96	51.5	256.27
24	C ₅	5	7.4	562.08	145.3	258.50
25	F _{8,1}	4	2.9	145.70	39.2	269.05
26	F _{10,2}	5	5.5	417.76	110.6	264.74
27	C ₁	5	6.5	493.72	121.7	264.50
28	B ₁	5	6	455.74	100.7	220.96
29	F _{10,3}	5	8.6	653.23	162.5	248.76
30	B ₃	5	6.9	524.10	132.3	252.43
31	E ₄	5	8.7	660.82	148.2	224.26
32	E ₃	5	7.5	569.67	143.7	252.25
33	E ₁	5	9	683.61	152.6	223.23

34	A ₂	5	6.5	493.72	136.0	275.46
35	E ₅	5	4.2	319.02	85.5	268.01
36	D ₁	5	6.6	501.34	120.50	240.35
37	E ₂	5	4.5	341.82	83.97	245.65
38	F _{10.1}	5	5.4	410.18	106.97	260.78
39	D ₄	5	6.4	486.14	113.73	233.95
40	F _{8,5}	4	4.5	226.08	56.62	250.45

2. Porosity index (weight, %) and shatter resistance

Porosity index (weight, %): The porosity index of briquettes was determined using equation:

$$PI (\%) = (W_w - W_s) / W_s * 100$$

Where: PI= porosity index, W_s =dry weight of the sample briquette (g) and W_w =wet weight of the briquette after immersed in water for 30 seconds (g)

Shatter resistance (%): The shatter resistance was determined by subtracting the percentage weight loss from 100 as presented by equation:

$$W_L (\%) = (W_1 - W_2) / W_1 * 100 \quad \text{and} \quad S_R (\%) = 100 - W_L$$

Where W_L (%) = weight loss percentage, W₁ =weight of briquette before shattering (g), W₂= weight of briquette after shattering (g) and S_R (%) = percentage shatter resistance.

Exp. No	Symbol	W _s (g)	W _w (g)	PI (%)	W ₁	W ₂	W _L	SR (%)
1	B ₃	131.7	246.54	87.2	132.3	131.7	0.44	99.56
2	E ₄	147.9	609.7	312.24	148.2	147.9	0.2	99.80
3	E ₃	143.2	525.5	266.97	143.7	143.2	0.35	99.65
4	D ₃	148.9	362.1	143.18	149.2	148.9	0.2	99.80

5	B ₁	100.3	175.2	74.68	100.7	100.3	0.4	99.60
6	C ₁	120.5	220.8	83.24	121.7	120.5	0.99	99.01
7	A ₃	149.7	210.8	40.81	150.1	149.7	0.27	99.73
8	E ₁	152.2	379.1	149.1	152.6	152.2	0.26	99.74
9	F _{10,5}	113.8	209.6	84.18	114.3	113.8	0.44	99.56
10	F _{10,3}	162.2	258.8	59.56	162.5	162.2	0.18	99.82
11	A ₄	104.8	140.4	33.97	105	104.8	0.19	99.81
12	F _{10,2}	110.2	195.7	77.56	110.6	110.2	0.36	99.64
13	C ₅	145.3	278.4	91.60	145.3	145.2	0.07	99.93
14	A ₅	162.7	260.1	59.86	162.7	162.5	0.12	99.88
15	B ₅	151.4	298.3	97.03	151.8	151.4	0.26	99.74
16	F _{6,3}	28.2	40.1	42.20	28.5	28.2	1.05	98.95
17	F _{8,4}	51.3	79.5	54.97	51.5	51.3	0.29	99.61
18	F _{6,4}	18.7	27.5	47.05	18.8	18.7	0.53	99.47
19	A ₁	171	257.6	50.64	171.7	171	0.41	99.59
20	F _{8,1}	38.2	53.5	40.05	38.2	38.1	0.26	99.74
21	F _{10,4}	100.1	151.7	51.55	100.4	100.1	0.3	99.70
22	F _{8,3}	51.9	74.3	43.16	52.2	51.9	0.58	99.42
23	F _{6,5}	43.2	65.7	52.08	43.3	43.2	0.23	99.77
24	B ₄	203.6	357.4	75.54	203.9	203.6	0.15	99.85
25	C ₄	192.2	373.3	94.22	192.3	192.2	0.05	99.95
26	D ₂	170.7	336.3	97.01	171.2	170.7	0.29	99.71
27	B ₂	182.9	290	58.56	183	182.9	0.06	99.94
28	C ₂	133.9	258.5	93.05	135	133.9	0.82	99.18
29	C ₃	155.7	283.9	81.75	156.2	155.7	0.22	99.68
30	D ₄	177.4	394.5	122.38	177.7	177.4	0.17	99.83

31	F _{6,2}	29.9	42.7	42.81	30.1	29.9	0.66	99.34
32	F _{6,1}	35.4	49.6	40.11	35.8	35.4	1.12	98.88
33	F _{8,2}	41.9	59.7	42.48	42	41.9	0.24	99.76
34	A ₂	80.3	125.6	56.41	136.9	136	0.67	99.34
35	F _{8,5}	27.9	47.1	68.82	27.9	27.8	0.36	99.64
36	E ₅	85.5	300.8	251.81	85.9	85.5	0.47	99.53
37	F _{10,1}	80.3	125.6	56.41	80.4	80.3	0.12	99.88
38	D ₁	96.7	189.19	95.65	170.9	170.47	0.25	99.75
39	E ₂	88.9	236.16	165.65	90.1	89.68	0.46	99.54
40	D ₄	76.7	170.72	122.58	167.2	166.98	0.13	99.87

B: Combustion properties of sawdust briquettes

1. Determination of percentage volatile matter, percentage ash content and percentage fixed carbon of briquettes

- Percentage volatile matter of briquettes was determined using equation:

$$VM (\%) = (W_2 - W_3) / W_2 * 100$$

Where, VM (%) = percentage volatile matter, W₂ = oven dried sample weight, g and W₃ = weight of sample after heating (nonvolatile part of the sample), g

- The ash content of briquettes was determined using the relation presented in equation:

$$AC (\%) = (W_a) / W_s * 100$$

Where, W₁ = Initial weight of oven dried sample (g), W₂ = weight of oven dried after complete combustion in furnace i.e. weight of ash (g) and AC (%) = percentage ash content (%).

- The PFC was calculated by subtracting the sum of percentage volatile matter and percentage ash content from 100 as shown in equation:

FC (%) =100-(PAC +PVM), Where FC (%) = fixed carbon percentage, PAC=Percentage ash content and PVM= percentage volatile matter.

Exp. No	Name	Volatile matter						Ash content			
		W _C (g)	W _{C+W₂} (g)	W _{C+W₃} (g)	W ₂ (g)	W ₃ (g)	VM (%)	W _s (g)	W _a (g)	AC (%)	FC (%)
1	F _{10,3}	26.72	30.32	27.32	3.24	0.6	81.48	6.27	0.23	3.64	14.88
2	A ₄	19.34	26.54	20.54	6.48	1.2	81.48	7.56	0.28	3.65	14.87
3	B ₂	27.27	30.57	27.72	2.97	0.45	84.85	6.69	0.27	4.03	11.12
4	E ₅	27.97	35.27	29.87	6.57	1.9	71.08	6.95	0.42	6.04	22.93
5	B ₅	19.34	26.64	20.84	5.04	1.5	70.24	9.38	0.52	5.50	24.26
6	C ₅	27.97	33.57	29.17	5.04	1.2	76.19	8.38	0.49	5.87	17.94
7	B ₃	19.34	27.24	21.44	7.11	2.1	70.46	6.27	0.16	2.49	27.05
8	B ₁	27.32	34.92	28.82	6.84	1.5	78.07	7.79	0.47	6.08	15.85
9	B ₄	19.34	25.94	20.39	5.94	1.05	82.32	9.2	0.51	5.54	9.24
10	D ₃	26.72	32.32	27.77	5.04	1.05	79.17	4.57	0.18	3.94	16.89
11	C ₁	19.34	22.52	19.64	3.18	0.3	90.56	7	0.19	2.74	6.7
12	D ₂	27.27	32.53	27.72	3.42	0.45	86.84	7.46	0.18	2.41	10.75
13	D ₄	27.97	33.56	27.37	5.59	0.6	89.27	5.87	0.23	3.88	14.93
14	A ₂	19.34	22.26	19.79	2.92	0.45	84.59	7.1	0.24	3.38	12.03
15	C ₃	27.97	32.97	28.87	5	0.9	82	4.72	0.27	5.72	12.28
16	E ₁	19.34	21.5	19.79	2.16	0.45	79.17	5.1	0.12	2.35	18.48
17	A ₅	27.32	32.52	28.37	5.2	1.05	79.81	8	0.42	5.25	14.94
18	E ₃	19.34	20.96	19.84	1.62	0.3	81.48	2.5	0.12	4.8	13.72
19	A ₃	27.27	31.17	28.02	3.9	0.75	80.77	6	0.3	5.00	14.23
20	F _{10,2}	28.31	30.65	28.76	2.34	0.45	80.78	3.6	0.18	5.0	14.22

21	F _{10,5}	27.97	32.26	29.17	4.29	1.2	72.03	6.6	0.48	7.27	20.7
22	F _{8,3}	27.27	32.07	28.05	4.8	0.78	83.75	7.38	0.31	4.23	12.02
23	F _{8,4}	28.31	32.83	29.19	4.52	0.88	80.42	6.96	0.35	5.09	14.49
24	F _{6,3}	27.97	30.53	28.39	2.56	0.42	83.59	3.94	0.17	4.26	12.15
25	F _{6,2}	19.34	21.54	19.73	2.2	0.39	82.27	3.39	0.16	4.60	13.13
26	F _{6,1}	19.34	21.52	19.64	2.18	0.3	86.24	3.97	0.12	3.02	10.74
27	F _{8,1}	19.34	21.12	19.64	1.78	0.3	83.15	3.24	0.12	3.70	13.15
28	F _{8,5}	19.34	21.72	19.82	2.38	0.48	79.83	4.32	0.19	4.44	15.73
29	A ₁	27.27	32.11	28.19	4.84	0.92	81.1	7.44	0.37	4.92	13.98
30	C ₂	28.31	31.71	28.67	3.40	0.36	89.41	6.18	0.14	2.33	8.26
31	E ₄	27.27	31.78	28.53	4.51	1.26	72.06	6.94	0.50	7.26	20.68
32	F _{10,4}	26.72	30.49	27.30	3.77	0.58	84.48	5.8	0.23	4.03	11.49
33	F _{10,1}	27.97	31.58	28.6	3.61	0.63	82.55	5.56	0.16	2.81	7.99
34	C ₄	26.72	30.98	27.41	4.26	0.69	83.80	6.56	0.28	4.21	11.99
35	F _{8,2}	27.97	30.31	28.31	2.34	0.34	81.62	4.26	0.14	3.24	11.49
36	F _{6,4}	19.34	22.16	19.88	2.82	0.54	80.85	5.13	0.22	4.21	14.94
37	F _{6,5}	19.34	22.39	20.00	3.05	0.66	78.36	5.54	0.26	4.76	16.88
38	D ₁	26.72	31.13	27.8	4.41	1.08	75.54	5.2	0.13	2.54	972
39	E ₂	27.97	30.92	28.58	2.95	0.61	79.35	3.25	0.08	2.56	16.65
40	D ₅	19.34	22.98	20.06	3.64	0.72	80.27	4.6	0.27	5.98	15.12

W_c is weight of empty crucible, W_1 = Initial weight of oven dried sample (g), W_2 =weight of oven dried sample, W_3 =weight of non volatile part of sample and W_a = weight of ash

Annexes

Annex 1: Certification letter



BiT

Bahir Dar Institute of Technology - Bahir Dar University

የባህር ልር ቴክኖሎጂ ሊንደር-ባህር ልር ዩኒቨርሲቲ

Office of the Scientific Director

የላይንቴራሽን ሳይሬክተር ጽ/ቤት

ቁጥር /Ref. No: 2658/22/mo

ቀን/ Date: 22 OCT 2015

To Dr-Ing Belay Woldeyes

Subject: - To write letter of certification

It is to certify that Muluken Mengist Moges has conducted his Msc. Thesis, entitled as Briquetting of Sawdust using waste paper and Avocado Kernel as a binder, experimental work here in Bahir Dar Institute of Technology, Faculty of Chemical and Food engineering, Chemical research grade laboratory from March 2015 to August 2015.

With best regards



Nigus
Nigus Gebbiya Habtu (Dr)
Scientific Director

Cc//

- Scientific Director Office
Bahir Dar Institute of Technology

In Reply, Please Quote Our Reference Number

> Contact Us: Tel: +251-582-221953

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PoB.26 Web: www.bit.bdu.edu.et

Bahir Dar, Ethiopia

Annex 2: Calorific values of briquettes



የኢትዮጵያ ፌዴራላዊ ዲሞክራሲያዊ ሪፐብሊክ
 የውሃ ግብይት ልማትና ኢንጅነሪንግ ሚኒስቴር
 The Federal Democratic Republic of Ethiopia
 Ministry of Water, Irrigation & Electricity

ቁጥር: *መ/የው/የኃ/የብ/የብ/26/01/360*

ቀን: *፲፮ ሚያዝያ ፲፱፻፲፱*

ሰነድ ለመግቢያ ስምምነት ሰነድ ስምምነት ስምምነት

አዲስ አበባ

ጉዳይ:- የላቦራቶሪ የመከራ ጠጠት ስለማሳወቅ

ተማሪ ሙሉተን መንግስት የተባሉት የሁለተኛ ደገሪ የመመሪያ ጸሐፊዎች በቀን 19/2/2008 በተደረገው ደብዳቤ የላቦራቶሪ ስርዓት የላንሮጂ ማለፍ በትብብር እንዲሰራላቸው መጠየቃችሁ ይታወቃል።

በመሆኑም ላቦራቶሪያችን በካሚኒየር ምርመራ የተገኘውን የመከራ ጠጠት ከዚህ ደብዳቤ ጋር አያይዘን የላክን መሆኑን እንገልጻለን።

Binder Percentage	Average gross calorific value , MJ/kg								
	A	B	C	D	E	F ₆	F ₈	F ₁₀	A _v
25%	16.7657	16.9873	18.1198	16.2906	17.0890	16.3980	18.5833	16.7409	17.1340
30%	16.3540	17.1469	17.5594	16.9423	16.8944	16.4070	16.9278	16.2187	17.5543
35%	16.2176	16.0072	17.2039	16.0306	16.5288	16.0902	16.4572	16.0768	17.4310
40%	16.0050	18.1331	15.9841	16.2648	15.6473	16.1203	16.0432	15.5051	17.7137
45 %	14.8980	15.8999	15.3990	15.5014	14.5021	15.7084	15.1310	15.1168	17.3876

ገልጻዊ

- ለአማራጭ ላንሮጂ ልማትና ሽግግር ማራገጥ
- ለወርክሽጥና ላቦራቶሪ ክፍል

ሰነድ ለመግቢያ ስምምነት ሰነድ ስምምነት ስምምነት



ሰነድ ለመግቢያ ስምምነት ሰነድ ስምምነት ስምምነት
[Signature]
 አዲስ አበባ
 የውሃ ግብይት ልማትና ኢንጅነሪንግ ሚኒስቴር
 ላቦራቶሪ ክፍል