DEVELOPMENT AND PERFORMANCE EVALUATION OF HYDRAULIC PISTON PRESS BIOMASS HOLLOW BRIQUETTE MAKING MACHINE

By

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NIGERIA.

JANUARY, 2017.

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Joshua Oluyinka AJIKASHILE, B.Eng. (UNIMAID) 2010
(M.Sc./ENG/30379/2012-2013)

A DISSERTATION SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES, AHMADU BELLO UNIVERSITY, ZARIA.

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF A MASTER DEGREE IN AGRICULTURAL ENGINEERING.

DEPARTMENT OF AGRICULTURAL ENGINEERING,
FACULTY OF ENGINEERING.
AHMADU BELLO UNIVERSITY, ZARIA.

JANUARY, 2017.

DECLARATION

I declare that the work in this dissertation entitled “Development and Performance Evaluation of Hydraulic Piston Press Biomass Hollow Briquette Making Machine” has been carried out by me in the Department of Agricultural Engineering, Ahmadu Bello University, Zaria. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this project dissertation was previously presented for another degree or diploma at this or any other institution.

____________________________ ____________________

Joshua Oluyinka AJIKASHILE Date

CERTIFICATION

This dissertation entitled "DEVELOPMENT AND PERFORMANCE EVALUATION OF HYDRAULIC PISTON PRESS BIOMASS HOLLOW BRIQUETTE MAKING MACHINE" by Joshua Oluyinka AJIKASHILE meets the regulations governing the award of the degree of Master of Engineering of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

______________________________ ______________________________

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Prof. M.L. Suleiman Date
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DEDICATION

I dedicate this project work to God Almighty for His grace upon my life through the course of this project work. Father, I am thankful.

ACKNOWLEDGEMENT

My deepest and foremost thanks and appreciation goes to the Almighty God, the creator of heaven and earth, the giver of life and every good thing for His love, mercy, care, and grace He gave to me successfully complete the Master Programme. May His name be praise forever.

I would like to convey my deep appreciation to my supervisors: Dr. M. Isiaka for his inestimable effort towards the success of this work, especially taken time-out of his tight schedule to thoroughly read through my dissertation and his support throughout the cause of this work. And Dr. M. A. Gwarzo for his guidance, encouragement and inspiration throughout my study.

I have no words to express my heart felt sense of gratitude to Prof. U. S. Mohammed for his help despite his much-preoccupied time, for the design of the biomass briquetting machine. His deep sense of involvement has made this task possible. And to Mal. Yakubu of Samaru College of Agriculture for his inestimable sense of commitment towards the successful fabrication of the machine.

I express my indebtness to my lovely wife and dearest son for their utmost understanding, prayer, love and care during the course of project work. And to my parents and siblings for showing much concern to completing the programme on time. I love you all.

My profound gratitude goes to Prof. & Mrs. Aderemi, Dr. Lawrence, Engr. Aiyejagbara, Engr. Osaze, Engr. Mohammed Abubakar, Mr. & Mrs. Jesulowo and my H.O.P – Engr. U. D. Idris for their advice, love, care and support. God bless you all.

I acknowledge every little effort of my colleagues, friends and students - Engr. Afolabi, my class rep., I. Dalha, Mr. Ajibodu, Engr. Suleiman, Felix, Engr. Ddam, Mr. Alhassan P., IBB, Muhammed Ibrahim, Idris G., Mr. Hamid (M.O), Mal. Aliu, Aminu and A. Sani to mention but few. Thank you all.

ABSTRACT

In this study, a simple four-mould hydraulic piston press biomass hollow briquette making machine, suitable for household and small-scale production of circular briquettes with a centre hole was developed. The briquetting machine was operated using a 4-tons hydraulic jack. Other members of the machine include: the mould, pistons, lower and upper compression plates, jack head and jack seat plates, and the machine stand. The performance evaluation of the machine was carried out using sorghum and millet stalk at moisture content of 8% and 6 % respectively. The biomass material was milled using hammer mill with sieve sizes 7mm (P_1), 5mm (P_2), and 3mm (P_3). Briquettes were produced from mixture of biomass at these three particle sizes P_1, P_2 and P_3 and cassava starch binder at three binder ratios of 20% (B_1), 30% (B_2) and 40% (B_3) by weight of biomass material. Four physical properties namely – compressed density, relaxed density, relaxation ratio, and shattered index of the briquettes; and five thermal properties namely – heat calorific value, ash content, volatile matter, fixed carbon content and thermal efficiency of briquetting materials were determined. The machine evaluation was based on Complete Randomized Design (CRD). The data obtained was statistically analyzed using Statistical Analysis System (SAS 9.1) software. Biomass particle size was found to be significant at 1% probability level on physical properties for sorghum-stalk briquette except on relaxation ratio, which was significant only at 5% probability level. The physical properties of sorghum-stalk briquettes improved with decrease in particle size. Mean values of 727.67kg/m^3, 222.35kg/m^3, 89.57% and 3.28 were recorded for compressed density, relaxed density, shattered index and relaxation ratio, respectively at sorghum-stalk particle size P_1(3mm). Binder ratio B_2 was found to have the best effect on the compressed density and relaxed density of sorghum-stalk briquettes while relaxation ratio and shattered index of sorghum-stalk briquettes improved with increase in binder ratio to B_3. Particle sizes and binder ratio were found to be significant at 1% probability level on the thermal properties of sorghum-stalk briquettes, with optimum mean values of 17.726 MJ/kg, 1.6%, 24.60 % and 24.66% for calorific value, ash content, volatile matter and thermal efficiency respectively at P_3. The thermal properties of sorghum-stalk briquette and Millet-stalk briquette were found to improve with decrease in binder ratio. However, starch binder was found to have no significant difference on the physical properties of millet-stalk briquettes. The physical properties of millet-stalk briquettes increased with decrease in particle size. Mean values of 814.41kg/m^3, 225.34kg/m^3 and 99.49% was obtained for compressed density, relaxed density and shattered index, respectively for millet-stalk briquette at particle size P_1(3mm). While particle size has no significant difference on the relaxation ratio of millet-stalk briquettes. On the other hand, particle size P_2 gave optimum mean thermal property values of 16.692 MJ/kg, 2.9%, 26.20 % and 28.15% for calorific value, ash content, volatile matter and thermal fuel efficiency respectively. Generally, the constructed briquetting machine is capable of producing quality briquettes from sorghum and millet stalk biomass at particle sizes 3mm (P_3) and 5mm (P_2) respectively. The developed prototype briquetting machine has a production capacity range of 4.64 kg/hr – 5.26 kg/hr depending on the material used in producing the briquette.

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LIST OF ABBREVIATIONS

ASAE	American Society of Agricultural Engineers
DAC	Division of Agricultural Colleges
ABU	Ahmadu Bello University
IAR	Institute of Agricultural Research
NAPRI	National Animal Production Research Institute
PVC	Polymerizing Vinyl Chloride
ANOVA	Analysis of Variance
LSD	Least Significant Difference
FC	Fixed Carbon
TFE	Thermal Fuel Efficiency
BDC	Bottom Dead Center
CRD	Completely Randomized Design
SAS	Statistical Analysis Software
FAO	Food and Agricultural Organization

CHAPTER ONE

1.0 INTRODUCTION

1.1 General Background

Globally, the trend of growth in energy consumption is on the rise and it is expected to keep rising primarily because of the expected growth in the world population and economic growth of the developing countries. It has been reported that 85% of the world's energy demand is met by combustion of fossil fuels which are depletable and the global energy demand is expected to grow by about 50% by 2025 with the major part of this increase coming from rapidly emerging countries (Edirin and Nosa, 2012). The current pattern of energy consumption has been characterized by heavy dependence on mineral and wood fuels, which cannot be sustained in the future due to their environmental impact (global warming) and depletion (Edirin and Nosa, 2012).

In Nigeria, the escalating cost of petroleum products and irregular electricity supply, makes fuel wood to become a major source of fuel for families and small to medium enterprises. Between 1989-2000, wood and charcoal constituted 32 and 40 % of the total primary fuel energy consumption with 39 million tonnes estimate in national demand in 2000 (Sambo, 2009). However, the use of wood as a fuel source comes with certain disadvantages: deforestation, climate change, soil erosion, desertification, and health problems as a result of exposure to carbon emission during indoor domestic cooking. There is the need to provide an alternative source of energy that will replace firewood. This alternative source should be economical and affordable to rural dwellers. Hence, biomass conversions have been one of the focal areas of research and development as a substitute to depleting fuels. One of the major ways to convert biomass into an efficient energy source is biomass densification otherwise known as briquetting.

Developing countries are known to produce large quantities of agricultural waste and residues. For example, Nigeria's total biomass potential consisting of animal and agricultural waste and wood residues was estimated to be $1.2x10^{15}$J in 1990 (Obioh and Fagbenle, 2009). In 2005, research revealed that bio-energy reserves/potential of Nigeria stood at 13,071,464 hectares, 61 million tonnes per year, 83 million tonnes for fuel wood, animal waste and crop residues respectively (Agba *et al.*, 2010). But these agricultural and forestry residues produced annually are vastly under-utilized. The common practice is to burn these residues or leave them to decompose causing extensive degradation to the environment (Jekayinfa and Omisakin, 2005). These residual materials, however, can be briquetted in order to optimize their use.

Briquetting is a mechanical compaction process for increasing the density of bulky biomass material. Briquettes are good substitute to firewood and charcoal for domestic cooking and agro-industrial operations. Besides, briquettes have advantages over wood fuel in terms of greater heat intensity, cleanliness, convenience in use, and relatively smaller space requirement for storage (Singh and Singh, 1982; Wamukonya and Jenkins 1995; Yaman *et al.*, 2000; Olorunnisola, 2004). Hence, using compressed biomass materials can reduce the use of wood fuel, reduce greenhouse gas emissions and pollution and waste management problems (Grover and Mishra, 1996; Demirbas and Sahin, 1997).

Research works on briquetting processes have been majored on three areas, which are:

i. Investigation of residues that could be subjected to briquetting process
ii. Evaluation of factors that could affect briquetting process as well as quality of produced briquettes, and
iii. Development of machines.

In comparison with the developed countries like United States, Japan and European countries, briquetting technology is yet to have a strong foothold in many developing countries because of the technical constraints involved and inability to adapt diverse briquetting technologies to suit local conditions (Grover and Mishra, 1996).

1.2 Statement of Problems

A major disadvantage of agricultural residues as a fuel is their low bulk density, which makes handling difficult, transport and storage expensive, and gives rise to poor combustion properties. However, these problems can be overcome by compacting into high density fuel by briquetting. Therefore, wastes can be recycled into a renewable energy source by converting the loose biomass into high density fuel which can be offered in acceptable form and at a reasonable price (Kaur *et al.*, 2012).

In Nigeria, briquetting is yet to get the attention of the populace. Fuel wood is used by over 70% of Nigerians living in the rural areas with an average daily consumption ranging from 0.5-1.0kg of dry wood fuel per person for cooking and domestic purposes (Ohunakin, 2010). Nigeria consumes over 50 million tonnes of fuel wood annually, a rate which exceeds the replenishment rate through various afforestation programs (Oyedepo, 2012). Sourcing wood fuel for domestic and commercial uses is a major problem to our environment which has led to desertification in the arid-zone states and deforestation in the southern part of the country. Desertification and deforestation further exposes the soil to erosion, land degradation, creating wood fuel crisis, imbalance in the ecosystem and unemployment for wood workers (Nordiana, 2009). Thus, the prospects of substituting briquettes for wood fuels are still very high.

Briquetting agricultural waste and residues requires briquetting machine. Research on briquetting techniques in Nigeria is still underway as many of the indigenous briquetting machines are manual press and low pressure technologies. Adekoya (1989) developed a manual press briquetting machine that produced six briquette pieces at a time; Olorunnisola (2007) fabricated a manually operated closed-end piston press; Oumarou and Oluwole (2010) designed a pedal operated briquette piston press. In like manner, a piston press briquetting machine, capable of producing 35 pieces of briquette at a time and suitable for use in rural communities was developed by Obi *et al.,* (2013). One major problem of these machines is that they produce briquettes that are completely solid, which are characterized with poor combustion characteristics (Grover and Mishra, 1996). Although research works on production of hollow briquettes have been done also, but the hollow briquettes were produced using a cumbersome process. Of course, these have presented a good leap into briquetting technology in Nigeria, and there is also need for research to be intensify in this direction until good quality briquette is achieved through better innovation and developments.

1.3 Aim and Objectives of Study

The aim of the study is to develop a hydraulic piston press biomass hollow briquette making machine. The objectives of the study are to:

i. design a hydraulic piston press biomass hollow briquette making machine.
ii. construct the designed piston press biomass hollow briquette making machine
iii. evaluate the performance of the machine using millet stalk and sorghum stalk.

1.4 Justification of Study

Briquetting of agricultural waste and residues offers numerous benefits which include additional source of income to farmers, waste management, source of energy, employment and entrepreneurship, pollution control and preservation of forest resources.

Agriculture, as the main occupation of most Nigerians, involves a lot of activities that generate so many wastes which are disposed indiscriminately (Ugwu and Agbo, 2013). These wastes can be an additional source of income to farmers by selling the waste for briquetting purpose. Also, biomass briquetting is capable of providing employment for many Nigerians. For example, in India according to Maninder *et al.* (2012), the potential of biomass briquetting was estimated at 61,000 MW, while the estimated employment generation by the industry is about 15.52 million and the farmers earn about $ 6 per ton of farm residues.

The over exploitation of forests to collect wood fuel have led to forest's constant exhaustion, soil erosions, non-uniform and unreliable rainfall distribution (Mani et al., 2006). In Nigeria, the rate of deforestation is about 350,000 ha/year, which is equivalent to 3.6% of the present area of forests and woodlands, whereas reforestation is only at about 10% of the deforestation rate (Oyedepo, 2012). One way of limiting the deforestation and protecting the environment is by briquetting of agricultural waste. Briquettes are flammable materials formed from the compression or densification of matter into solid form to be used as fuel in stoves, charcoal iron and boilers, and burns with cleaner emission than wood.

Also, compacting wastes to briquette could provide a lasting solution to the problems of waste management and disposal on farms and within Nigeria cities. Every year, agricultural wastes are collected in large volumes from farms, homes, markets and processing industries to the landfills. This contributes to biochemical reactions which take place on landfill sites leading to formation of methane that pollute the atmosphere and ground water (Sugumaran and Seshadri, 2010). Some homes dry the waste in the back yards and later burnt inefficiently in the loose form causing air pollution. In Nigeria, the habit of people throwing away wastes into water channels during rainy season has been the major cause of floods in some areas. Most people have not realized that these agricultural wastes are potential huge source of energy giving materials derived from the animal and plant residues (Jekayinfa and Omisakin, 2005).

1.5 Scope and Limitation of the Study

This research is limited to:

i. Design and fabrication of a prototype biomass briquetting machine.

ii. Conversion of some selected agricultural waste (sorghum stalk and millet stalk) and starch binder to briquettes in an attempt to determine the performance of the designed and constructed machine.

iii. Characterization of the briquette produced for physical and thermal properties.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Background

Historically, biomass briquetting technology has been developed in two distinct directions. Europe and the United States has pursued and perfected the reciprocating ram/piston press while Japan has independently invented and developed the screw press technology (Grover and Mishra, 1996). The screw extrusion briquetting technology was invented and developed in Japan in 1945. As of April 1969, there were 638 plants in Japan engaged in manufacturing saw dust briquettes (Wamukonya and Jenkins, 1995). Although both technologies have their merits and demerits, it is universally accepted that the screw pressed briquettes are far superior to the ram pressed solid briquettes in terms of their storability and combustibility. Other briquetting technologies that have been developed over the years include roller press, pellet press, low pressure or manual press or briquetting.

2.2 Briquetting Technologies

Briquetting technologies involve processes which convert loose agricultural residues into high density solid fuels. These solid biofuels can be further used for burning purposes with greater efficiency and lesser pollution. The main types of briquetting techniques involve screw press, piston press, hydraulic press, roller press, pellet press and low pressure or manual presses (Maninder *et al.,* 2012).

2.2.1 Screw press technology

In the screw-presses, pressure is applied continuously by passing the material through a screw with diminishing volume (i.e. with tapered end as shown in Fig. 2.1). The compaction ratio of screw presses ranges from 2.5:1 to 6:1 or even more because of the ability of the press to develop high pressures (100MPa and above) (FAO, 1990). Screws press major component include; the hopper, barrel (cylindrical housing), conical screw or auger and the die. The cylindrical screws may be with or without external heating of the die and conical screws. If the die is not heated then temperatures may not rise sufficiently to cause lignin flow and a binding material may have to be added, which can be molasses, starch or some other cheap organic materials. It is also possible to briquette carbonized material in a screw-press and in this, as lignin have been destroyed; a binder has to be employed. But if the die is heated then the temperature is normally raised to 250-300 °C, which produces a good quality briquette from virtually all organic feeds provided the initial moisture is below 15%.

The screw press briquettes are also homogenous and do not disintegrate easily and produces briquettes with concentric hole which gives better combustion characteristics due to a larger specific area. Having a high combustion rate, these can substitute for coal in most applications and in boilers (Debdoubi *et al.,* 2005). Briquettes can be produced with a density of 1200kg/m^3 from loose biomass of bulk density 100 to 200kg/m^3 (Ndiema, 2001).

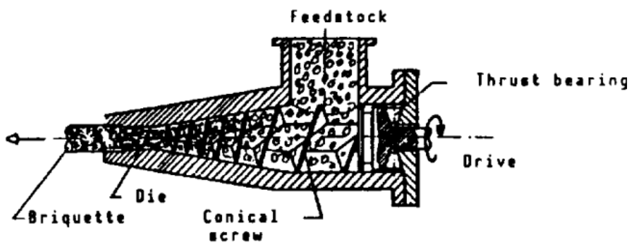


Fig. 2. 1: A sectional View of a Screw Extruder
Source: FAO, (2009)

2.2.2 Piston press technology

In the piston press, pressure is applied discontinuously by the action of a piston on material packed into a cylinder (FAO, 1990). Piston-press can be driven either by mechanical means from a flywheel via a crankshaft or use of hydraulic action to drive the piston. Mechanical press generally produces hard and dense briquettes from most materials whilst hydraulic press, which work at lower pressures, gives briquettes which are less dense and are sometimes soft and friable. Hydraulic piston press is different from the mechanical piston press in that the energy to the piston is transmitted from an electric motor via a high-pressure hydraulic oil system. Also, hydraulic piston press machine is compact and lighter but because of the slower press of the materials in the cylinder compared to that of the mechanical machine, it results in lower outputs. That is, flywheel drive machines can produce between 250-750kg of briquettes per hour while hydraulic machines typically produce up to 200kg per hour (Hamish, 2012). Piston presses are reliable, once they have been installed properly with ram and die shaped correctly for the raw materials used.

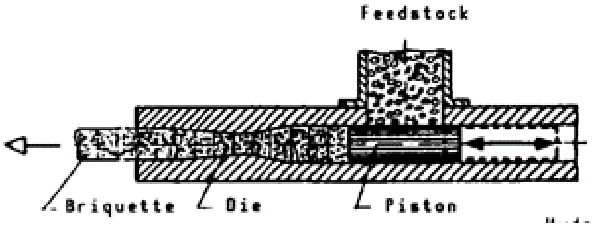


Fig. 2. 2: A Sectional View of a Piston press system
Source: FAO, (2009)

Grover and Mishra (1996) reported a comparison between a piston press and a screw extruder, as shown in Table 2.1.

Table 2. 1: Comparison between a Piston Press and a Screw Extruder

	Mechanical/Hydraulic Piston Press	Screw Extruder
Optimum moisture content of raw material	10-15 %	8-9 %
Wear of contact parts	Low in case of ram and die	High in case of screw
Output from the machine	Low in case of ram and die	High in case of screw
Power consumption	50 kW/ton	60 kW/ton
Density of briquette	1-1.2 g/cm^3	1-1.4 g/cm^3
Maintenance	High	Low
Combustion performance of briquettes	Not so good	Very good
Carbonization to charcoal	Not possible	Makes good charcoal
Suitability in gasifiers	Not suitable	Suitable
Homogeneity of briquettes	Non-homogenous	Homogenous

Source: Grover and Mishra (1996)

2.2.3 Roller press

Roller Presses are commonly used to make charcoal briquettes from carbonized biomass (Maninder *et al.,* 2012). The feedstock falls in between two rollers, rotating in opposite directions and is compacted into oval-shaped briquettes. Roller presses involve two adjacent counter-rotating rollers with indentations (Hamish, 2012). Charcoal powder is fed from above, which falls into the indentation and is compressed as the rollers turn. The briquette then exits the machine as a single pillow shaped lump. The level of compaction achieved by a roller press is relatively low compared to a piston or screw extruder and so is suited more to briquetting of wet powders mixed with binding agent. However, production rate of a roller press can be very high, reaching 1.5 tonnes per hour (Hamish, 2012).

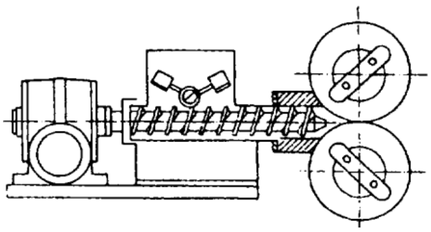


Fig. 2. 3: A Sectional View of a Roller-Presses
Source: FAO (2009)

2.2.4 Pellet press

Pelletizing is closely related to briquetting processes. The main difference is that the dies have smaller diameters (usually up to approx. 30 mm) and each machine has a number of dies arranged as holes bored in a thick steel disk or ring. The material is forced into the dies by means of rollers (normally two or three) moving over the surface on which the raw material is distributed (Fig. 2.4). The pressure is built up by the compression of this layer of material as the roller moves perpendicular to the centerline of the dies. Thus, the main force applied results in shear stresses in the material which often is favourable to the final quality of the pellets. The velocity of compression is also markedly slower when compared to piston presses, which means that air locked into the material is given ample time to escape and that the length of the die (i.e. the thickness of the disk or ring) can be made shorter while still allowing for sufficient retention time under pressure (FAO, 1990).

There are two main types of pellet presses namely: flat/disk and ring types. Other types of pelletizing machines include the Punch press and the Cog-Wheel pelletizer (Maninder *et al.,* 2012). 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.

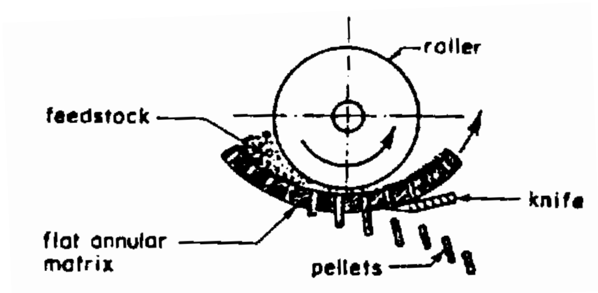


Fig. 2. 4: A Sectional View of a Pellet Presses
Source: FAO (2009)

2.2.5 Manual presses (Low-pressure briquetting)

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

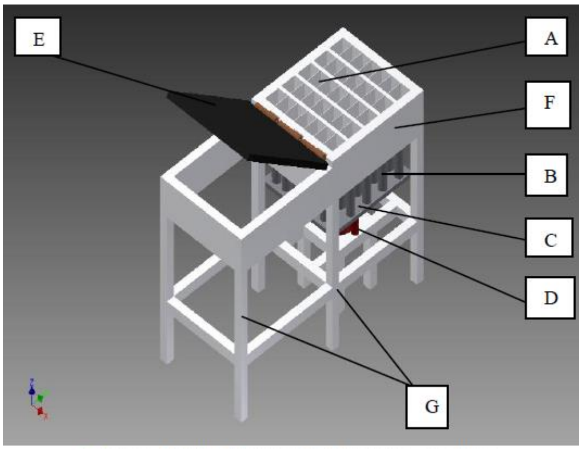
2.3 Existing Briquetting Machines

Many researchers have come up with different prototype models of briquetting machines. Olorunisola (2007) constructed a manually-operated closed-end die piston press (Plate 2.3) for the purpose of production of fuel briquettes from waste paper and coconut husk admixtures. The machine produced complete solid circular briquettes of 73mm diameter at an average pressure of 1.2 x 103 N/m^2.

Sani (2008) designed and constructed a manually operated screw press briquetting machine to produce rectangular briquettes of dimensions 260mm *x* 48mm *x* 48mm in length, width and height respectively. The 10-mould briquetting machine was reported to perform well with capacity of 240-320 briquettes per day (eight working hour).

Nordiana (2009), developed and electrically operated biomass briquetting machine. The machine consisted of a hydraulic pump, a hydraulic jack (10 tons in capacity), nine piston rams attached to a moveable lower compression plate, nine fixed moulds, an upper compression plate and two helical springs. It was tested using four (4) biomass materials namely sawdust, rice husks, wood shavings and composite biomass to produce solid circular briquettes of 55mm diameter and 90mm in length. The machine was reported to perform satisfactorily having a machine capacity of 198 briquettes per hour.

Oumarou and Oluwole (2010), designed and constructed a small pedal operated briquette press to produce three (3) briquettes of about 220 mm length at a time using agricultural and wood wastes (Plate 2.3). The machine produces completely solid rectangular shaped briquettes with average true and apparent densities of 338.2 kg/m^3 and 263.04 kg/m^3 respectively and capable of producing 120 briquettes per hour.



A – Moulds, B – Pistons, C – Flat plate, D – Hydraulic jack,
E – Mould cover, F – Mould box, G – Iron frame.

Plate 2. 1: Biomass Briquetting Machine
Source: Obi et al. (2013)

Plate 2. 2: Briquette compression machine with briquette samples
Source: Oumarou and Oluwole (2010)

Plate 2. 3: Manually operated briquetting machine
Source: Olorunisola (2007)

Also, Obi *et al.* (2013), developed an appropriate briquetting machine for use in rural communities. The machine comprised of 36 moulds (each having a dimension 100 x 70 x 150mm) and pistons, driven by a 20-ton capacity hydraulic jack (Plate 2.1). The machine was evaluated using sawdust at different biomass-binder (starch) ratio. It produces completely solid rectangular briquettes with compressed density range of 0.7 – 0.72 g/cm^3 and has a production capacity of 43 kg/hr.

2.4 Materials for the Production of Briquettes

Wide range of plant and animal wastes have been used in producing briquettes. The raw material mostly used in developed countries are sawdust and wood wastes (Grover and Mishra, 1996). Sawdust is practically the dominant raw material in Korea, Malaysia, Philippines, Thailand, and Bangladesh whereas materials such saw dust, ground nut shell, coffee husk, bagasse, cotton stalks, sun flower stalks, coffee waste have been used in India in the production of briquettes (Grover and Mishra, 1996).

Likewise, researchers in Nigeria have used different materials in briquettes production. Frank and Akhihiero (2013) worked on the production of briquettes from a mixture of water hyacinth and cow dung. Water hyacinth and cow dung were reported to have gross calorific values of 13.41 and 14.4 MJ/kg respectively and corresponding ash content of 24.6 % and 19.1 %. For production of briquette, the water hyacinths were chopped and stored for two weeks to allow the materials to partially decomposed. The decomposed material was thoroughly mixed manually with dry cow dung until a uniformly blended mixture was obtained before compacting in a manual press briquetting machine. Briquettes produced from mixture ratio of 70: 30 % of water hyacinth to cow dung were reported to give the best results of 1970kg/m^3, 1296kg/m^3 and 1.52 for compressed density, relaxed density and relaxation ratio respectively.

Davis and Mohammed (2013) established the suitability of using a mixture of water hyacinth and plantain peels as alternative source for briquette production. The water hyacinth collected was dried and milled into three particle size levels of 0.5mm, 1.6mm and 4mm. Plantain peel was used as binder at binder ratio of 10, 20, 30, 40 and 50 % by weight of each water hyacinth particles. The water hyacinth briquettes were produced using manually operated hydraulic piston press at four pressure levels of 3, 5, 7 and 9 Mpa. Report showed that, briquette quality increases with increased pressure and binder ratio. Biomass particle size of 0.5mm was reported to produce the most stable briquettes at pressure of 7Mpa and above.

Oladeji and Oyetunji (2013) Investigated the physical and fuel characteristics of briquettes produced from cassava and yam Peels. They reported an initial, maximum and relaxed densities of 251.50 kg/m^3; 741.13 kg/m^3 and 386.4 kg/m^3 respectively for briquettes produced from cassava peel, and corresponding values for briquettes produced from yam peel to be 283.40 kg/m^3; 911.45 kg/m^3 and 512.54 kg/m^3 respectively. The heating value of cassava peel briquettes reported to be 12,765 kJ/kg and yam peel to be 17,348 kJ/kg.

Other materials that has been confirmed suitable for briquettes production in Nigeria include: mixture of waste paper and coconut husk; plant parts of guinea corn residues; maize cobs; corncob; and sawdust (olorunisola, 2007; Bamgboye and Bolufawi, 2008; Bello, 2005; Olajide and Enweremadu, 2012; Ajayi and Osumune, 2013). Grover and Mishra (1996) reported that a biomass is qualified for use as feedstock for briquetting based on three important characteristics namely biomass moisture content, ash content and composition, and flowability of the materials apart from its availability in large quantities.

2.5 Factors Affecting Briquette Production

In order to produce good quality briquettes, feed preparation is very important. Factors such as particle size, moisture content and temperature of biomass feedstock, temperature of the die, addition of additives and use of binder have been reported to play a practicable role in briquetting technology (Grover and Mishra, 1996).

2.5.1 Biomass particle size and shape

Particle size and shape are of great importance for densification. Grover and Mishra (1996) stated that biomass material of 6-8 mm size with 10-20 % powdery component (< 4 mesh) gives the best results for screw press technology. Although the screw extruder which employs high pressure (1000 - 1500 bar), is capable of briquetting material of larger particles, however, the briquetting will not be smooth and clogging might take place at the entrance of the die resulting in jamming of the machine. However, piston press technology is appropriate for biomass particle size greater than 8mm.

Particle size of biomass has been reported to have significant effect on physical and thermal properties of briquettes differently. Saptoadi (2008) reported that the smaller the particle size, the more the density of the briquettes produced and burns slower. He concluded from his experiments that briquette dimensions should be as small as possible but their composing particle sizes should be as coarse as possible. Zakari *et al.* (2013) shows that finely grinded particles (about 1.75mm and 2.00mm) had low calorific values as the grinding resulted in a loss of some heat and made the sample vulnerable to air oxidation. Likewise, Tokan *et al.* (2014) stated that the calorific value for sawdust particle, corncobs and prosopis Africana charcoal increased with increase in particle size. They observed that for all the materials investigated, an increase in particle size was accompanied by higher energy output. Research has shown that fine particles <3mm although produces briquettes with higher values of physical properties but these briquettes gives lower energy output.

2.5.2 Biomass moisture content

The percentage of moisture in the biomass material is a very critical factor. In general, it has been found that when the material moisture content is 8-10 %, the briquettes will have 6-8% moisture (Grover and Mishra, 1996). 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, weak and the briquetting operation is erratic. Excess steam is also produced at higher moisture content leading to the blockage of incoming materials from the hopper, and sometimes it shoots out the briquettes from the die. Therefore, it is necessary to maintain an optimum moisture content (Grover and Mishra, 1996). Also, lower moisture content of biomass material favours milling operations when milling is required before briquetting (Kaliyan and Morey, 2009).

2.5.3 Biomass temperature

By varying the temperature of biomass, the briquette density, crushing strength and moisture stability can be varied. In a screw extruder, the temperature does not remain constant in the axial direction of the press but gradually increases. Internal and external friction causes local heating and the material develops self-bonding properties at elevated temperatures. It can also be assumed that the moisture present in the material forms steam under high pressure conditions which then hydrolysis the hemicellulose and lignin portions of biomass into lower molecular carbohydrates, lignin products, sugar polymers and other derivatives (Grover and Mishra, 1996). These products, when subjected to heat and pressure in the die, act as adhesive binders and provide a bonding effect “in situ”. The addition of heat also relaxes the inherent fibers in biomass and apparently softens its structure, thereby reducing their resistance to briquetting which in turn results in a decreased specific power consumption and a corresponding increase in production rate and reduction in wear of the contact parts. However, the temperature should not be increased beyond the decomposition temperature of biomass which is around 300 °C (Grover and Mishra, 1996).

2.5.4 Die temperature

The distinctive feature of a screw type briquetting machine is that it can be designed such that external heat is applied to the die 'bush' section of the cylinder. This brings about two important operational advantages. The machine can be operated with less power and the life of the die is prolonged. Further, the surface of the briquette is partially carbonized to a dark brown color making the briquette resistant to atmospheric moisture during storage. So, if external heating of the die is applied, the temperature of the die should be kept at about 280-290°C (Grover and Mishra, 1996). If the die temperature is more than the required one, the friction between the raw material and the die wall decreases such that compaction occurs at lower pressure which results in poor densification and inferior strength. Conversely, low temperature will result in higher pressure, power consumption and lower production rate (Grover and Mishra, 1996).

2.5.5 External additives and binders

The briquetting process does not add to the calorific value of the base biomass. In order to upgrade the specific heating value and combustibility of the briquette, certain additives like charcoal and coal, in very fine form, can be added. About 10-20% char fines can be employed in briquetting without impairing their quality (Grover and Mishra, 1996).

Binding on the other hand, is the process of 'sticking together' the compacted material by the use of a binding agent also called binder. When briquetting at low temperature, binder needs to be added to compacted material to enhance or activate the binding process unlike when briquetting at high temperature (usually achieve through heating of die), naturally occurring substance called lignin can melt and under pressure, this can act as glue (Hamish, 2012). Zakari *et al.* (2013) reported that using gum Arabic and starch as binder improves the caloric value of briquettes. Research have shown that the following common binder listed in order of performance can be used as binder for briquetting: gum-arabic, cassava starch, cassava flour, molasses, wheat flour, fine clay, red soil etc.

2.6 Briquettes' Performance Characteristics

Biomass briquette characteristics or performance characteristics have been reported and discussed by researchers in three (3) major categories which include its physical, mechanical and thermal (combustion) properties, depending on the measured parameters.

2.6.1 Physical properties

The physical properties include compressed density, relaxed density, relaxation ratio, and shattered density.

2.6.1.1 Compressed density

Compressed density (also called maximum density) is defined as the ratio of the mass of the briquette after ejection to its volume. FAO (1990) stated that the compressed density of a briquette will depend to some extent on a range of factors including the nature of the original material, the machine used and its operating condition, and other factors. The compressed density of a briquette from nearly all materials normally vary between 1,200 - 1,400 kg/m^3 for high pressure briquetting processes. Lower density can result from densification in presses using hydraulic pistons. However, a range of 600 – 700kg/m^3 was reported good for briquette production (FAO, 1990; Mani *et al.*, 2004 and Gilbert *et al.*, 2009).

2.6.1.2 Relaxed density

Relaxed density is defined as the ratio of mass of a briquette to its volume, determined 30 days after removal from the press (ASAE., 2003). According to Obi *et al.* (2013), Bamgboye and Bolufawi (2008) relaxed density of a briquette depends largely on the compressed density of the briquette. Oladeji (2012) carried out a comparative research on the quality of briquette from corncob, groundnut shell, melon shell, cassava, and yam peels. He reported the values of the compressed and relaxed densities of briquettes produced from yam peel, cassava peel, corncob, melon shell and groundnut shell to be 911.45kg/m^3 and 512.54kg/m^3, 741.13kg/m^3 and 386.2kg/m^3, 650kg/m^3 and 385kg/m^3, 561kg/m^3 and 286.42kg/m^3, 524kg/m^3 and 236kg/m^3 respectively. The result shows that briquette with the higher value of compressed density also has a higher value of relaxed density and vice versa.

2.6.1.3 Relaxation ratio

Relaxation ratio is defined as the ratio of the compressed density to the relaxed density of briquettes (Oyelaran *et al.*, 2014). It is an indication of how stable a briquette is when exposed to atmospheric conditions. Although no information on acceptable values of relaxation ratio for quality briquette has been reported but research has shown that lower value of relaxation ratio indicates a more stable briquette, while higher value indicates high tendency towards relaxation. Oladeji (2012) reported the relaxation ratio of briquette from corncob, groundnut shell, melon shell, cassava and yam peel to be 1.60, 2.20, 1.95, 1.92 and 1.78, respectively.

2.6.1.4 Shattered Index

Shattered index is a measure of briquette durability. It is a decisive factor regarding briquettes ability to withstand severe handling during transportation, storage, and adverse weather conditions of the locations where the products are transported, stored or exposed. Therefore, the measurement of durability is critical in describing briquette quality, in view of the fact that it predicts briquette performance in transportation, storage and adverse weather conditions. Adapa *et al.* (2003), Tabil and Sokhansanj (1996) classified the durability of briquettes into high (>0.8), medium (0.7-0.8) and low (< 0.7) depending on the values. Wamukonya and Jenkins (1995), Olorunisola, (2007) and Oyelaran *et al.* (2014), reported that the shattering resistance of briquette depends upon the concentration of binders, it increases with increase concentration of binders.

2.6.2 Thermal properties

The volatile matter, ash content, fixed carbon and calorific value of biomass are major parameters considered for determining the thermal characteristics of briquettes. These properties also depend on the biomass residue material employed.

2.6.2.1 Volatile Matter in biomass

High proportion of volatile matter has been attributed to high proportion of organic matter in a biomass material (Olorunnisola, 2007). Materials with relatively high volatile matter indicates easy ignition, fast burning and proportionate increase in flame length. Some biomass generally contains high volatile matter of around 70 - 80% with low char content (Akowuah *et al.*, 2012).

2.6.2.2 Ash content of biomass

Ash is the non-combustible component of biomass and it has influence on the heat transfer to the surface of briquette fuel as well as the diffusion of oxygen to the fuel surface during char combustion. High ash content results into dust emissions which lead to air pollution and affects the combustion volume and efficiency. The higher the fuel’s ash content, the lower its calorific value because ash content influences the fuel’s burning rate due to minimization of the heat transfer to fuel's interior parts and diffusion of oxygen to the briquette surface during char combustion (Katimbo *et al.*, 2014).

Furthermore, ash content of different types of biomass is an indicator of slagging behaviour of the biomass. Usually slagging takes place with biomass fuels containing more than 4% ash and non-slagging fuels with ash content less than 4% (Grover and Mishra, 1996). Table 2.2 shows the ash contents of some types of biomass materials.

Table 2. 2: Ash Content of Common Biomass Materials

Biomass	Ash content (%)	Biomass	Ash content (%)
Corn cob	1.2	Coffee husk	4.3
Jute stick	1.2	Cotton shells	4.6
Sawdust (mixed)	1.3	Tannin waste	4.8
Pine needle	1.5	Almond shell	4.8
Soya bean stalk	1.8	Areca nut shell	5.1
Bagasse	1.8	Castor stick	5.4
Coffee spent	1.9	Groundnut shell	6.0
Coconut shell	1.9	Coir pith	6.0
Sunflower stalk	3.1	Bagasse pith	8.0
Jowar straw	3.2	Bean straw	10.2
Olive pits	3.2	Barley straw	10.3
Arhar stalk	3.4	Paddy stalk	15.5
Lantana camara	3.5	Tobacco dust	19.1
Subabul leaves	3.6	Jute dust	19.1
Tea waste	3.8	Rice husk	22.4
Tamarind husk	4.2	Deoiled bran	28.4

Source: Oumarou and Oluwole (2010)

2.6.2.3 Fixed carbon

Fixed carbon of the briquette is a percentage of carbon (solid fuel) available for char combustion after volatile matter is distilled off or lost to the atmosphere. Therefore, fixed carbon gives a rough estimate of the heating value of fuel and acts as the main heat generator during burning (Akowuah *et al.,* 2012).

2.6.2.4 Calorific value

Calorific value is the amount of heat released by the combustion of a mass of fuel. Emerhi (2011), Olorunnisola, (2007) and Katimbo *et al.* (2014) observed that the calorific value of biomass-briquette is enhanced by the type of binder used. They stated that the type of binder used is one of the important factors which should be considered for briquetting in order to achieve enough heat release. Cassava starch, as reported in their works, has the ability to release as much heat as possible. Briquettes produced using starch binder were observed to exhibit better flame length, good ignition qualities and generated enough heat energy capable of being used in processing industries and households. The shape of briquettes was also observed to enhance the calorific value of briquettes. Briquette with hole(s) was reported to give better combustion properties. The presence of hole(s) help in the circulation of air for continuous burning (Katimbo,*et al.*, 2014).

2.6.3 Mechanical property

The mechanical property of briquette is measured in terms of its compressive strength, which defines the strength of the briquettes. Briquettes with low breaking strength are weak, crumble faster during burning and easily break during transportation to the potential end users. Also, such briquettes burn faster and less heat is generated in the process. High compressive stress indicates more volume displacement which is good for packaging, storage and transportation and above all, it is an indication of good quality briquettes because of the strong inter-particle bonds (Kaliyan and Morey, 2009).

2.7 Research Gap

The investigation of waste materials that can be converted to briquettes and evaluation of the quality of briquettes produced from the identified indigenous waste materials has gained much attention of researchers in Nigeria with little attention being given to design and development of briquetting machine.

Majority of the indigenous briquetting machine are designed to produce completely solid briquettes which can pose serious challenges when burn for domestic use, as a result of inability of the briquettes to allow for efficient air circulation during burning thereby, giving rise to poor combustion. Although research works have been carried out on production of hollow briquettes, but these hollow briquettes were produce using cumbersome machines. This therefore, necessitate the development of simple briquetting machine for production of homemade, hollow briquettes with good combustion property.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Materials Selection

3.1.1 Material selection for the construction of briquette making machine

The materials selection for the briquetting machine components was based on the type of force acting on the machine members, the environmental condition in which they function, cost and their availability in the local market. A36 mild steel with a minimum yield stress of 250Mpa and ultimate tensile strength of 440 Mpa was selected for the production of the briquetting machine members such as upper and lower compression plate, stands (support) and the jack seat plate. While the machine moulds and pistons were produced from galvanized steel alloy because of rust.

3.1.2 Material selection for the evaluation of briquette making machine

Sorghum and millet stalk biomass materials were selected for the production of briquette using the hollow briquette making machine. The choice of the aforementioned biomasses is owing to the fact that such materials are readily available in semi-arid and arid zones (Sokoto, Yobe, Borno, Jigawa and Kano) of the country that are faced with desertification. This is due to deforestation activities of the dwellers, mostly for domestic cooking purposes. Meanwhile, much waste is generated from sorghum and millet which can be briquetted and use for domestic cooking because sorghum and millet crop have been reported to be the major staple food grown in this part of the country (Nzeka, 2014). However, starch extracted from cassava tuber was selected as binder in production of sorghum and millet stalk briquettes. Katimbo *et al.* (2014) observed that, during combustion starch bounded briquettes exhibited better flame length and ignition qualities with desired energy values which are good to produce the required heat to be used in processing industries and households.

3.2 Equipments

The following equipments were used for production and characterization of the briquettes:

1. Hammer mill, TRF 800, made in Brasil, installed in DAC, ABU Zaria, for size reduction of agricultural materials.
2. Gallenhamp Furnace (0℃ -3000℃ temperature range), model LH120/14, made in England, installed in IAR, ABU Zaria, for determination of volatile matter and ash content of the briquettes.
3. E2K Bomb calorimeter, model A1329DD, made in china and installed in NAPRI, for determination of the calorific value of briquette
4. Gallenhamp Oven, model OV-010 (9A-122-B), made in England and installed in IAR, ABU Zaria, for drying residue materials
5. Digital weighing machine and Mettler P163 weighing machine installed in NAPRI, ABU Zaria, for measuring the mass of samples
6. Vernier caliper for measuring diameters and height of briquettes
7. Stop watch for measuring time during briquetting process
8. Crucible, a heat resistant container used to put sample in the furnace
9. Desiccator, is a device used to prevent heated sample from absorbing moisture.
10. Mesh (3mm, 5mm &7mm)

3.3 Design Considerations

The design consideration includes:

i. Cost: It is important that the machine cost is low and affordable for household production of briquette since majority of targeted users are local farmer who generates enough farm waste residues which can be briquetted.

ii. Portability: In order to make the machine portable, the components such as the mould, piston, stands and hydraulic jack are designed to be detachable from one another and easy to re-assemble.

iii. Simplicity and durability: The machine is simple in design for easy construction, usage and maintenance.

3.4 Machine Design

When a cylindrical shell is subjected to an internal pressure, its walls are subjected to tensile stresses. If these stresses exceed the permissible limit, the cylinder is likely to fail by either splitting into two troughs or breaking into two cylinders (Khurmi, 2005). Hence, the most important features of the machine design include the determination of the: briquette size, allowable tensile stress in the mould, thickness of the machine moulds and capacity of the hydraulic jack to be used.

3.4.1 Briquette size

The briquette size is important in determining the machine's mould dimensions. For the circular hollow briquette, an outer diameter, inner diameter and height of 100mm, 25mm and 50mm was chosen. This is because, the briquettes would be suitable for use in convectional charcoal stoves.

3.4.2 Determination of allowable tensile stress

The allowable tensile stress (i.e. circumferential or hoop stress) was calculated using Khurmi (2005) relationship as:

$$\sigma_c = \frac{\text{Tensile strength}}{\text{factor of safety}} \qquad 3.1$$

Using the ultimate tensile strength of mild steel to be 440Mpa and a factor of safety of 5

$$\sigma_c = \frac{440}{5} = 88\text{N/mm}^2$$

3.4.3 Determination of thickness of cylinder

Failures in cylindrical shell was reported by Khurmi (2005) to be due to two types of tensile stresses, which are circumferential and longitudinal stresses.

3.4.3.1 Circumferential or hoop stress:

As a result of the internal pressure, the mould has the tendency to split into two troughs along its circumferential axis (Fig. 3.1).

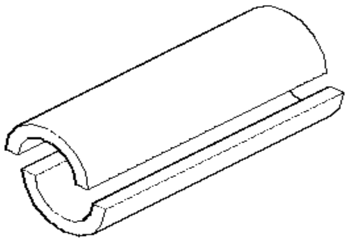


Fig. 3. 1: Schematic Diagram of Failure Due to Circumferential Stress in Cylindrical Shell

It is therefore necessary to determine the minimum thickness of the mould shell that will withstand the internal pressure during briquetting. The minimum thickness that will prevent the splitting of the cylindrical mould along its circumferential axis was calculated using Khurmi (2005) relationship as:

$$t = \frac{p \cdot d}{2\sigma_c \eta} \qquad 3.2$$

Where: t = thickness of shell (mm)

P = internal pressure in cylinder (MPa)

d = internal diameter of cylinder (mm)

σ_c = allowable tensile stress (MPa)

η = efficiency of riveted joint. (neglected)

$\therefore \quad t = \frac{5 \, x \, 102}{2 \, x \, 88} = 2.898\text{mm} \approx 3\text{mm}$ (standard size)

3.4.3.2 Longitudinal Stress:

Considering the fact that the internal pressure also has the tendency to break the cylindrical mould into two cylindrical pieces along its longitudinal axis (Fig. 3.2).

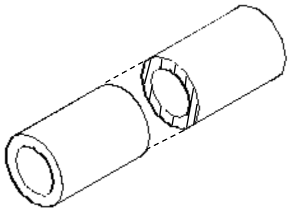


Fig. 3. 2: Schematic Diagram of Failure Due to Longitudinal Stress in Cylindrical Shell

The minimum thickness of the mould that will prevent breaking of the cylindrical mould along its longitudinal axis was determined using (Khurmi, 2005) relationship as:

$$t = \frac{p \cdot d}{4\sigma_c \eta} \quad 3.3$$

Where; t = thickness of shell (mm)

P = internal pressure in cylinder (MPa)

d = internal diameter of cylinder (mm)

σ_c = allowable tensile stress (MPa)

η = efficiency of riveted joint. (neglected)

$\therefore \quad t = \frac{5 \ x \ 102}{4 \ x \ 88} = 1.449\text{mm} \approx 1.5\text{mm}$

Since the thickness required to prevent failure of the briquetting mould along its circumferential axis is greater than that required to prevent failure along its longitudinal axis (i.e. 3mm > 1.5mm), the minimum thickness of 3mm (standard size) was considered for the design of the briquetting mould.

3.4.4 Determination of the Capacity of Compressing Device (Hydraulic Jack)

The capacity of the hydraulic jack used for the briquetting machine was designed using Nordiana (2009) procedures which include determination of the following:

i. The weight of the machine components to be lifted by the jack (i.e. lower compression plate and four pistons).

ii. The weight of briquette in the mould

iii. The force required for compacting the loose biomass in the mould into briquette.

3.4.4.1 Determination of the weight of lower compression plate

The lower compression plate is made up of mild steel of density 7850kg/m^3. Considering the size and arrangement of the pipes in the mould, if the compression plate has dimensions of 300mm x 300mm x 3mm corresponding to length, width and thickness respectively, the weight of the lower compression plate was calculated using equation 3.4 as used by Nordiana (2009):

$$W_{lcp} = l \times w \times t \times \rho \times g \qquad 3.4$$

Where: W_{lcp} = Weight of lower compression plate (N)

l = length of plate = 0.3m,

w = width of plate = 0.3m,

t = thickness of plate = 0.003m,

ρ = density of mild steel = 7850kg/m^3 and

g = acceleration due to gravity = 9.81m/s^2.

$\therefore W_{lcp}$ = **20.79N**

3.4.2.2 Determination of weight of four pistons

The piston is a hollow cylindrical body with a circular head (top). The piston is made up of two (small and big) cylinders and a connecting hollow pipe as illustrated in Fig. 3.3 below:

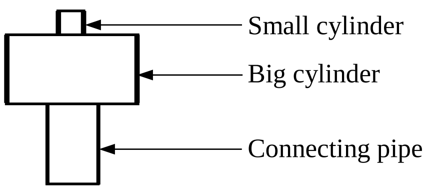


Fig. 3. 3: Cross-sectional view of the piston ram

If the small cylinder has an internal and outer diameter of 15.5mm and 20.5mm, respectively. The weight of this cylinder was calculated using equation 3.5 as used by Nordiana (2009):

$$W_{sc} = \frac{\pi}{4}(d_o^2 - d_i^2)\ x\ h\ x\ \rho\ x\ g \qquad 3.5$$

Where: W_{sc} = weight of small cylinder (N)

d_o = outer diameter of small cylinder = 0.0205m,

d_i = inner diameter of small cylinder = 0.0155m,

h = height of small cylinder = 0.02m,

π = pi = 3.142

ρ = density of mild steel = 7850kg/m^3 and

g = acceleration due to gravity = 9.81m/s^2

$\therefore W_{sc} = 0.22N$

Considering the size of the briquette to be produced and the designed thickness of the machine members, if the big cylinder has an internal and outer diameter of 94mm and 100mm, respectively, the weight of the cylinder was calculated using equation 3.6 as used by Nordiana (2009):

$$W_{bc} = \frac{\pi}{4}\left[(d_o^2 - d_i^2)\ x\ h + 2d_h^2\ x\ t\right]\rho\ x\ g \qquad 3.6$$

Where: W_{bc} = weight of big cylinder (N)

d_o = outer diameter of big cylinder = 0.1m,

d_i = inner diameter of big cylinder = 0.094m,

h = height of piston head = 0.05m,

d_h = diameter of the circular head = 0.1m,

t = thickness of circular head = 0.003m,

π = pi = 3.142

ρ = density of mild steel = 7850kg/m^3 and

g = acceleration due to gravity = 9.81m/s^2

$\therefore W_{bc}$ = 39.81N

The connecting cylinder has an internal and outer diameter of 54mm and 60mm, respectively in order to ensure balancing. The weight of the connecting cylinder was calculated using equation 3.5:

$$W_{cs} = \frac{\pi}{4}(d_o^2 - d_i^2)\ x\ h\ x\ \rho\ x\ g$$

Where: W_{cs} = weight of connecting cylinder (N)

d_o = outer diameter of connecting cylinder = 0.060m,

d_i = inner diameter of big cylinder = 0.054m,

h = 0.1m,

π = pi = 3.142

ρ = density of mild steel = 7850kg/m^3 and

g = acceleration due to gravity = 9.81m/s^2

$\therefore W_{cs}$ = 4.14N

The weight of a piston, $W_p = W_{sc} + W_{bc} + W_{cs}$ = 0.22N + 39.81N + 4.14N= 44.17N

The total weight of four (4) piston rams = 41.17N x 4 = 1**76.68N**

3.4.2.3 Determination of weight of four briquettes

The briquettes are circular briquettes of approximately 100mm diameter with a single centre hole of 25mm diameter. Assuming the density of the briquette to be 1.2g/cm^3 or 1200kg/m^3 (Grover and Mishra, 1996) and height of briquette after compaction to be 50mm, the theoretical weight of briquette was calculated using equation 3.5 as used by Nordiana (2009):

$$W_b = \frac{\pi}{4}[(d_o^2 - d_i^2)\ x\ h\ x\ \rho\ x\ g]$$

Where: W_b = theoretical weight of briquette (N)

d_o = outer diameter of briquette = 0.1m,

d_i = internal diameter of briquette = 0.025m,

h = height of briquette = 0.05m,

ρ = assumed density of briquette = 1200kg/m^3 and

g = acceleration due to gravity = 9.81m/s^2

$\therefore W_b$ = 4.33N

The total weight of four briquettes = 4.33N *x* 4 = **17.32N**

Total weight to be lifted by the hydraulic jack was estimated to be = 17.32N + 176.68N + 20.79N = **214.79N**

3.4.2.4 Determination of force for compaction

If the force required for the compaction of briquette of cross-section area of 0.003m^2 is 35.7kN, the total force required for the hydraulic jack to overcome machine components and briquette weights and force of compaction was estimated to be (Nordiana, 2009):

35 700N + 214.79N = 35,914.79N ≈ 36kN.

Hence, the minimum capacity of the hydraulic jack was: $= \frac{36000}{9.81}$

= 3669.7kg ≈ 4 tons

3.4.4 Summary of Design Calculation

Table 3. 1 Design components and Formulae

S/N	Design Component	Initial Data	Calculations	Result
1.	Allowable tensile stress	Tensile strength = 440 N/mm^2 Factor of safety = 5	$\sigma_c = \frac{\text{Tensile strength}}{\text{factor of safety}}$	$\sigma_c = 88N/mm^2$
2.	Thickness of Mould to withstand circumferential or hoop stress	P = 5Mpa d = 102mm $\sigma_c = 88N/mm^2$	$t = \frac{p\,.\,d}{2\sigma_c\eta}$	t ≈ 3mm
3.	Thickness of Mould to withstand longitudinal stress	P = 5Mpa d = 102mm $\sigma_c = 88N/mm^2$	$t = \frac{p\,.\,d}{4\sigma_c\eta}$	t ≈ 1.5mm
4.	Weight of lower compression plate	l = 0.3m w = 0.3m t = 0.003m $\rho = 7850kg/m^3$ $g = 9.81m/s^2$	$W_{lcp} = l\ x\ w\ x\ t\ x\ \rho\ x\ g$	W_{lcp} = 20.79N
5.	Weight of small cylinder on piston	d_o = 0.0205m d_i = 0.0155m h = 0.02m $\rho = 7850kg/m^3$	$W_{sc} = \frac{\pi}{4}\left(d_o^2 - d_i^2\right) x\ h\ x\ \rho\ x\ g$	W_{sc} = 0.22N
6.	Weight of big cylinder of piston	d_o = 0.1m d_i = 0.094m h = 0.05m d_h = 0.1m t = 0.003m	$W_{bc} = \frac{\pi}{4}\left[\left(d_o^2 - d_i^2\right) x\ h + 2d_h^2\ x\ t\right] \rho\ x\ g$	W_{bc} = 39.81N
7.	Weight of piston's connecting cylinder	d_o = 0.06m d_i = 0.054m h = 0.1m $\rho = 7850kg/m^3$	$W_{cs} = \frac{\pi}{4}\left(d_o^2 - d_i^2\right) x\ h\ x\ \rho\ x\ g$	W_{cs} = 4.14N
8.	Total weight of a piston	W_{sc} = 0.22N W_{bc} = 39.81N W_{cs} = 4.14N	$W_{sc} + W_{bc} + W_{cs}$	W_p = 44.17N Weight of four pistons = $W_p\ x\ 4$ = 176.68N

9.	Theoretical weight of a briquette	$d_o = 0.1m$ $d_i = 0.025m$ $h = 0.05m$ $\rho = 1200kg/m^3$ (assumed)	$W_b = \frac{\pi}{4}\left[\left(d_o^2 - d_i^2\right) x\ h\ x\ \rho\ x\ g\right]$	$W_b = 4.33N$ Weight of four briquettes = $W_b\ x\ 4$ =17.32N
11.	Force of compaction		Assuming the force required for compaction of briquette of cross section area of $0.003m^2$ = 35.7kN	F = 35700N
12.	Minimum capacity of hydraulic jack		(Weight of four piston + weight of four briquettes + force of compaction) divided by 9.81	= 4tons

3.5 Fabrication procedure of briquetting machine

The machine fabrication was carried out in the Department of Agricultural and Bio-Environmental Engineering Technology Workshop, Division of Agricultural Colleges, Ahmadu Bello University, Zaria. The fabrication process of the briquetting machine can be divided into four stages (See Fig. 4.1 for the picture of the fabricated briquetting machine):

i. Fabrication of the upper compression plate
ii. Fabrication of the mould
iii. Fabrication of the pistons lower compression plate
iv. Fabrication of the machine stand (support)

3.5.1 Fabrication of the upper compression plate

The upper compression plate is a mild steel plate of dimensions 300mm *x* 300mm *x* 5mm corresponding to length, breadth and thickness, respectively (See detailed drawing in Appendix H).

Four circular holes of diameter, 28 mm each, were systematically drilled on the upper compression plate, such that the holes have common centre with the corresponding mould and piston. Also, on the plate were drilled five smaller holes of 8.5 mm diameter (arranged as shown in Fig. 3.4) in order to fasten the plate to the mould using bolt and nut, during compaction. The side of the plate with no bolt point was hinged to the mould of the briquetting machine.

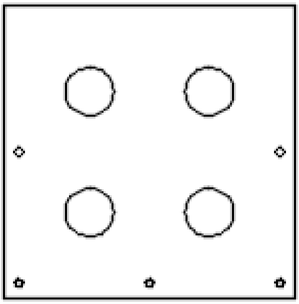


Fig. 3. 4: Schematic Diagram of Upper Compression Plate

3.5.2 Fabrication of the Mould

The mould consists of four galvanized steel cylindrical pipe. The pipes have a length, outer and inner diameters of 150mm, 116 mm and 102 mm respectively. out of the 150mm length of the pipe, the piston occupies 50mm length from the bottom of the pipe at its bottom dead centre (BDC) and the remaining 100mm length was available for occupying feedstock to be compacted. The inner diameter of 102mm was considered in order to allow the pistons to move freely in the moulds with minimum tolerance. The pipes were welded to plates at the top and bottom. The plates dimensions are 300 mm *x* 300 mm *x* 3 mm corresponding to the length, breadth and thickness respectively. but prior to the welding operation, four circular plates of 116 mm diameter were cut out of each plate using drilling and cutting tools due to inaccessibility of blanking machine. The circular plates were cut at a distance of 30 mm from the edge of the plate. The plates were welded to the cylindrical pipes as shown in Fig. 3.5 (See detailed drawing in Appendix I).

One end of the top plate was hinged to the upper compression plate. And five holes of diameter 8.5 mm each, arranged at the sides and other end of the top plate as shown in Fig.

3.5, were drilled in order to fasten the mould to the upper compression plate using bolts and nuts during briquetting process. The bottom plate also carries four holes of diameter 12.5 mm to fasten the mould to the four rod stands.

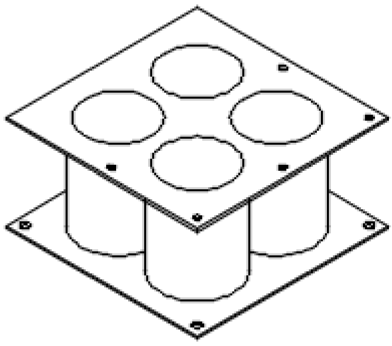


Fig. 3. 5: Schematic Diagram of Machine Mould

3.5.3 Fabrication of the piston and lower compression plate

The piston consists of small cylinder, big cylinder covered at top and bottom and connecting pipe which connects the piston head to the lower compression plate as shown in Fig 3.6. (See detailed drawing in Appendix J).

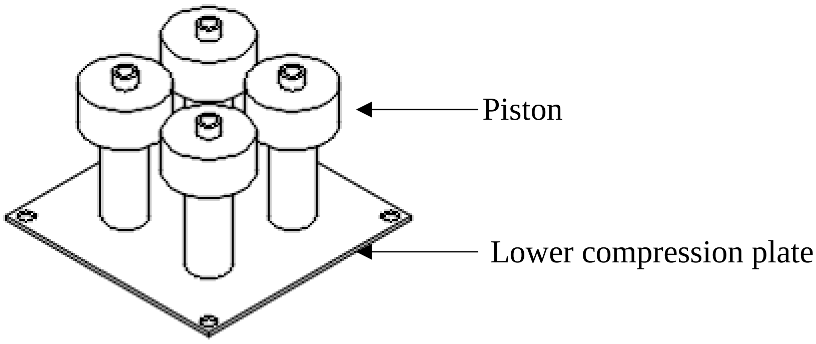


Fig. 3. 6: Schematic Diagram of Machine Pistons

The small cylinder is an open cylinder with inner diameter and outer diameter of 18 mm and 26 mm respectively and height of 2mm. The cylinder was neatly welded to piston head. Its purpose is to allow insertion of PVC cylindrical pipe in order to create the centre hole in the briquette. The bigger cylinder is made of hollow cylindrical pipe of 100 mm and 94 mm corresponding to outer and inner diameter respectively and height of 50 mm. The hollow cylinder was covered at the top and bottom to form the piston head. The piston head was welded to the connecting pipe. The connecting pipe is a hollow cylindrical pipe of dimensions 50 mm *x* 45 mm *x* 120mm corresponding to outer diameter, inner diameter and height respectively. The small, big and connecting pipes were welding such that, they have a common centre. The pistons were then welded to the lower compression plate. At the four edges of the compression plate were drilled, holes of diameter 18.5 mm. The piston and lower compression plate were mounted on rod stand (support) and travels up and down along the rod stand during briquetting.

3.5.4 Fabrication of the machine stand (support)

The machine stand (support) comprises of the jack seat plate, jack head plate, pipe and rod stands as shown in Fig. 3.7 (See detailed drawing in Appendix K). The jack seat plate and jack head plate are 5mm mild steel plate with length and breadth of 300 mm *x* 300 mm respectively. The jack head plate consists of four drilled holes of diameter 18.5 mm through which it is mounted on the pipe stand, and a centre hole of diameter approximately 30 mm through which the jack head passes through.

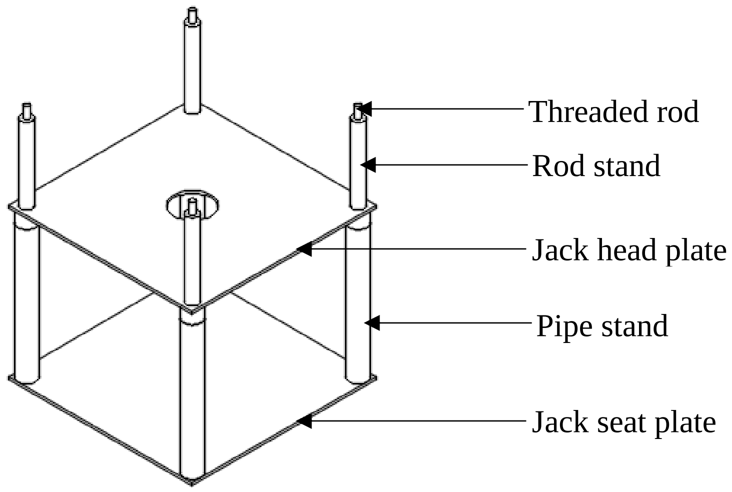


Fig. 3. 7: Stand (support) of Briquetting Machine

The steel rods and pipes stand were welded concentrically on the jack seat plate as shown in Fig. 3.6. The rod of 18 mm in diameter and length of 400 mm runs through the pipe stand, jack head plate, the lower compression plate and the mould bottom plate when the machine is assembled. The mould is fastened to the threaded part of the rod using washer and nut. The pipe stand has a total length of 220 mm. 200 mm length was welded to the jack seat plate and 20 mm length was welded to the jack head plate, which serve as a stopper for the jack head plate.

3.6 Cost of Materials

Table 3. 2: List and Cost of Material for the Construction of Machine

S/N	MATERIALS	QTY	PRICE (₦: K)
1.	4mm Plate (30 x 30cm)	3	2000.00
2.	3mm plates (30 x 30cm)	3	1500.00
3.	1½ inch round pipe	1 length	1000.00
4.	¾ inch solid rod	1 length	1500.00
5.	100mm diameter cylinder pipes for pistons	1 length	2000.00
6.	116mm diameter cylinder pipes for mould	1 length	3000.00
7.	Hydraulic jack (5 tons capacity)	1	2000.00
8.	Spring	2	200.00
9.	Machining		8000.00
10.	Packet of electrode	1	1200.00
11.	Cutting disc	1	250.00
12.	Grinding disc	1	650.00
13.	Labour		8000.00
	TOTAL		**₦31,300.00**

3.7 Evaluation Procedures

The performance evaluation of the constructed briquetting machine was carried out as follows:

3.7.1 Biomass collection and preparation

Millet and sorghum stalks were from Samaru College of Agriculture farm lands and cleaned. The cleaned materials were crushed into three different particle sizes using hammer mill with screen size openings of 7, 5 and 3mm.

3.7.2 Starch binder preparation

Starch paste was prepared from cassava starch obtained from Samaru market, Zaria. To prepare the starch paste used as binder, 1litre of water was measured and out of which about $10cm^3$ was used to dissolve the semi-solid cassava starch. The remaining $90cm^3$ was poured into an electric kettle and allowed to boil. The hot water was poured into the already dissolved starch solution and stirred to form the cassava starch paste. This procedure was used to prepare 10%, 20% and 30% starch by weight of biomass, each at a time. Three replicates were prepared for each procedure.

3.7.3 Determination of moisture content of the prepared samples

The moisture content of milled biomass samples was determined using the oven-drying method in compliance with the procedure described in ASAE (2003). The method involved oven-drying the samples at temperature of 103℃ for 24hours. The weight of the samples was measured and recorded before and after oven-drying. The moisture content (wet basis) was calculated as ratio of the weight of moisture to the initial weight of sample, expressed in percentage as given in equation 3.6.

$$MC_{(wb)} = \frac{W_i - W_f}{W_i} \text{ x } 100 \qquad 3.7$$

Where: mc_{wb}= moisture content (dry basis) (%)

w_i = Initial weight of the sample (g)

w_f = Final weight of the sample (g)

3.8 Machine Evaluation

The evaluation of the developed biomass briquetting machine was carried out by producing briquettes with the machine. Some physical and thermal properties of the briquettes produced using the fabricated machine were determined to ascertain the quality of briquettes.

3.8.1 Determination of physical properties

The following physical properties were determined:

3.8.1.1 Compressed density

The compressed density of the briquettes was determined immediately after ejection using equation 3.8 (Olorunnisola, 2007 and Obi *et al.*, 2013). The volume of briquette was determined using the fundamental formula of cylinder while subtracting off the volume of the hole within the briquette (Katimbo *et al.,* 2014).

$$\rho_{mc} = \frac{m_e}{V_e} \qquad 3.8$$

Where: ρ_c = compressed density (kg/m^3)

m_e = mass of sample after ejection (kg)

$V_e = \frac{\pi}{4} H(D^2 - d^2)$ = volume of briquette after ejection (m^3)

H = height of briquette after ejection (m)

D = outer diameter of briquette after ejection (m)

d = inner diameter of briquette after ejection (m)

3.8.1.2 Relaxed density

The relaxed density (density of dry briquette) of randomly selected briquette samples was determined 30days after the briquette were produced (ASAE, 2003). The mass of the dry briquette was measured using electric weighing balance while volume was calculated using the cylinder basic dimensions.

$$\rho_r = \frac{m_d}{V_d} \qquad 3.9$$

Where: ρ_r = relaxed density (kg/m^3)

m_d = mass of dried briquette (kg)

$V_d = \frac{\pi}{4} H(D^2 - d^2)$ = volume of dried briquette (m^3)

H = height of dried briquette (m)

D = outer diameter of dried briquette (m)

d = inner diameter of dried briquette (m)

3.8.1.3 Relaxation ratio

The relaxation ratio was determined as the ratio of compressed density to relaxed density (Oyelaran *et al.,* 2014). That is;

$$\text{Relaxation ratio} = \frac{\text{compressed density}}{\text{relaxed density}} \qquad 3.10$$

3.8.1.4 Shattered index

The shattered index was determined as described by Suparin *et al.* (2008). This involved dropping the briquette samples repeatedly from a height of 1.5m onto a solid base. The percentage weight loss was first determined using equation 3.10. Then, the shatter resistance was obtained by subtracting the percentage weight loss from 100 (Ghorpade and Moule, 2006 and Sengar, *et al.,* 2012).

Shatter resistance = 100 - percentage weight loss

And;

$$\% \text{ weight loss} = \frac{\text{initial weight before shatter} - \text{weight after shattering}}{\text{initial weight of briquette before shattering}} x\ 100 \qquad 3.11$$

3.8.2 Determination of thermal properties

The thermal properties of the briquettes determined were calorific value, volatile matter, ash content and fixed carbon.

3.8.2.1 High calorific value

The direct determinations of high calorific values of briquette samples were made using E2k bomb calorimeter. 0.5g of pulverized briquette sample was placed in the crucible. The crucible and content was then placed in vessel lid assembly. A length of pure cotton thread was tied to the firing wire with its tail touching the sample placed in the crucible. Then, the vessel lid assembly was gently placed in the vessel (the bomb). The vessel (with the vessel lid assembly) was placed in the filling station to pressurize with oxygen to 3MPa. This is required so that the sample will ignite and burn away completely. The pressurized vessel is transferred into the calorimeter where the pressurized vessel is ignited. The vessel has a combustion chamber, which contains the burning process and transfers the resulting heat into the vessel's walls, where it is measured with the aid of sensor. The vessel has temperature sensors built into the wall so that the temperature rise can be measured and converted to an energy value. The calorific value of the sample in the machine was displayed on screen. The result was taken and recorded. After a calorific value determination, the vessel was cooled in the cooler. The cooler was used to return the vessel back to ambient temperature within a few minutes and the procedure repeated.

3.8.2.2 Volatile matter

The percentage volatile matter of briquette sample was determined according to Obi *et al.*, (2013). 1g of sample was placed in crucibles of known masses and oven dried to a constant weight. The mass of crucible and oven dried sample was measured using a high precision weighing machine (Mettler P163 weighing machine), capable of measuring to four decimal places. The furnace was put on and set to a temperature of 550℃ and allowed to rise to the set temperature. Then, the oven dried samples arranged in a rectangular metallic container was transferred into the heated furnace using a tong, where it was heated at a temperature of 550℃ for 10 minutes and then cooled in a desiccator. The mass of cooled sample and crucible was measured and the percentage volatile matter was determined as the percentage loss in mass to the oven dried mass of sample after subtracting the mass of crucible, using equation 3.12:

$$\text{Volatile matter} = \frac{\text{mass of heated sample}}{\text{mass of oven dried sample}}\ x\ 100 \qquad 3.12$$

3.8.2.3 Ash content

The percentage ash content of briquette samples was also determined according to Obi *et al.,* (2013). 1g of samples was placed in crucibles of known masses. The furnace was put on and set to a temperature of 550℃ and allowed to rise to the set temperature. Then, samples were arranged in a rectangular metallic container and transferred into the heated furnace using a tong. The samples were heated in the heated furnace for 4 hours and then cooled in a desiccator. The mass of cooled sample and crucible was measured using a high precision weighing machine (Mettler P163 weighing machine), capable of measuring to four decimal places. The percentage ash content was determined as the percentage loss in mass to the initial mass of sample after subtracting the mass of crucible, using equation 3.13:

$$\text{Ash content} = \frac{\text{mass of heated sample}}{\text{initial mass of sample}}\ x\ 100 \qquad 3.13$$

3.8.2.4 Fixed carbon

The percentage fixed carbon was calculated using equation 3.14 as used by Obi *et al.* (2013), where the sum of the percentages ash content and volatile matter was subtracted from 100%.

$$FC = 100 – (\% \text{ volatile matter} + \% \text{ ash content}) \quad 3.14$$

Where: FC = % Fixed Carbon

3.8.1.5 Thermal fuel efficiency

The thermal efficiency indicates how well energy in fuel will be converted to heat. The thermal fuel efficiency of briquette sample was determined by carrying out water boiling test as described by Sengar *et al.*, (2012). The water boiling test setup is shown in Plate 3.1. Water boiling test was undertaken by combusting 124g of briquette in a Chinese metallic stove called ‘safe80’ (i.e. the stove burns only 20% of its fuel per time). The ‘safe80’ stove (Plate 3.1) is a hexagonal shaped stove made of stainless steel plate, comprising of a burning chamber and a pot.

Plate 3. 1: Water Boiling Test Set-up

One litre of water was put into the pot, the mass of the water was measured and recorded. The briquettes were sprinkled with about 5mL of kerosene for ignition (because the briquette was observed to require a starter). The initial temperature of the water was taken and recorded by a thermometer held in between corks fixed to a retort stand (Plate 3.1). The briquettes were ignited, after the kerosene had burnt out, the pot of water was placed on the stove. The time taken for the water to boil and the temperature of the water was taken and recorded. Boiling was allowed to continue until briquette samples in the stove was used up. The weight of the evaporated water was calculated from the difference between the final weight of water after cooling and the initial weight of water in the pot. Equation 3.13 as used by Oladeji (2011) and Davies (2012) was used to determine the thermal efficiency of the briquettes:

$$\text{Thermal efficiency} = \frac{m_w C_p (T_2 - T_1) + m_e L}{m_f E_f} \, x \; 100\% \qquad 3.15$$

Where: m_w = mass of water in the pot (kg)

m_e = mass of water evaporated (kg)

m_f = mass of fuel burnt (kg)

C_p = specific heat of water (kJ/kgK)

T_1 = Initial temperature of water (K)

T_2 = final temperature of boiling water (K)

L = latent heat of vaporization (kJ/kg)

E_f = calorific value of the fuel (kJ/kg)

3.8.3 Machine output capacity

The machine output capacity was according to Obi *et al*. (2013) as the ratio of the mass of four briquettes in kg, produced by the biomass briquetting machine to the average time used in production of the briquette. The machine production time components include: biomass loading time (s), biomass compaction time (s), briquette residence time (s), and briquette ejection time (s). That is;

$$\text{Machine output capacity (kg/s)} = \frac{\text{mass of four briquettes (kg)}}{\text{briquettes}'\text{production time (s)}} \qquad 3.16$$

3.9 Experimental Procedures

3.9.1 Briquetting production (Machine operation)

Biomass sample of 150g was measured and mixed with each set of starch binder prepared. The biomass-binder mixture was produced in the ratio of 100:20, 100:30 and 100:40 percent by weight of biomass and hand fed into the briquetting machine. Thereafter, the upper compression plate of the machine, which is hinged at one end to the mould was bolted at the other end and sides to the machine mould and compaction was done using the hydraulic jack. During the compaction process, excess water in the biomass-binder mixture was released and after compaction the briquette was left in the machine for 10min (residence time) before ejection (See Appendix O). Four briquettes were produced per time. Then, the pistons were lowered to their initial point (BDC) by turning the jack's release valve anti-clockwise. Two helical springs were attached to the piston plate in order to facilitate easy return of the piston to its initial point. Immediately after ejection, the mass of the briquettes was measured using digital weighing balance and recorded, while the height, internal and outer diameter of the briquettes were measured using vernier caliper and recorded. At each biomass: binder level, 12 briquettes were produced.

3.9.2 Experimental Design and Layout

The machine evaluation was based on Complete Randomized Design (CRD). The experiment was conducted using three biomass materials (millet stalk and sorghum stalk). In each case, three different levels of particle size of 7mm, 5mm and 3mm (P_1, P_2 and P_3 respectively) and three binder ratios of 20%, 30% and 40% by weight of biomass material (B_1, B_2, and B_3 respectively) were employed. Each of the experiment was repeated three times. The experiment is a two-factor experiment (that is biomass particle sizes and binder ratios, each at three levels). The data obtained was statistically analyzed using Statistical Analysis System (SAS 9.1) package. Fig. 3.8 and Fig 3.9 show the treatment combinations and the experiment layout respectively. while Table 3.3 shows the structure of the Analysis of Variance (ANOVA).

	B_1	**B_2**	**B_3**
P_1	P_1B_1	P_1B_2	P_1B_3
P_2	P_2B_1	P_2B_2	P_2B_3
P_3	P_3B_1	P_3B_2	P_3B_3

Fig. 3. 8: Combination of Particle Size and Binder at 3 levels each

R_I	R_{II}	R_{III}
P_3B_3	P_2B_2	P_2B_1
P_2B_1	P_1B_2	P_3B_1
P_3B_2	P_2B_3	P_1B_1
P_1B_3	P_3B_2	P_2B_3
P_2B_3	P_1B_1	P_1B_3
P_2B_2	P_2B_1	P_3B_3
P_1B_2	P_3B_3	P_2B_2
P_1B_1	P_3B_1	P_3B_2
P_3B_1	P_1B_3	P_1B_2

Fig. 3. 9: A Layout of 3x3 Experiment involving three Particle Size (P_1, P_2, and P_3) and three Binder Ratio (B_1, B_2 and B_3) arranged in Complete Randomized Design (CRD), with three replications

Table 3. 3: Structure of Analysis of Variance (ANOVA) for Two Factorial, 3*3 Experiments in Complete Randomized Design (CRD)

Source of variance	Degree of freedom	Sum of square	Mean squares	Computed F	Tabulated F	
					5%	1%
Particle size (P)	(p-1) = 2					
Binder ratio (B)	(b-1) = 2					
P *x* B	(p-1) (b-1) = 4					
Error	t(r-1) = 18					
Total	(t*r) – 1 = 26					

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 The Developed Hydraulic Piston Press Biomass Hollow Briquette Making Machine

Plates 4.1 and 4.2 presents the developed briquetting machine and samples of briquettes produced using the developed briquetting machine. The hollow briquette making machine consists of upper compression plate, mould, lower compression plate, and the machine stand (support). It is operated by a 4-ton hydraulic jack.

Plate 4. 1: Developed Hydraulic Press Biomass Hollow Briquette Making Machine

A B

Plate 4. 2: Samples of Briquettes Produced by the Developed Briquetting Machine A: Sorghum-Stalk Briquettes and B: Millet-Stalk Briquettes

4.1.1 Upper compression plate

The upper compression plate is made of mild steel plate. It a square plate with length and thickness of 300 mm *x* 5 mm respectively. It has four holes at its top as shown in appendix H, for free passage of the removeable PVC pipes from the top of the pistons during compaction (as shown in Plate 4.3). The Plate is hinged to the machine mould at one end. The other end and sides of the plate were provided with holes to fasten the upper compression plate to the machine mould before compaction.

Plate 4. 3: Briquetting Stage Before Ejection of Briquette from the Machine Mould

4.1.2 Machine mould

The machine mould consists of two square plate and four cylindrical pips (moulds). The plates are made of mild steels having length and thickness of 300 mm *x* 3 mm respectively while the moulds are made of galvanized steel with outer diameter, inner diameter and height of 116 mm *x* 102 mm (See Appendix I).

4.1.3 Machine pistons

The piston consists of a ram cylinder and a piston rod (or connecting rod). The ram cylinder is hollow cylinder closed at both ends and made of galvanized steel. It has a diameter of 100 mm and height of 50 mm. The cylinder pipe of diameter 26 mm and height 15 mm, also made of galvanized steel is joined to the top of the ram while the piston rod is joined to the bottom of the ram cylinder as shown in Appendix J. the piston rod has a diameter of 50 mm and height of 120 mm, also made of galvanized steel.

4.1.4 Lower compression plate

The lower compression plate is square plate of length 300 mm and thickness 3 mm, made of mild steel. The pistons are joined to the lower compression plate (Appendix J). Its purpose to convey the pistons in the mould, from its bottom dead centre (BDC) to its top dead centre (TDC), to and fro – during and after compaction. It receives its drive from the 4-ton hydraulic jack.

4.1.5 Machine stand (support)

The machine stand consists of jack head plate, iron rod, cylindrical pipe, and the jack seat plate (as shown in Appendix K). the jack head plate is a square, made of mild steel plate having length and thickness of 300 mm *x* 5 mm respectively. At its centre is a hole of diameter 30 mm in order to allow free passage and provide support for the piston of the hydraulic jack. Also, the jack head plate serves as a resting point for the lower compression plate (as shown in Fig. 4.1 above). The iron rod is of length 389mm and diameter 18.34 mm. it is joined to each corner of the jack set plate with some part of it housed by the cylindrical pipe (Appendix K). It has a threaded part (at the top) on which the mould is bolted and the lower compression plate travels up and down the exposed part of the iron rod. The cylindrical pipe has a length of 400 mm. It serves as a stopper for jack head plate and subsequently the lower compression plate. The jack seat plate is similar to the jack head plate with exception of the centre hole. The provide seat for the jack and the iron rod and cylindrical pipes are joined to it to provide rigidity for the briquetting machine.

4.2 Effect of Particle Size and Binder Ratio on Sorghum-Stalk Briquette Quality Parameters.

4.2.1 Compressed density of sorghum-stalk briquette

The results for the experimental evaluation of the effect of particle size and binder ratio on the compressed density of sorghum-stalk briquette produced by the constructed briquetting machine using Completely Randomized Design (CRD) are as presented in Appendix A. The Analyses of Variance (ANOVA) results for the compressed density are as presented in Table 4.1:

Table 4. 1: Analysis of Variance for Compressed Density of Sorghum-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F 5%	1%
Particle size (P)	2	66671.34613	33335.67306	37.07^{**}	3.55	6.01
Binder ratio (B)	2	7447.04634	3723.52317	4.14^{*}	3.55	6.01
P * B	4	9361.60659	2340.40165	2.60^{NS}	2.93	4.58
Error	18	16187.92091	899.32894			
Total	26	99667.91996				

Note: **significant at 1% level; *significant at 5% level; ^{NS} not significant

The ANOVA results (Table 4.1) show that the effect of particle size of the sorghum-stalk biomass on the compressed density was significant at 1% probability level. The effect of binder ratio on the compressed density was also significant at 5% probability level. However, the interaction effect between the biomass and binder was not statistically significant.

Further analysis results of the effect of particle size, using Least Significant Difference (LSD), are shown in Table 4.2. The results of the ranking revealed that the mean compressed density of 727.67 kg/m^3 for particle size P_3 is significantly different from the mean value of 652.04 kg/m^3 for particle size P_1.

Table 4. 2: LSD Result of Particle Size on Compressed Density of Sorghum-Stalk Briquettes

Performance indicator	Particle sizes		
	P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Mean Compressed Density (kg/m^3)	652.04^b	607.26^c	727.67^a

It is also evident from these results that the mean compressed density of 652.04 kg/m^3 for particle size P_1 is significantly different from the mean value of 607.26 kg/m^3 for particle size P_3. It can be concluded from the results that fine particle size P_3 gave the highest compressed density using the developed briquetting machine. Similar result was obtained by Saptoadi, (2008) who reported the lowest and highest compressed density of 492.1 kg/m^3 and 941.2 kg/m^3 at rice husk particle sizes of 425µm and 150 µm respectively. He reported that particle sizes determine briquette porosities. The smaller the particle size, the lesser will be the porosity and the higher will be the density. This agrees also with FAO (1990) and Krizan (2007) reports that in reality, in briquetting, when a large proportion of the raw material is of finer particles, the briquette produced will have a higher density because finer particles gives a larger surface area for bonding which results in the production of briquette with higher density. Contrarily, Davies (2012) and Oladeji (2012) reported decrease in compressed density of water hyacinth and corncob briquettes respectively with decrease particle size. Davies (2012) reported compressed densities of 715.75 kg/m^3 and 1031.36 kg/m^3 at water hyacinth particle sizes 0.5mm and 4mm respectively while Oladeji (2012) reported compressed densities of 750 kg/m^3, 605 kg/m^3 and 600 kg/m^3 at corncob particle sizes 4.70mm, 2.40mm and 0.60mm, respectively. The compressed densities of sorghum-stalk briquettes produced from the developed briquetting machine are higher than the minimum value of 600kg/m^3 recommended by Mani *et al*. (2004) and Gilbert *et al*. (2009) for efficient transportation and safe storage of briquettes at all the three particle sizes considered.

Also, further analysis results on the effect of binder ratio, using Least Significant Difference (LSD), are shown in Table 4.3.

Table 4. 3: LSD Result of Binder Ratio on Compressed Density of Sorghum-Stalk Briquettes

Performance indicator	Binder ratios		
	B_1 (20%)	B_2 (30%)	B_3 (40%)
Mean Compressed Density (kg/m^3)	665.21^{ab}	681.06^{a}	640.69^{b}

Means with the same letter are not significantly different

The results of the ranking revealed that the mean compressed densities of 681.06 kg/m^3 for binder ratio B_2 and 665.21 kg/m^3 for binder ratio B_1 are not significantly different from one another but are significantly different from the mean compressed density of 640.69 kg/m^3 for binder ratio B_3. The LSD results showed that the mean compressed density increased from 665.21 kg/m^3 at binder ratio B_1 to 681.06 kg/m^3 at binder ratio B_2 and decreased to 640.69 kg/m^3 at binder ratio B_3. Therefore, it could be implied that the compressed density of briquettes produced from sorghum stalk using the developed briquetting machine decrease with increase in binder ratio above B_2 (30% by weight of biomass). This might be due to the fact that, the pore spaces within the particles, filled by the semi-fluid starch binder (40% by weight of biomass) might have limited compressibility (Appendix A). It could be concluded from these results that binder ratio B_2 gave the highest compressed density using the developed briquetting machine. Similar trend was reported by Oyelaran *et al.* (2014), Obi *et el.* (2013) and Oladeji (2012) for groundnut shell, saw dust and corncob, respectively using starch binder. Obi *et al.* (2013) reported mean compressed densities of 612.5 kg/m^3 at starch binder ratio of 15% by weight of saw dust biomass and 726.9 kg/m^3 at binder ratio 25% and a decline in mean compressed density to 702.8 kg/m^3 with further increase in starch binder ratio to 35% by weight of biomass. Oyelaran *et al.* (2014) recorded a decrease in mean compressed density from 441.08 kg/m^3 to 411.11 kg/m^3 when starch binder ratio was increased from 5% - 20% by weight of groundnut shell biomass while Oladeji (2012) recorded decrease in mean compressed density from 651.67 kg/m^3 to 551.33 08 kg/m^3 as starch binder ratio was increased from 20 – 30% by weight of corncob biomass.

4.2.2 Relaxed density of sorghum-stalk briquette

The results of the effect of particle size and binder ratio on the relaxed density of sorghum-stalk briquette produced by the constructed briquetting machine using Completely Randomized Design (CRD) are as presented in Appendix A. The Analyses of Variance (ANOVA) results for the relaxed density are as presented in Table 4.4:

Table 4. 4: Analysis of Variance for Relaxed Density of Sorghum-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F 5%	Tabular F 1%
Particle size (P)	2	10881.34788	5440.67394	53.90**	3.55	6.01
Binder ratio (B)	2	2089.96465	1044.98233	10.35**	3.55	6.01
P * B	4	1446.53588	361.63397	3.58*	2.93	4.58
Error	18	1816.94285	100.94127			
Total	26	16234.79126				

Note: **significant at 1% level; *significant at 5% level

The ANOVA results (Table 4.4) show that the effect of particle size of the sorghum-stalk biomass on relaxed density was significant at 1% probability level. The effect of binder ratio on relaxed density was also significant at 1% probability level. And the interaction effect between the biomass and binder was significant at 5% probability level.

Results for further analysis, using Least Significant Difference (LSD), are shown in Table 4.5. The results of the ranking revealed that the mean relaxed density of 222.35 kg/m^3 for particle size P_3 is significantly different from the mean value of 183.28 kg/m^3 at particle size P_1. However, the LSD results (Table 4.4) showed that there was no significant difference between the mean relaxed density of 183.28 kg/m^3 for particle size P_1 and 176.95 kg/m^3 for particle size P_2.

Table 4. 5: LSD Result of Particle Size on Relaxed Density of Sorghum-Stalk Briquettes

Performance indicator	Particle sizes		
	P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Mean Relaxed density (kg/m^3)	183.28^b	176.95^b	222.35^a

Means with the same letter are not significantly different

It could be concluded from these results that fine particle size P_3 gave the highest relaxed density when the briquettes were exposed to atmospheric conditions. Although the experimental results (Appendix A) gave no particular pattern. However, Obi *et al.* (2013), Bamgboye and Bolufawi, (2008) reported that the relaxed density of briquette depends largely on the compressed density of the briquette, due to the fact that high compressed density indicates high bonding between briquette particles in presence of binder and as a result, the briquettes tend to experience lesser relaxation when exposed to the atmospheric conditions.

In the case of binder ratio, the results of further analysis, using Least Significant Difference (LSD), are shown in Table 4.6.

Table 4. 6: LSD Result of Binder Ratio on Relaxed Density of Sorghum-Stalk Briquettes

Performance indicator	Binder ratios		
	B_1 (20%)	B_2 (30%)	B_3 (40%)
Mean Relaxed density (kg/m^3)	181.93^b	202.19^a	198.44^a

Means with the same letter are not significantly different

The results of the ranking revealed that there was no significant difference between the mean relaxed density of 202.19 kg/m^3 at binder ratio B_2 and 198.44 kg/m^3 at binder ratio B_3. However, mean relaxed density of 198.44 kg/m^3 at binder ratio B_3 is significantly different from the mean value of 181.93 kg/m^3 at binder ratio B_1. It could be concluded from these results that binder ratio B_2 gave the best relaxed density when the briquettes were exposed to the atmospheric conditions.

At each particle size level, the relaxed density of the sorghum-stalk briquettes was observed to increase with increase in binder ratio (Appendix A1) except at particle size P_2, where the highest relaxed density was recorded at binder ratio B_2. Similar results were reported by Obi *et al.* (2013), Bamgboye and Bolufawi, (2008). Obi *et al.* (2013) reported an increase in relaxed density from 266.6 kg/m^3 to 287.8 kg/m^3 as binder ratio increased from 15 % - 35 % by weight of sawdust biomass, while Bamgboye and Bolufawi, (2008) reported an increase in relaxed density from 235 kg/m^3 to 281 kg/m^3 as binder ratio increased from 40 % - 55 % by weight of guinea corn residue.

The results for further analysis of interaction effect between particle sizes and starch binder ratios using Least Significant Difference (LSD), are shown in Table 4.7. The results of the ranking revealed that there was no significant difference in the interaction between fine particle size P_3 and the three binder ratios; B_3, B_2 and B_1, with mean relaxed density 228.92 kg/m^3, 225.52 kg/m^3 and 221.59 kg/m^3 for interactions between P_3: B_3, P_3: B_2, and P_3: B_1 respectively. However, the results showed that there was a significant difference in the mean relaxed density of the interaction effect between the fine particle size P_3 and binder ratios and the interaction effect between the medium and coarse particle sizes P_2 and P_1 and binder ratios considered. No definite pattern was established in the mean relaxed density of the interaction effect between binder ratios and particle sizes P_2 and P_3 but it was observed that the mean relaxed density of the interaction effect between particle sizes P_2 and P_1 at higher binder ratios B_2 and B_3 were better ranked than the mean relaxed density of the interaction effect between particle sizes P_2 and P_1 at the least binder ratio B_1. This confirms lesser relaxation of the briquette at higher binder ratio and finer particle size of the briquettes when exposed to atmospheric conditions.

Table 4. 7: LSD Results of Interaction Between Biomass and Binder on Sorghum-Stalk Briquettes

Treatments	Mean Relaxed Density kg/m^3	Ranks
P_3B_3	228.92	a
P_3B_2	225.52	a
P_3B_1	221.59	a
P_2B_2	197.36	b
P_1B_3	185.69	c
P_1B_2	183.69	c
P_2B_3	180.73	c
P_1B_1	180.47	c
P_2B_1	152.75	d

Means with the same letter are not significantly different

Therefore, it can be concluded from these results that the interaction between fine particle size P_3 and binder ratio B_3 gave the highest relaxed density of sorghum-stalk briquettes produced from the developed biomass briquetting machine.

4.2.3 Relaxation ratio of sorghum-stalk briquette

The results for the effect of particle size and binder ratio on the relaxation ratio of sorghum-stalk briquette using Completely Randomized Design (CRD) are as presented in Appendix A. The Analyses of Variance (ANOVA) results for the relaxation ratio are as presented in Table 4.8. The ANOVA results (Table 4.8) show that the effect of particle size on the relaxation ratio was significant at 5% probability level. The effect of binder ratio on the relaxation ratio was also significant at 1% probability level. However, the interaction effect between the biomass and binder was not statistically significant.

Table 4. 8: Analysis of Variance for Relaxation Ratio of Sorghum-Salk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F 5%	Tabular F 1%
Particle size (P)	2	0.37243148	0.18621574	4.03^{*}	3.55	6.01
Binder ratio (B)	2	0.92604594	0.46302297	10.03^{**}	3.55	6.01
P * B	4	0.18047074	0.04511769	0.98^{NS}	2.93	4.58
Error	18	0.83092304	0.04616239			
Total	26	2.30987120				

Note: **significant at 1% level; *significant at 5% level; ^{NS} not significant

Further analysis results using Least Significant Difference (LSD), are shown in Table 4.9.

Table 4. 9: LSD Result of Particle Size on Relaxation Ratio of Sorghum-Stalk Briquettes

Performance indicator	Particle sizes P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Mean Relaxation ratio	3.56^{b}	3.47^{ab}	3.28^{a}

Means with the same letter are not significantly different

The results of the ranking revealed that the mean relaxation ratio of 3.28 for particle size P_3 is not significantly different from the mean value of 3.47 for particle size P_2. The mean relaxation ratio 3.47 for particle size P_2 is also, not significantly different from the mean value of 3.56 for particle size P_1. However, the mean relaxation ratio of 3.28 for particle size P_3 is significantly different from mean value of 3.56 for particle size P_1. It can be concluded from the results that fine particle size P_3 produced a briquette with better stability indicating from low value of relaxation ratio. The mean relaxation ratio of sorghum-stalk briquettes was observed to decrease with decrease in particle size. The relaxation ratio of sorghum-stalk briquettes was however observed to be higher compared with values for other agricultural wastes as reported by Olorunnisola (2007), Oladeji *et al.,* (2009), O'Dogherty (1989), and Oladeji (2010) with values of 1.80 - 2.25, 1.97, 1.45, 1.65 - 1.80, and 2.33 for coconut husk, groundnut, melon, hay materials and rice husk, respectively.

Also, further analysis results on the effect of binder ratio, using Least Significant Difference (LSD), gave the results presented in Table 4.10.

Table 4. 10: LSD Result of Binder Ratio on Relaxation Ratio of Sorghum-Stalk Briquettes

Performance parameter	Binder ratios		
	B_1 (20%)	B_2 (30%)	B_3 (40%)
Mean Relaxation ratio	3.69^b	3.38^a	3.24^a

Means with the same letter are not significantly different

The results (Table 4.10) of the ranking revealed that the mean relaxation ratio of 3.24 for binder ratio B_3 is not significantly different from the mean value of 3.38 for binder ratio B_2. However, the mean relaxation ratio 3.38 for binder ratio B_2 is significantly different from the mean value of 3.69 for binder ratio B_1. It can be seen from the results that 30 and 40 % binder ratios gave more stable briquettes when compared with values obtained for

20% binder ratio. In conclusion, relaxation ratio of sorghum-stalk briquettes can be said to decrease with increase in binder ratio.

4.2.4 Shattered index of sorghum-stalk briquette

The results for the experimental evaluation of the effect of particle size and binder ratio on the shattered index of sorghum-stalk briquette produced by the constructed briquetting machine using Completely Randomized Design are as presented in Appendix A. The Analyses of Variance (ANOVA) results for shattered index are as presented in Table 4.11: The results show that the effect of particle size on the shattered index was significant at 1% probability level. The effect of binder ratio index was also significant at 5% probability level. However, the interaction effect between the biomass and binder was not statistically significant.

Table 4. 11: Analysis of Variance for Shattered Index of Sorghum-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F 5%	Tabular F 1%
Particle size (P)	2	768.9879428	384.4939714	11.28^{**}	3.55	6.01
Binder ratio (B)	2	373.1624910	186.5812455	5.48^{*}	3.55	6.01
P * B	4	119.4836613	29.8709153	0.88^{NS}	2.93	4.58
Error	18	613.287469	34.071526			
Total	26	1874.921564				

Note: **significant at 1% level; *significant at 5% level; ^{NS} not significant

Further analysis results using Least Significant Difference (LSD) are shown in Table 4.12.

Table 4. 12: LSD Result of Particle Size on Shattered Index of Sorghum-Stalk Briquettes

Performance parameter	Particle sizes P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Mean Shattered Index (%)	76.82^{b}	80.71^{b}	89.57^{a}

Means with the same letter are not significantly different

The results of the ranking revealed that the mean shattered index of 89.76 % for particle size P_3 is significantly different from the mean value of 80.71 % for particle size P_2. The mean shattered index of 80.71 % for particle size P_2 is, however, not significantly different from the mean value of 76.82 % for particle size P_1. It can be concluded from the results that fine particle size P_3 gave the best shattered index. The shattered index result can be classified into 'high' (>0.8) according to Adapa *et al.* (2003), Tabil and Sokhansanj (1996). The result compare well with the shattered index of 88.90 %, 87.2 %, 89.8 % and 87.52 reported for briquettes produced from groundnut shell (Oyelaran *et al.*, 2014), sawdust, rice husk and groundnut shell mixture (Tembe *et al.*, 2014), water hyacinth and cow-dung mixture (Frank and Akhihiero, 2013) and sawdust (Obi *et al.*, 2013), respectively.

Further analysis results for the effect of binder ratio, using Least Significant Difference (LSD), are shown in Table 4.13.

Table 4. 13: LSD Result of Binder Ratio on Shattered Index of Sorghum-Stalk Briquettes

Performance indicator	Binder ratios		
	B_1 (20%)	B_2 (30%)	B_3 (40%)
Mean Shattered Index (%)	77.77[b]	82.45[ab]	86.87[a]

Means with the same letter are not significantly different

The results revealed that the mean shattered index of 86.87 % for binder ratio B_3 is not significantly different from the mean value of 82.45 % for binder ratio B_2. The mean shattered index 82.45 % for binder ratio B_2 is also not significantly different from 77.77 % or binder ratio B_1. There is, however, significant difference between mean shattered index of 77.77 and 86.87 for binder ratio of B_1 and B_3 respectively. It can be concluded from these results that binder ratio B_3 gave the best shattered index. The mean shatter resistance of sorghum-stalk briquettes was observed to increase with increase in binder ratio at each particle size considered. Similar trend was reported by Oyelaran *et al.* (2014) and Sotannde *et al.* (2010) when blending ratio was varied, durability rating increased with increase in binder fraction of the briquette and both concluded that shatter resistance depends on the concentration of binder.

4.2.5 High calorific value of sorghum-stalk briquette

The results for the experimental evaluation of the effect of particle size and binder ratio on the calorific value of sorghum-stalk briquette using Completely Randomized Design (CRD) are as presented in Appendix B. The Analyses of Variance (ANOVA) results for the calorific value are as presented in Table 4.14:

Table 4. 14: Analysis of Variance for Calorific Value of Sorghum-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F 5%	1%
Particle size (P)	2	12.52160000	6.26080000	33.42^{**}	3.55	6.01
Binder ratio (B)	2	18.57223400	9.28611700	49.57^{**}	3.55	6.01
P * B	4	4.08355400	1.02088850	5.45^{**}	2.93	4.58
Error	18	3.37222800	0.18734600			
Total	26	38.54961600				

Note: **significant at 1% level.

The ANOVA results (Table 4.14) show that the effects of particle size and binder ratio on the calorific value were significant at 1% probability level. And the interaction effect between the particle size and binder was also significant at 1% probability level.

The effect of the particle size was further analyzed, using Least Significant Difference (LSD) and the results are as shown in Table 4.15. The results of the ranking revealed that the mean calorific value of 17.726 MJ/kg for particle size P_3 is significantly different from the mean value of 16.353 MJ/kg for particle size P_2. However, the mean value of 16.353

MJ/kg for particle size P_2 is not significantly different from 16.220 MJ/kg for particle size P_1. It can be concluded from the results that particle size P_3 gave the best calorific value.

Table 4. 15: LSD Result of Particle Size on High Calorific Value of Sorghum-Stalk Briquettes

Performance indicator	Particle sizes		
	P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Mean calorific value (MJ/kg)	16.220^b	16.353^b	17.726^a

Means with the same letter are not significantly different

Similar results were reported by Tokan *et al.* (2014) for sawdust and corncob with calorific values of 17.82 MJ/kg and 17. 51 MJ/kg, respectively.

Further analysis results of the effect of binder ratio, using Least Significant Difference (LSD), are shown in Table 4.16.

Table 4. 16: LSD Result of Binder Ratio on High Calorific Value of Sorghum-Stalk Briquettes

Performance indicator	Binder ratios		
	B_1 (20%)	B_2 (30%)	B_3 (40%)
Mean calorific value (MJ/kg)	17.725^a	16.871^b	15.702^c

The results of the ranking revealed that the mean calorific value of 17.725 MJ/kg for binder ratio B_1 is significantly different from the mean value of 16.871 MJ/kg for binder ratio B_2. It is also evident from the results that the mean value of 16.871 MJ/kg for binder ratio B_2 is significantly different from 15.702 MJ/kg for binder ratio B_3. It can be concluded from these results that binder ratio B_1 gave the best calorific value. The calorific value of sorghum stalk briquettes was observed to decrease with increase in binder ratio. Similar trend was reported by Chirchir *et al.* (2013) and Obi *et al.* (2013). The results compare well with many biomass materials such as groundnut shell briquette with 12.6 MJ/kg and rice husk with 13.389 MJ/kg (Kaliyan and Morey, 2009); cowpea residues with 14.373 MJ/kg and soybeans with 12.953 MJ/kg (Enweremadu *et al.,* 2004) and Mango seed cover with 16.140 MJ/kg (Katimbo *et al.,* 2014).

Further analysis of interaction effect of particle size and starch binder ratios, using Least Significant Difference (LSD), gave results shown in Table 4.17.

Table 4. 17: LSD Results of Interaction Between Biomass Particle Sizes and Binder Ratios on Calorific Value of Sorghum-Stalk Briquettes

Treatments	Mean calorific value (MJ/kg)	**Ranks**
P_3B_1	19.165	a
P_3B_2	17.280	b
P_2B_1	17.128	b
P_1B_2	16.997	b
P_1B_1	16.883	bc
P_3B_3	16.734	c
P_2B_2	16.338	c
P_2B_3	15.593	d
P_1B_3	14.779	e

Means with the same letter are not significantly different

The results showed that the interaction between particle size P_3 and binder ratio B_1 gave the highest calorific value with mean calorific value of 19.165 MJ/kg, which is significantly different from the mean value of 17.280 MJ/kg for interaction between particle size P_3 and binder ratio B_2. Thereafter, the interaction effect between particle size and binder gave no definite pattern on high calorific value of sorghum-stalk briquette but could be generally concluded that fine particles with less binder have higher calorific value and coarse particle with more starch binder gave the lower calorific value, with least calorific value of 14.779 MJ/kg was obtained for interaction between coarse particle size P_1 and binder ratio, 40%.

4.2.6 Ash content of sorghum-stalk briquette

The results for the experimental evaluation of the effect of particle size and binder ratio on the ash content using Completely Randomized Design (CRD) are as presented in Appendix B. The Analyses of Variance (ANOVA) results for the ash content are as presented in Table 4.18. The results show that the effects of particle size and binder ratio on ash content were significant at 1% probability level. And the interaction effect between the biomass and binder was also significant at 1% probability level.

Table 4. 18: Analysis of Variance of Sorghum-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F 5%	Tabular F 1%
Particle size (P)	2	5.00666667	2.50333333	59.29**	3.55	6.01
Binder ratio (B)	2	1.64666667	0.82333333	19.50**	3.55	6.01
P * B	4	3.23333333	0.80833333	19.14**	2.93	4.58
Error	18	0.76000000	0.04222222			
Total	26	10.64666667				

Note: **significant at 1% level.

Further analysis results of the effect of the particle size, using Least Significant Difference (LSD), are shown in Table 4.19.

Table 4. 19: LSD Result of Particle Size on Ash Content of Sorghum-Stalk Briquettes

Performance indicator	Particle sizes		
	P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Mean Ash content (%)	2.6^c	2.3^b	1.6^a

The results of the ranking revealed that the mean ash content of 1.6 % for particle size P_3 is significantly different from the mean value of 2.3 % for particle size P_2. It is also evident from the results that the mean value of 2.3 % for particle size P_2 is significantly different from 2.6 % for particle size P_1. It can be concluded that the fine particle size P_3 gave the lowest ash content for sorghum-stalk briquettes. Katimbo *et al.* (2014) reported that low ash content is an indicator for less smoke, longer flaming and high heating value when briquette is burnt and makes briquette suitable for household cooking. The values obtained for ash content of sorghum-stalk briquette is lower when compared with ash content of 11.37 % for sawdust briquette (Obi *et al.*, 2013), 4.4 % and 3.86 % for cassava peel and yam peel briquette respectively (Oladeji and Oyetunji, 2013), 7.69 %, 9.09 % and 10 % for sawdust, corncob and prosopis africana charcoal, respectively (Tokan *et al.*, 2014).

Further analysis results of the effect of binder ratio, using Least Significant Difference (LSD), are shown in Table 4.20. The results of the ranking revealed that the mean ash content of 1.9 % for binder ratio B_1 is significantly different from the mean value of 2.1 % for binder ratio B_2.

Table 4. 20: LSD Result of Binder Ratio on Ash Content of Sorghum-Stalk Briquettes

Performance indicator	Binder ratio		
	B_1 (20%)	B_2 (30%)	B_3 (40%)
Mean Ash content (%)	1.9^a	2.1^b	2.5^c

It is also evident from the results that the mean value of 2.1 % for binder ratio B_2 is significantly different from 2.5 % for binder ratio B_3. It can be concluded from these results that binder ratio B_1 gave the lowest ash content.

Further analysis results of interaction effect between particle size and starch binder ratios, using Least Significant Difference (LSD), are shown in Table 4.21. The results showed that the interaction between particle size P_3 and binder ratio B_1 gave the least ash content of 1.3%, which is significantly different from the mean ash content of 1.7% for interaction between particle size P_3 and binder ratio B_2. Afterwards, the interaction effect between particle size and binder gave no definite pattern on the ash content of sorghum-stalk briquette. However, it was observed that fine particle size P_3 exhibited lower ash content compared to medium and coarse particle sizes P_2 and P_3 respectively.

Table 4. 21: LSD Results of Interaction Between Biomass and Binder on Sorghum-Stalk Briquettes

Treatments	Ash content (%)	Ranks
P_3B_1	1.3	a
P_3B_2	1.7	b
P_3B_3	1.8	b
P_2B_3	2.1	c
P_1B_1	2.1	c
P_1B_2	2.2	c
P_2B_1	2.3	cd
P_2B_2	2.5	d
P_1B_3	3.6	e

Means with the same letter are not significantly different

The highest ash content of 3.6 % was obtained for interaction between coarse particle size P_1 and the highest binder ratio B_3. It can therefore be concluded that interaction effect between the least binder ratio B_1 and fine particle size gave the least low ash content which is an indicator of good thermal property of briquette.

4.2.7 Volatile matter of sorghum-stalk briquette

The results for the effect of particle size and binder ratio on the volatile matter of sorghum-stalk briquette produced by the constructed briquetting machine, using Completely Randomized Design (CRD), are as presented in Appendix B. The Analyses of Variance (ANOVA) results for the volatile matter are as presented in Table 4.22.

Table 4. 22: Analysis of Variance for Volatile Matter of Sorghum-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F 5%	1%
Particle size (P)	2	74.52666667	37.26333333	103.83**	3.55	6.01
Binder ratio (B)	2	48.44666667	24.22333333	67.50**	3.55	6.01
P * B	4	69.29333333	17.32333333	48.27**	2.93	4.58
Error	18	6.4600000	0.3588889			
Total	26	198.7266667				

Note: **significant at 1% level.

The results show that the effect of particle size and binder ratio on volatile matter were significant at 1% probability level. And the interaction effect between the biomass and binder was also significant at 1% probability level.

Further analysis results of the effect of the particle size, using Least Significant Difference (LSD), are shown in Table 4.23.

Table 4. 23: LSD Result of Particle Size Volatile Matter of Sorghum-Stalk Briquettes

Performance indicator	Particle sizes		
	P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Volatile matter (%)	20.77[c]	21.50[b]	24.60[a]

The results of the ranking revealed that the mean volatile matter of 24.0 % for particle size P_3 is significantly different from the mean value of 21.50 % for particle size P_2. It is also evident from the results that the mean value of 21.50 % for particle size P_2 is significantly different from 20.77 % for particle size P_1. It can be concluded that the fine particle size P_3 gave the best volatile matter for sorghum-stalk briquettes. Volatile matter observed for sorghum is lower when compared with volatile matter reported by many researchers. However, in terms of quality specification, the low volatile matter recorded implies that, although the briquettes might not be easily ignited, but once ignited they will burn smoothly with clean flame giving off little or no smoke (Sotannde *et al.*, 2009). The fuels related to smokeless grade are known to contain no more than 20% volatile substances (Ivanov *et al.*, 2003).

Further analysis results of the effect of binder ratio using Least Significant Difference (LSD), are shown in Table 4.27.

Table 4. 24: LSD Result of Binder Ratio on Volatile Matter of Sorghum-Stalk Briquettes

Performance indicator	Binder ratios		
	B_1 (20%)	B_2 (30%)	B_3 (40%)
Volatile matter (%)	23.83^{a}	22.47^{b}	20.57^{c}

The results of the ranking revealed that the mean volatile matter of 23.83 % for binder ratio B_1 is significantly different from the mean value of 22.47 % for binder ratio B_2. It is also evident from the results that the mean value of 22.47 % for binder ratio B_2 is significantly different from 20.57 % for binder ratio B_3. It can be concluded from these results that binder ratio B_1 gave the best volatile matter.

Further analysis of the interaction effect between particle size and starch binder ratios, using Least Significant Difference (LSD), yielded results presented in Table 4.25. The results of the ranking gave no definite pattern in the interaction effect. However, it was revealed from the results that the highest volatile matter of 26.2 % was recorded for interaction between fine particle size P_3 and the least binder ratio B_1. And the lowest volatile matter of 17.4 % was recorded for the interaction between coarse particle size P_1 and the highest binder ratio B_3. High volatile matter in briquette is an indicator of easy ignition of the briquette.

Table 4. 25: LSD Results of Interaction Between Biomass Particle Sizes and Binder Ratio on Volatile Matter of Sorghum-Stalk Briquettes

Treatments	Volatile matter (%)	Ranks
P_3B_1	26.2	a
P_3B_3	25.5	b
P_2B_1	23.5	c
P_1B_2	23.1	c
P_2B_2	22.2	d
P_3B_2	22.1	e
P_1B_1	21.8	e
P_2B_3	18.8	f
P_1B_3	17.4	g

Means with the same letter are not significantly different.

Therefore, it can be concluded that interaction between fine particle size P_3 and low binder ratio B_1 gave the best volatile matter for sorghum-stalk briquette.

4.2.8 Fixed carbon of sorghum-stalk briquette

The results for the effect of particle size and binder ratio on the fixed carbon of sorghum-stalk briquette produced by the constructed briquetting machine, using Completely Randomized Design (CRD), are as presented in Appendix B. The Analyses of Variance (ANOVA) results for the fixed carbon are as presented in Table 4.26. The results show that the effect of particle size and binder ratio on fixed carbon was significant at 1% probability level. And the interaction effect between the biomass and binder was also significant at 1% probability level.

Table 4. 26: Analysis of Variance for Fixed Carbon of Sorghum-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F 5%	Tabular F 1%
Particle size (P)	2	41.28000000	20.64000000	54.48**	3.55	6.01
Binder ratio (B)	2	32.24000000	16.12000000	42.55**	3.55	6.01
P * B	4	62.26000000	15.56500000	41.08**	2.93	4.58
Error	18	6.8200000	0.3788889			
Total	26	142.6000000				

Note: **significant at 1% level.

The results of further analysis of the effect of the particle size, using Least Significant Difference (LSD), are shown in Table 4.30.

Table 4. 27: LSD Result of Particle Size Fixed Carbon of Sorghum-Stalk Briquettes

Performance indicator	Particle sizes P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Fixed carbon (%)	76.60^{a}	76.20^{a}	73.80^{b}

Means with the same letter are not significantly different.

The results of the ranking revealed that the mean volatile matter of 76.60 % for particle size P_1 is not significantly different from the mean value of 76.20 % for particle size P_2. However, the mean value of 76.20 % for particle size P_2 is significantly different from 73.80 % for particle size P_3. It can be concluded that particle size P_1 and P_2 gave better performance in terms of fixed carbon. The value obtained are higher than fixed carbon of mango cover seed (Katimbo *et al.*, 2014), saw dust (Obi *et al.*, 2013), yam peel and cassava peel (Oladeji and Oyetunji, 2013). Since fixed carbon gives a rough estimate of the heating value of fuel and acts as the main heat generator during burning (Akowuah *et al.*, 2012), sorghum-stalk can be said to produce quality briquette. This justify the high heating value of the briquettes.

Further analysis results of the effect of binder ratio, using Least Significant Difference (LSD), are shown in Table 4.28.

Table 4. 28: LSD Result of Binder Ratio on Fixed Carbon of Sorghum-Stalk Briquettes

Performance indicator	Binder ratios		
	B_1 (20%)	B_2 (30%)	B_3 (40%)
Fixed carbon (%)	74.27^{c}	75.40^{b}	$76.93^{\mathbf{a}}$

The results of the ranking revealed that the mean fixed carbon of 76.93 % for binder ratio B_3 is significantly different from the mean value of 75.40 % for binder ratio B_2. It is also evident from the results that the mean value of 75.40 % for binder ratio B_2 is significantly different from 74.27 % for binder ratio B_3. It can be concluded from these results that briquette with high level of binder ratio gave the best volatile matter. This was expected because, Katimbo *et al.*, (2014) reported that starch alone as binder gave a significantly high percentage of fixed carbon when compared with starch-clayey soil and starch-red soil binder types used in production of briquettes with mango seed cover wastes.

Further analysis results of interaction effect between sorghum-stalk biomass particle sizes and starch binder ratios using Least Significant Difference (LSD), are shown in Table 4.32.

Table 4. 29: LSD Results of Interaction Between Biomass and Binder on Sorghum-Stalk Briquettes

Treatments	**Mean Fixed Carbon (%)**	**Ranks**
P_2B_3	79.1	a
P_1B_3	79.0	a
P_3B_2	76.2	b
P_1B_1	76.1	b
P_2B_2	75.3	c
P_1B_2	74.7	c
P_2B_1	74.2	d
P_3B_3	72.7	e
P_3B_1	72.5	e

Means with the same letter are not significantly different.

The results of the ranking show that the highest fixed carbon content of 79.1 % for sorghum-stalk briquette was obtained at interaction between medium particle size P_2 and binder ratio B_3 (40% by weight of biomass). However, there is no significant difference between the mean fixed carbon of 79.1 % and mean fixed carbon value of 79.0 % for interaction effect between coarse particle size P_1 and binder ratio B_3. Afterwards, no definite pattern was established in the interaction effect between particle size and binder ratio on fixed carbon of sorghum-stalk briquette. However, it is evident from the results that high binder ratio with medium particle size gave the best performance while low binder ratio and fine particle size gave the least performance.

4.2.9 Thermal fuel efficiency of sorghum-stalk briquette

Fig. 4.1 shows the effect of particle size and binder ratio on the thermal efficiency of sorghum stalk briquette. The experimental result is as presented in Appendix C.

It could be observed from the result (Fig. 4.1) that there was obvious difference in the thermal fuel efficiency of sorghum-stalk briquette as the particle size and binder ratio changes. The mean thermal efficiency for particle sizes P_1 and P_2, having similar trend, deceases from 21.37% and 19.14% respectively to 21.30% and 16.97% respectively as binder ratio increases from B_1 to B_2. Then, the mean thermal efficiency for particle sizes P_1 and P_2 increase from 21.30% and 16.97% respectively to 23.73% and 21.71% respectively with further increase in binder ratio from B_2 to B_3. For particle size P_3 however, the mean thermal efficiency increases from 20.96% to 24.66% as binder ratio increases from B_1 to B_2 and then decrease from 24.66% to 22.57% with further increase in binder ratio from B_2 to B_3. The highest thermal fuel efficiency of 24.66% was obtained at biomass: binder ratio of P_3:B_2. It could be implied from the result that the thermal efficiency of sorghum-stalk briquette improved with decrease in biomass particle size.

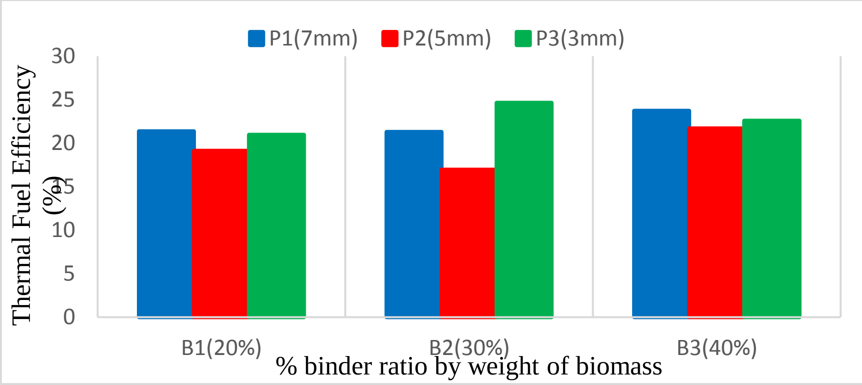


Fig. 4. 1: Thermal Fuel Efficiency of Sorghum-Stalk Briquette

Similarly, Davies (2012) reported that the thermal efficiency of water hyacinth improved with increase in binder proportion, increase in compaction pressure and decrease in particle size.

The thermal efficiency of sorghum-stalk briquette compared well with the thermal efficiency of 10.68%, 22.42%, 15.4% 18.52% and 12.29% for briquettes produced from rice straw, rice husk, sawdust, rice husk + sawdust and firewood respectively (Sani, 2008); 15.5% for cashew shell (Sengar *et al.*, 2012) and 28.17% for water hyacinth briquette (Davies, 2012).

4.3 Effect of Particle Size and Binder Ratio on Millet-Briquette Quality Parameters.

4.3.1 Compressed density of millet-stalk briquette

The results for the experimental evaluation of the effect of particle size and binder ratio on the compressed density of millet-stalk briquette produced by the constructed briquetting machine using Completely Randomized Design (CRD) are as presented in Appendix D. The Analyses of Variance (ANOVA) results for the compressed density are as presented in Table 4.30. The ANOVA results show that the effect of particle size of the millet-stalk biomass on the compressed density was significant at 1% probability level. However, the effect of binder ratio on the compressed density was not significant. Also, the interaction effect between the biomass particle size and binder was not significant.

Table 4. 30: Analysis of Variance for Compressed Density of Millet-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F	
					5%	1%
Particle size (P)	2	145913.3640	72956.6820	29.69**	3.55	6.01
Binder ratio (B)	2	921.9886	460.9943	0.19^{NS}	3.55	6.01
P * B	4	23183.0039	5795.7510	2.36^{NS}	2.93	4.58
Error	18	44227.5259	2457.0848			
Total	26	214245.8824				

Note: **significant at 1% level; ^{NS} not significant.

The non-significance of binder ratio on the compressed density of millet-stalk briquettes may be traced to the following observation during briquetting process. During compaction process, millet-stalk was observed to released high viscous liquid indicating the release of high starch content along with excess water at all binder ratio considered (observed by rubbing ejected liquid between palms). Whereas, sorghum-stalk behaved differently during compaction process with release of low viscous liquid, indicating the release of little starch content along with excess water. This observation however, may best be explained based on the chemical composition such as lignin, extractive, cellulose and hemicellulose contents of the biomass materials (Karunanithy, 2011).

Further analysis results of the effect of particle size, using Least Significant Difference (LSD), are as presented in Table 4.31. The results of the ranking revealed that the mean compressed density of 814.41 kg/m^3 for particle size P_3 is significantly different from the mean value of 687.74 kg/m^3 for particle size P_1. However, the LSD results (Table 4.31) showed that the mean compressed density of 687.74 kg/m^3 for particle size P_1 is not significant different from the mean value of 640.24kg/m^3 for particle size P_2. It can be concluded from these results that fine particle size P_3 gave the best compressed density using the developed briquetting machine.

Table 4. 31: LSD Result of Particle Size on Compressed Density of Millet-Stalk Briquettes

Performance parameter	Particle sizes		
	P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Mean Compressed Density (kg/m^3)	687.74^b	640.24^b	814.41^a

Means with the same letter are not significantly different.

Similar result was obtained for the compressed density of the sorghum-stalk briquette discussed above. Comparatively, millet-stalk briquette, however, gave a higher compressed density than sorghum-stalk briquette.

4.3.2 Relaxed density of millet-stalk briquette

The results of the effect of particle size and binder ratio on relaxed density of millet-stalk briquette produced by the constructed briquetting machine using Completely Randomized Design (CRD) are as presented in Appendix D. The Analyses of Variance (ANOVA) for the relaxed density are as shown in Table 4.32.

Table 4. 32: Analysis of Variance for Relaxed Density of Millet-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F 5%	Tabular F 1%
Particle size (P)	2	8869.212986	4434.606493	73.10**	3.55	6.01
Binder ratio (B)	2	241.302863	120.651431	1.99^{NS}	3.55	6.01
P * B	4	1123.833891	280.958473	4.63**	2.93	4.58
Error	18	1092.04096	60.66894			
Total	26	11326.39070				

Note: **significant at 1% level; *significant at 5% level; ^{NS} not significant.

The ANOVA results (Table 4.32) show that the effect of particle size of the millet stalk biomass on the relaxed density was significant at 1% probability level. The effect of binder ratio on the relaxed density was not statistically significant. While the interaction effect between the biomass and binder was significant at 1% probability level.

Results for further analysis, using Least Significant Difference (LSD), are shown in Table 4.33. The results of the ranking revealed that the mean relaxed density of 225.34 kg/m^3 for particle size P_3 is significantly different from the mean value of 188.24 kg/m^3 for particle size P_1. However, the mean relaxed density of 188.24 kg/m^3 for particle size P_1 is not significantly different from the mean value of 185.68 kg/m^3 for particle size P_2. It can be concluded from these results that fine particle size P_3 gave the highest relaxed density when the briquettes were exposed to the atmospheric conditions.

Table 4. 33: LSD Result of Particle Size on Relaxed Density of Millet-Stalk Briquettes

Performance parameter	Particle sizes		
	P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Mean Relaxed density (kg/m^3)	188.24^b	185.68^b	225.34^a

Means with the same letter are not significantly different.

Similar result was obtained for the effect of particle size on relaxed density of sorghum-stalk briquette. The results showed that, fine particle size P_3 with the highest compressed density gave the highest relaxed density for both sorghum and millet stalk briquettes. This confirms the report by Obi *et al.* (2013), Bamgboye and Bolufawi, (2008), that the relaxed density of briquette depends largely on the compressed density of the briquette.

The results for further analysis of interaction effect between particle size and starch binder, using Least Significant Difference (LSD), are shown in Table 4.34: The results of the ranking revealed gradual decrease in the mean relaxed density from 235.04 kg/m^3 to 209.14 kg/m^3 in interaction between fine particle size P_3 and binder ratios as binder ratio increased from B_1 to B_3. After which, no definite pattern was established. The least relaxed density of 181.90 kg/m^3 was recorded for the interaction between medium particle size P_2 and binder ratio B_1. Therefore, it can be concluded from these results that fine particle size P_3 and binder ratio B_1 (20% by weight of biomass) gave the best interaction effect on the relaxed density of millet-stalk briquettes produced from the developed briquetting machine.

Table 4. 34: LSD Results of Interaction Between Biomass Particle Sizes and Binder Ratios on Relaxed Density of Millet-Stalk Briquettes

Treatments	Mean Relaxed Density kg/m^3	Ranks
P_3B_1	235.04	a
P_3B_2	231.85	a
P_3B_3	209.14	b
P_1B_2	191.70	c
P_2B_3	189.74	c
P_1B_3	188.44	c
P_2B_2	185.39	c
P_1B_1	184.58	cd
P_2B_1	181.90	d

Means with the same letter are not significantly different.

Similar results were obtained by Oladeji (2012) and Sotannde *et al.* (2009). Both researchers recommended fine particles of corncobs and carbonized need wood residues respectively for production briquettes using 20% starch binder ratio by weight of biomass. This implies millet-stalk biomass blended with little starch binder is capable of producing stable briquette which can resist severe atmospheric condition and handling compared to sorghum-stalk briquette.

4.3.3 Relaxation ratio of millet-stalk briquette

The results for the effect of particle size and binder ratio on the relaxation ratio of millet-stalk briquette, using Completely Randomized Design (CRD) are as presented in Appendix

D. The Analyses of Variance (ANOVA) results for the relaxation ratio are as presented in Table 4.35.

Table 4. 35: Analysis of Variance for Relaxation Ratio of Millet-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F 5%	Tabular F 1%
Particle size (P)	2	0.23010617	0.11505309	2.32^{NS}	3.55	6.01
Binder ratio (B)	2	0.15762490	0.07881245	1.59^{NS}	3.55	6.01
P * B	4	1.23957208	0.30989302	6.24^{**}	2.93	4.58
Error	18	0.89365914	0.04964773			
Total	26	2.52096230				

Note: **significant at 1% level; *significant at 5% level; ^{NS} not significant.

The ANOVA results (Table 4.35) show that the effect of particle size and binder ratio on the relaxation ratio were not statistically significant. However, the interaction effect between the biomass and binder was significant at 1% probability level.

Further analysis of the interaction effect between particle sizes and starch binder, using Least Significant Difference (LSD), gave the results presented in Table 4.36: The results of the ranking revealed the least mean relaxation ratio value of 3.35 for the interaction between fine particle size P_3 and binder ratio B_1. Exactly the same value was obtained for the interaction between medium particle size P_2 and binder ratio B_2. Although a higher mean relaxation ratio value of 3.40 was obtained for the interaction between coarse particle size P_1 and binder ratio B_3 but has no significant difference with mean relaxation ratio 3.35. This implies that lower relaxation of millet-stalk briquettes is achievable at the three-particle considered when binder ratio is increase with increase in particle size of the biomass. The more the starch binder between maize-stalk biomass particle at higher particle sizes, the stronger the biomass particle remain sticked-together when exposed to atmospheric condition. Subsequently, no definite pattern could be observed in the result of the interaction effect.

Table 4. 36: LSD Results of Interaction Between Biomass Particle Sizes and Binder Ratios on Relaxation Ratio of Millet-Stalk Briquettes

Treatments	Mean Relaxation Ratio	Ranks
P_3B_1	3.35	a
P_2B_2	3.35	a
P_1B_3	3.40	a
P_2B_1	3.45	ab
P_3B_2	3.46	b
P_2B_3	3.55	b
P_1B_2	3.66	b
P_1B_1	3.92	c
P_3B_3	4.08	c

Means with the same letter are not significantly different.

The highest relaxation ratio of 4.08 was obtained at interaction between fine particle size P_3 and binder ratio B_3. It can be concluded from these results that interaction between fine particle size P_3 and binder ratio B_1 gave the least relaxation ratio for millet-stalk briquettes. Similarly, to the results of relaxation ratio of sorghum-stalk briquette, the relaxation ratio of millet-stalk briquette is higher than reported relaxation ratio of some agricultural residues (section 4.1.3).

4.3.4 Shattered index of millet-stalk briquette

The results for the experimental evaluation of the effect of particle size and binder ratio on the shattered index of millet-stalk briquettes produced by the constructed briquetting machine using Completely Randomized Design (CRD) are as presented in Appendix D. The Analyses of Variance (ANOVA) results for shattered index are as presented in Table 4.37. The results show that the effect of particle size on the shattered index was significant at 1% probability level. However, the effect of binder ratio was not statistically significant as well as the interaction effect between the biomass and binder.

Table 4. 37: Analysis of Variance Shattered Index of Millet-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F 5%	1%
Particle size (P)	2	12.91287568	6.45643784	7.67**	3.55	6.01
Binder ratio (B)	2	1.35365946	0.67682973	0.80NS	3.55	6.01
P * B	4	0.47363595	0.11840899	0.14NS	2.93	4.58
Error	18	15.15593637	0.84199646			
Total	26	29.89610745				

Note: **significant at 1% level; NS not significant.

Further analysis results using Least Significant Difference (LSD) are shown in Table 4.38.

Table 4. 38: LSD Result of Particle Size on Shattered Index of Millet-Stalk Briquettes

Performance parameter	Particle sizes		
	P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Mean Shattered Index (%)	98.65^{ab}	97.79^{b}	99.49^{a}

Means with the same letter are not significantly different.

The results of the ranking revealed that the mean shattered index of 99.49 % for particle size P_3 is not significantly different from the mean value of 98.65 % for particle size P_1. The mean shattered index of 98.65 % for particle size P_1 is also not significantly different from the mean value of 97.79 % for particle size P_2. But the mean shattered index of 99.49 % for particle size P_3 is significantly different from the mean value of 97.79 % for particle size P_2. It can be concluded from the results that fine particle P_3 gave the best shattered index.

The shattered index result of millet-stalk can be classified as 'high' (>0.8) as that of sorghum-stalk briquettes, according to Adapa *et al.* (2003), Tabil and Sokhansanj (1996). However, millet-stalk briquettes exhibited higher resistance to shattering than sorghum-stalk briquettes and many other briquettes produced from agricultural waste such as groundnut shell (Oyelaran *et al.*, 2014), sawdust, rice husk and groundnut shell mixture (Tembe *et al.,* 2014), water hyacinth and cow-dung mixture (Frank and Akhihiero, 2013) and sawdust (Obi *et al.,* 2013).

4.3.5 High calorific value of millet-stalk briquette

The results for the experimental evaluation of the effect of particle size and binder ratio on the calorific value of millet-stalk briquette produced by the constructed briquetting machine using Completely Randomized Design (CRD) are as presented in Appendix E. The Analyses of Variance (ANOVA) results for the calorific value are as presented in Table 4.39.

Table 4. 39: Analysis of Variance for Calorific Value of Millet-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F	
					5%	1%
Particle size (P)	2	1.220568	0.610284	7.90^{**}	3.55	6.01
Binder ratio (B)	2	0.228638	0.114319	1.48^{NS}	3.55	6.01
P * S	4	2.889016	0.722254	9.34^{**}	2.93	4.58
Error	18	1.391228	0.077290			
Total	26	5.72945000				

Note: **significant at 1% level.

The ANOVA results (Table 4.45) show that the effects of particle size of the millet-stalk biomass on the calorific value was significant at 1% probability level. The effect of binder ratio on the calorific value was not statistically significant. However, the interaction effect between the particle size and binder was significant at 1% probability level.

The effect of the particle size was further analyzed, using Least Significant Difference (LSD), and the results are as presented in Table 4.40. The results of the ranking revealed that the mean calorific value of 16.692 MJ/kg for particle size P_2 is not significantly different from the mean value of 16.686 MJ/kg for particle size P_3. However, the mean value of 16.686 MJ/kg for particle size P_3 is significantly different from 16.238 MJ/kg for particle size P_1. It can be concluded from the results that medium particle size P_2 gave the best calorific value.

Table 4. 40: LSD Result of Particle Size on Calorific Value of Millet-Stalk Briquettes

Performance parameter	Particle sizes		
	P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Mean calorific value (MJ/kg)	16.238^b	16.692^a	16.686^a

Means with the same letter are not significantly different.

The heating value of millet-stalk briquette is slightly lower than the heating value of sorghum-stalk briquettes. However, millet-stalk exhibited higher heating value than reported heating values for groundnut shell and rice husk (Kaliyan and Morey, 2009); cowpea residues and soybeans (Enweremadu *et al.,* 2004) and Mango seed cover (Katimbo *et al.,* 2014).

Further analysis of interaction effect particle size and starch binder ratios, using Least Significant Difference (LSD), gave results shown in Table 4.41. No definite pattern was established in the interaction effect. But it could be deduced from the result of the ranking that interaction between fine and medium particle sizes (P_3 and P_2 respectively) of millet-stalk biomass and binder ratio B_2 gave the best calorific value of millet-stalk briquette. While interaction between coarse particle size P_1 and binder ratio B_2 gave the least calorific value of 15.544 MJ/kg. Similar result was obtained for the high calorific value of sorghum-stalk briquette. Therefore, briquettes produced from fine particle size P_3 blended with low binder ratio can be concluded to be a good and efficient high energy giving fuel.

Table 4. 41: LSD Results of Interaction Between Biomass and Binder on Sorghum-Stalk Briquettes

Treatments	Mean calorific value (MJ/kg)	Ranks
P_3B_2	16.898	a
P_2B_2	16.842	a
P_2B_3	16.813	a
P_1B_1	16.782	a
P_3B_1	16.756	a
P_2B_1	16.422	b
P_3B_3	16.405	b
P_1B_3	16.389	b
P_1B_2	15.544	c

Means with the same letter are not significantly different

4.3.6 Ash content of millet-stalk briquette

The results for the experimental evaluation of the effect of particle size and binder ratio on the ash content, using Completely Randomized Design (CRD) are as presented in Appendix E. The Analyses of Variance (ANOVA) results for the ash content are as presented in Table 4.42.

Table 4. 42: Analysis of Variance for Ash Content of Millet-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F 5%	Tabular F 1%
Particle size (P)	2	0.54	0.27	6.75^{**}	3.55	6.01
Binder ratio (B)	2	7.98	3.99	99.75^{**}	3.55	6.01
P * B	4	1.20	0.30	7.50^{**}	2.93	4.58
Error	18	0.72	0.04			
Total	26	10.44				

Note: **significant at 1% level.

The results show that the effect of particle size and binder ratio on ash content were significant at 1% probability level. And the interaction effect between the biomass and binder was also significant at 1% probability level.

Further analysis results of the effect of the particle size, using Least Significant Difference (LSD), are shown in Table 4.43.

Table 4. 43: LSD Result of Particle Size on Ash Content Millet-Stalk Briquettes

Performance parameter	Particle sizes		
	P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Ash content (%)	3.1^b	2.9^a	2.9^a

Means with the same letter are not significantly different.

The results of the ranking revealed that the mean ash content 2.9 % for particle sizes P_2 and P_3 is significantly different from the mean value of 3.1 % for particle size P_1. It can be concluded from the results that the medium and fine particle sizes P_2 and P_3 gave the lowest ash content for millet-stalk briquette. Similar result was obtained for sorghum-stalk briquette but the ash content of millet-stalk briquette was observed to be slightly higher than ash content of sorghum-stalk briquette. However, millet-stalk briquette ash content is also lower to the reported ash content for sawdust briquette (Obi *et al.,* 2013), cassava peel and yam peel briquette respectively (Oladeji and Oyetunji, 2013), sawdust, corncob and prosopis africana charcoal (Tokan *et al.,* 2014). This implies that the millet-stalk briquettes have low non-combustible component and has the potential to burn with less smoke and high heating values making the millet-stalk briquettes suitable for household cooking.

Further analysis results of the effect of binder ratio, using Least Significant Difference (LSD), are shown in Table 4.44. The results of the ranking revealed that the mean ash content 2.2 % for binder ratio B_1 is significantly different from the mean value of 3.1 % for binder ratio B_3.

Table 4. 44: LSD Result of Binder Ratio on Ash Content of Millet-Stalk Briquettes

Performance parameter	Binder ratios		
	B_1 (20%)	B_2 (30%)	B_3 (40%)
Ash content (%)	2.2^{a}	3.5^{c}	3.1^{b}

It is also evident from the results that the mean value of 3.1 % for binder ratio B_3 is significantly different from the mean value of 3.5 % for binder ratio B_2. It can be concluded from the results that the binder ratio B_1 gave the lowest ash content. Similar result was obtained for sorghum-stalk briquette.

Further analysis results of interaction effect between particle size and starch binder ratios, using Least Significant Difference (LSD), are shown in Table 4.45:

Table 4. 45: LSD Results of Interaction Between Biomass Particle Sizes and Binder Ratios on Ash Content of Millet-Stalk Briquettes

Treatments	Ash Content (%)	**Ranks**
P_2B_1	2.1	a
P_3B_1	2.2	a
P_1B_1	2.4	b
P_2B_3	2.7	c
P_3B_3	3.1	d
P_3B_3	3.3	d
P_1B_2	3.5	e
P_1B_1	3.6	e
P_2B_2	3.8	f

Means with the same letter are not significantly different.

The results showed that the interaction between particle size P_2 and binder ratio B_1 gave the least ash content of 2.1 %, although not significantly different from the mean ash content of 2.2 % for interaction between particle size P_3 and binder ratio B_1. Subsequently, the interaction effect between particle size and binder gave no definite pattern. The highest ash content of 3.8 % was obtained for interaction between medium particle size P_2 and the binder ratio B_2. Although the ash content of millet-stalk briquette is higher than the ash content of sorghum-stalk briquette, the ash content of millet-stalk briquette is lower compared to the recommended ash content of 4% (Grover and Mishra, 1996).

4.3.7 Volatile matter of millet-stalk briquette

The results for the effect of particle size and binder ratio on the volatile matter of millet-stalk briquette produced by the constructed briquetting machine, using Completely Randomized Design (CRD) are as presented in Appendix E. The Analyses of Variance (ANOVA) results for the volatile matter are as presented in Table 4.46. The results show that the effect of particle size and binder ratio on volatile matter were significant at 1% probability level. And the interaction effect between the biomass and binder was also significant at 1% probability level.

Table 4. 46: Analysis of Variance for Volatile Matter of Millet-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F 5%	Tabular F 1%
Particle size (P)	2	43.24666667	21.62333333	78.79**	3.55	6.01
Binder ratio (B)	2	10.16666667	5.08333333	18.52**	3.55	6.01
P * B	4	19.73333333	4.93333333	17.98**	2.93	4.58
Error	18	4.94000000	0.27444444			
Total	26	78.08666667				

Note: **significant at 1% level.

Further analysis results of the effect of particle size, using Least Significant Difference (LSD), are shown in Table 4.47. The results of the ranking revealed that the mean volatile matter of 26.20 % for particle size P_2 is significantly different from the mean value of 24.67 % for particle size P_1. It is also evident from the results that the mean volatile matter of 24.67 % for particle size P_1 is significantly different from the mean value of 23.10 % for particle size P_3. It is can be concluded from these results that the medium particle size P_2 gave the best volatile matter.

Table 4. 47: LSD Result of Particle Size Volatile Matter of Millet-Stalk Briquettes

Performance parameter	Particle sizes		
	P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Volatile matter (%)	24.67^b	26.20^a	23.10^c

Similarly, to the volatile matter content of sorghum-stalk briquettes, the volatile matter observed for millet stalk briquette is lower when compared with volatile matter reported for briquettes produced from many other agricultural wastes. Which implies that millet-stalk briquette may require starter for ignition but once ignited it will burn smoothly with clean flame giving off little or no smoke (Sotannde *et al.*, 2009).

Further analysis results of the effect of binder ratio, using Least Significant Difference (LSD), are shown in Table 4.54.

Table 4. 48: LSD Result of Binder Ratio on Volatile Matter of Millet-Stalk Briquettes

Performance indicator	Binder ratios		
	B_1 (20%)	B_2 (30%)	B_3 (40%)
Volatile matter (%)	$24.60^{\mathbf{b}}$	25.43^a	23.93^c

The results of the ranking revealed that the mean volatile matter of 25.43 % for binder ratio B_2 is significantly different from the mean value of 24.60 % for binder ratio B_1. It is also evident from the results that the mean volatile matter of 24.60 % for particle size B_1 is significantly different from the mean value of 23.93 % for binder ratio B_3. It is can be concluded from these results the binder ratio B_2 gave the best volatile matter.

Further analysis of the interaction effect between particle size and starch binder ratios, using Least Significant Difference (LSD), yielded the results presented in Table 4.49:

Table 4. 49: LSD Results of Interaction Between Biomass and Binder on Sorghum-Stalk Briquettes

Treatments	Volatile matter (%)	**Ranks**
P_2B_2	27.0	a
P_2B_3	26.6	ab
P_1B_1	26.1	b
P_1B_2	25.2	c
P_2B_1	25.0	c
P_3B_2	24.1	d
P_3B_1	22.7	e
P_1B_3	22.7	e
P_3B_3	22.5	e

Means with the same letter are not significantly different.

It could be observed from the results (Table 4.49) that interaction between medium and coarse particle sizes (P_2 and P_3 respectively) with binder ratios B_2 and B_1 were better ranked than interaction between fine particle size and binder ratios. Which indicates easy ignition, fast burning and proportionate increase in flame length for briquettes produced from medium and coarse particle sizes of millet-stalk biomass. Hence, the results of the ranking revealed interaction effect between particle size P_2 and binder ratio B_2 gave the best interaction effect on the volatile matter of millet-stalk briquettes produced from the developed briquetting machine.

4.3.8 Fixed carbon of millet-stalk briquette

The results for the effect of particle size and binder ratio on the fixed carbon of millet-stalk briquette produced by the constructed briquetting machine, using Completely Randomized Design (CRD), are as presented in Appendix E. The Analyses of Variance (ANOVA) results for the fixed carbon are as presented in Table 4.50. The results show that the effect of particle size and binder ratio on volatile matter were significant at 1% probability level. And the interaction effect between the biomass and binder was also significant at 1% probability level.

Table 4. 50: Analysis of Variance for Fixed Carbon of Millet-Stalk Briquettes

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	Computed F	Tabular F 5%	Tabular F 1%
Particle size (P)	2	43.84666667	21.92333333	64.27**	3.55	6.01
Binder ratio (B)	2	24.64666667	12.32333333	36.13**	3.55	6.01
P * B	4	16.75333333	4.18833333	12.28**	2.93	4.58
Error	18	6.14000000	0.34111111			
Total	26	91.38666667				

Note: **significant at 1% level.

The results of further analysis of the effect of particle size, using Least Significant Difference (LSD), are shown in Table 4.57.

Table 4. 51: LSD Result of Particle Size Fixed Carbon of Millet-Stalk Briquettes

Performance indicator	Particle sizes		
	P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Fixed carbon (%)	72.17^b	70.93^c	74.03^a

The results of the ranking revealed that the mean fixed carbon of 74.03 % for particle size P_3 is significantly different from the mean value of 72.17 % for particle size P_1. It is also evident from the results that the mean volatile matter of 72.17 % for particle size P_1 is significantly different from the mean value of 70.93 % for particle size P_2. It can be concluded that particle size P3 gave best performance in terms of fixed carbon.

The percentage fixed carbon of the millet-stalk briquettes is slightly lower to fixed carbon values of sorghum-stalk briquette, but higher than fixed carbon of mango cover seed, saw dust, yam peel and cassava peel reported by Katimbo *et al.* (2014), (Obi *et al.*, 2013), and Oladeji and Oyetunji (2013), respectively.

Further analysis results of the effect of binder ratio, using Least Significant Difference (LSD), are shown in Table 4.52.

Table 4. 52: LSD Result of Binder Ratio on Fixed Carbon of Millet-Stalk Briquettes

Performance indicator	Binder ratios		
	B_1 (20%)	B_2 (30%)	B_3 (40%)
Fixed carbon (%)	73.17^{a}	71.03^{b}	72.93^{a}

Means with the same letter are not significantly different.

The results of the ranking revealed that the mean fixed carbon of 73.17 % for binder ratio B_1 is not significantly different from the mean value of 72.93 % for binder ratio B_3. However, the mean fixed carbon of 72.93 % for binder ratio B_3 is significantly different from the mean value of 71.03 % for binder ratio B_2. It is can be concluded from these results the binder ratio B_1 and B_3 gave better performance in terms of fixed carbon.

Further analysis results of interaction effect between sorghum-stalk biomass particle sizes and starch binder ratios using Least Significant Difference (LSD), are shown in Table 4.59. From the result, no definite pattern was established in the interaction effect on fixed carbon content of millet-stalk briquette, but it could be seen that interaction fine particle size P_3 and binder B_1 with fixed carbon of 75.1 % is significantly different from fixed carbon of 74.4% for interaction between coarse particle size P_1 and binder ratio B_3 and subsequent interactions. Although, higher starch binder ratio was expected to increase the fixed carbon content (Solid fuel) of briquettes (Katimbo *et al.*, 2014).

Table 4. 53: LSD Results of Interaction Between Biomass Particle Sizes and Binder Ratios on Fixed Carbon of Sorghum-Stalk Briquettes

Treatments	Mean Fixed Carbon (%)	**Ranks**
P_3B_1	75.1	a
P_3B_3	74.4	b
P_1B_3	73.7	c
P_2B_1	72.9	d
P_3B_2	72.6	d
P_1B_1	71.5	e
P_1B_2	71.3	ef
P_2B_3	70.7	f
P_2B_2	69.2	g

Means with the same letter are not significantly different.

The interaction effect between particle size P_3 and binder ratio B_1 however, gave the best interaction effect on the fixed carbon of millet-stalk briquettes produced from the developed briquetting machine.

4.3.9 Thermal fuel efficiency of millet stalk briquette

The effect of particle size and binder ratio on the thermal efficiency of millet-stalk briquette is as shown in Fig. 4.2. The experimental result is as presented in Appendix F.

The results (Fig. 4.1) show that the mean thermal efficiency for particle sizes P_2 and P_3, having similar trend, deceases from 24.03% and 19.97% respectively to 23.46% and 18.47% respectively as binder ratio increases from B_1 to B_2. Then, the mean thermal efficiency for particle sizes P_1 and P_2 increase from 23.46% and 18.47% respectively to 28.15% and 24.47% respectively with further increase in binder ratio from B_2 to B_3.

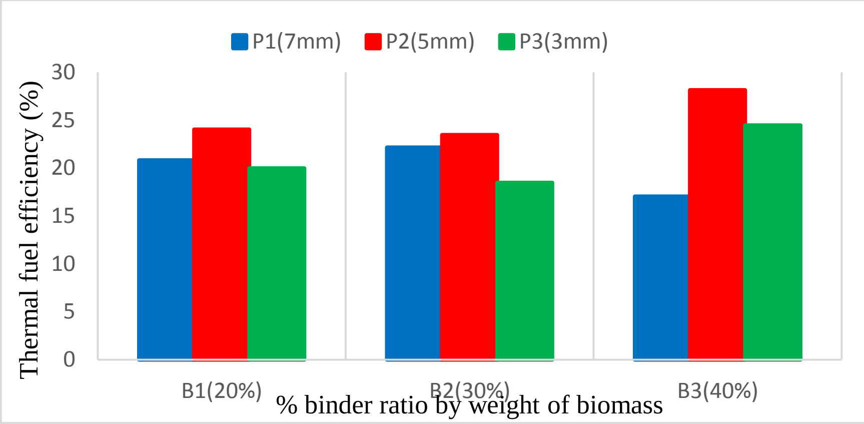


Fig. 4. 2: Thermal Fuel Efficiency of Millet-Stalk Briquette

For particle size P_1, the mean thermal efficiency increases from 20.81% to 22.14% as binder ratio increases from B_1 to B_2 and then decrease from 22.14% to 17.05% with further increase in binder ratio from B_2 to B_3. The optimal thermal fuel efficiency of 28.15% was obtained at biomass: binder ratio of P_2:B_3. The thermal fuel efficiency of millet-stalk compared well with that of sorghum-stalk briquette and many other agricultural wastes.

4.4 Machine Output Capacity

The result of the machine output capacity was estimated based on the mass of the ejected briquettes and the average time taken to produce briquette.

4.4.1 Mass of Ejected Briquettes

The results for the experimental evaluation of the effect of particle size and binder ratio on the mass of ejected sorghum-stalk and millet-stalk briquette produced by the constructed briquetting machine using Completely Randomized Design (CRD) are as presented in Appendix C1. The Analyses of Variance (ANOVA) results for the ejected mass of sorghum and millet stalk briquette are as presented in Table 4.55. The ANOVA result shows that particle size has a significant effect at 1% level of probability on the ejected mass of sorghum stalk briquette and significant at 5% level of probability on the ejected mass of millet stalk briquette.

Table 4. 54: Analysis of Variance for Results of Ejected Mass of Briquettes

Factors	Mass of Sorghum-Stalk Briquette (kg)	Mass of Millet-Stalk Briquette (kg)
Particle size (P)	0.0002^{**}	0.0230^{*}
Binder ratio (B)	0.7277^{NS}	0.0554^{NS}
P*B	0.0033^{**}	0.0110^{*}

Note: **significant at 1% level; *significant at 5% level; ^{NS} not significant

However, effect of binder ratio on the ejected mass of sorghum and millet stalk briquettes was not statistically significant. While the interaction effect between particle size and binder ratio has a significant effect at 1% level of probability on the ejected mass of sorghum stalk briquette and significant at 5% level of probability on the ejected mass of millet stalk briquette.

The results of further analysis of the effect of particle size, using Least Significant Difference (LSD), are shown in Table 4.57. The results of the ranking revealed that the mean mass of sorghum-stalk briquette of 222.18 kg for particle size P_3 is not significantly different from the mean value of 222.07 kg for particle size P_1 but significantly different from the mean value of 204.64 kg for particle size P_2.

Table 4. 55: LSD Result of Particle Size on Compressed Density of Sorghum-Stalk Briquettes

Type of Briquette	Particle Size (P)		
	P_1 (7mm)	P_2 (5mm)	P_3 (3mm)
Mass of Sorghum-Stalk Briquette (kg)	222.07^{a}	204.64^{b}	222.18^{a}
Mass of Millet-Stalk Briquette (kg)	223.68^{b}	241.30^{ab}	251.90^{a}

Means with the same letter in each row are not significantly different.

Likewise, the mean mass of millet-stalk briquette of 251.90 kg for particle size P_3 is not significantly different from the mean value of 241.30 kg for particle size P_2 but significantly different from the mean value of 223.68 kg for particle size P_1. These results confirm that the smaller the particle size, the lesser will be the porosity and the higher will be the density (Saptoadi, 2008).

4.4.2 Briquette Production time

The result of the machine production time components is presented in Table 4.56

Table 4. 56: Average Briquetting Time

Production Time Components	**Mean Time (seconds)**
Biomass Loading Time	12
Biomass Compaction Time	58
Briquettes Residence Time (10mins)	600
Briquettes Ejection Time	23
TOTAL	**693**

An average time of 693 seconds which is equivalent to 11.53minutes was used per production of four briquettes using the developed biomass briquetting machine.

4.4.3 Output Capacity of the Machine

Thus, the result of the machine output capacity based on the highest output mass and average production time is as presented in Table 4.57

Table 4. 57: Output Capacity of the Developed Biomass Briquetting Machine

	Sorghum-Stalk Briquette (kg/hr)	Millet-Stalk Briquette (kg/hr)
Machine output capacity (kg/hr.)	4.64	5.26

The output capacity of the developed hollow briquette making machine is lower compared to the briquetting capacity of the machine developed by Sani (2008), Nordiana (2009) and Obi *et al.* (2013). This is because the number of mould and subsequently the number of briquettes produced per time by the developed hollow briquette making machine, which is four is small compared to that of Sani (2008), Nordiana (2009) and Obi *et al.* (2013) with 10 moulds, 9 moulds and 36 moulds respectively. But the developed hollow briquette making machine has an advantage of simplicity, probability and low cost compared to existing local briquetting machines.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The construction of the hydraulic piston biomass briquetting machine was successful. Also, the production of briquette with the constructed briquetting machine was successful using sorghum-stalk and millet-stalk biomass, at the three particle size levels: P_1 (7mm), P_2 (5mm) and P_3 (3mm) and three starch binder ratios: B_1 (20%), B_2 (30%) and B_3 (40%) by weight of biomass. For the three particle sizes used, particle size P_3 gave the highest compressed density, relaxed density and shattered index of 727.67 kg/m^3, 222.35 kg/m^3 and 89.57 % respectively for sorghum-stalk briquettes and 814.41 kg/m^3, 225.34 kg/m^3 and 99.49 % respectively for millet-stalk briquettes. And for the three levels of starch binder ratio used, B_2 gave the best compressed density and relaxed density for sorghum-stalk briquettes while the relaxation ratio and shattered index of sorghum-stalk briquette improved with further increase in binder ratio to B_3. Starch binder gave non-significance difference in the mean values of the physical properties of millet-stalk briquette. It can therefore be concluded based on physical properties results of the briquettes, the combination of particle size P_3 and starch binder ratio B_2 gave the best results for sorghum-stalk briquettes and combination of particle size P_3 and starch binder ratio B_1 have the best results for millet-stalk briquettes.

For the thermal characteristics of sorghum-stalk, particle size P_3 gave the highest calorific value, volatile matter and thermal efficiency of 17.726 MJ/kg, 24.60 % and 24.66 % respectively, and the least ash content of 1.6 %. The thermal properties of sorghum-stalk briquette were found to improve with decrease in binder ratio. The fixed carbon of sorghum-stalk briquette however, was found to increase with increase in particle size and binder ratio. While for Millet-stalk briquette, particle size P_2 gave the highest calorific value, volatile matter and thermal efficiency of 16.692 MJ/kg, 26.20 % and 28.15 % respectively, and the least ash content of 2.9 %. Particle size P_1 however, gave the highest fixed carbon of 74.03 %. Similarly, the least binder ratio B_1, gave the optimum thermal properties of millet-stalk briquettes. Therefore, it can be concluded based on thermal properties of the briquettes, the combination of particle size P_3 and starch binder ratio B_1 gave the best results for sorghum-stalk briquettes and combination of particle size P_2 and starch binder ratio B_1 gave the best results for millet-stalk briquettes.

Particle size P_1 (7mm) was observed to exhibit the worst results for both the physical and thermal parameters evaluated. It can be concluded that the developed briquetting machine is not suitable for briquetting large particle size.

The machine efficiency and output capacity was found to vary with type of biomass and increase with decrease in biomass particle size. For sorghum-stalk briquette, at particle size P_3, the machine efficiency and output capacity was found to be 60.6 % and 4.64 kg/hr respectively while for millet-stalk briquette, the machine efficiency and output capacity was found to be 67.9 % and 5.26 kg/hr respectively, at particle size P_3.

5.2 Recommendations

The following are recommended for production of sorghum and millet stalk briquettes using the developed briquetting machine and for further works:

1. The combination of fine particle size P_1 (3mm) and starch binder ratio B_2 is recommended for briquetting of sorghum-stalk biomass materials while a combination of particle size P_1 (3mm) and starch binder ratio B_1 is recommended for briquetting of millet-stalk biomass materials using the developed briquetting machine based on the physical characteristics of the briquette.

2. However, based on the thermal properties of the briquettes produced, a combination of fine particle size P_1 (3mm) and starch binder ratio B_1 is recommended for briquetting of sorghum-stalk biomass materials and a combination of medium particle size P_2 (5mm) and starch binder ratio B_1 is recommended for briquetting of millet-stalk biomass materials.
3. Further study is recommended on improving the efficiency and output capacity of the biomass briquetting machine.
4. Also, incorporating a biomass chopper for size reduction and mixer for blending biomass and binder is recommended for further studies.
5. Machine automation can be considered for the purpose of uniformity in pressure application during compaction and in order to increase ease of operation of the machine and reducing drudgery.

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APPENDICES

Appendix A: Experimental Values of the Physical Properties of Sorghum-Stalk Briquettes

Treatments	Compressed density (kg/m^3)	Mean Compressed density (kg/m^3)	Relaxed density (kg/m^3)	Mean Relaxed density (kg/m^3)	Relaxation ratio	Mean Relaxation ratio	Shattered index (%)	Mean Shattered index (%)	Axial expansion (%)	Mean Axial expansion (%)
$P_1B_1R_1$	704.26		178.54		3.95		60.79		6.42	
$P_1B_1R_2$	704.43	680.95	180.61	180.47	3.90	3.77	80.78	68.71	6.51	6.71
$P_1B_1R_3$	634.16		182.26		3.48		64.58		7.19	
$P_1B_2R_1$	624.51		195.21		3.20		75.04		6.75	
$P_1B_2R_2$	626.49	637.63	179.80	183.69	3.48	3.48	78.34	76.87	5.37	5.90
$P_1B_2R_3$	661.87		176.06		3.76		77.26		5.58	
$P_1B_3R_1$	694.88		200.00		3.47		94.56		6.46	
$P_1B_3R_2$	623.58	637.53	177.46	185.69	3.51	3.43	74.82	81.61	4.52	5.30
$P_1B_3R_3$	594.13		179.60		3.31		85.21		4.93	
$P_2B_1R_1$	616.10		161.82		3.81		71.47		5.48	
$P_2B_1R_2$	572.13	589.20	146.29	152.75	3.91	3.86	82.20	76.97	6.02	5.64
$P_2B_1R_3$	579.38		150.14		3.86		77.25		5.41	
$P_2B_2R_1$	667.00		186.27		3.58		78.27		5.61	
$P_2B_2R_2$	648.35	653.46	216.17	197.36	2.30	3.33	84.91	81.47	5.01	5.26
$P_2B_2R_3$	645.02		189.65		3.40		81.24		5.17	
$P_2B_3R_1$	580.25		167.89		3.46		79.15		4.64	
$P_2B_3R_2$	587.64	579.11	183.74	180.73	3.20	3.21	88.73	83.67	4.31	4.53
$P_2B_3R_3$	569.44		190.55		2.99		83.14		4.64	
$P_3B_1R_1$	722.56		212.51		3.40		82.75		3.81	
$P_3B_1R_2$	709.73	725.49	225.29	212.59	3.15	3.42	91.79	87.62	4.64	4.68
$P_3B_1R_3$	744.17		199.97		3.72		88.30		5.6	
$P_3B_2R_1$	789.68		228.06		3.46		86.01		4.28	
$P_3B_2R_2$	750.23	752.09	227.17	225.52	3.30	3.33	92.23	89.01	4.44	4.26
$P_3B_2R_3$	716.367		221.32		3.24		88.80		4.06	
$P_3B_3R_1$	737.05		228.12		3.23		91.88		4.92	
$P_3B_3R_2$	701.72	705.42	231.36	228.92	3.03	3.08	92.36	92.08	3.14	4.10
$P_3B_3R_3$	677.49		227.29		2.98		91.99		4.23	

Appendix B: Experimental Values of the Thermal Properties of Sorghum-Stalk Briquettes

Treatments	Ash content (%)	Mean ash content (%)	Volatile matter (%)	Mean Volatile matter (%)	Fixed Carbon (%)	Mean Fixed carbon (%)	Calorific value (MJ/kg)	Mean Calorific value (MJ/kg)
$P_1B_1R_1$	1.8		22.1		76.1		17.00	
$P_1B_1R_2$	2.2	2.1	21.5	21.8	76.3	76.1	16.64	16.883
$P_1B_1R_3$	2.3		21.8		75.9		17.01	
$P_1B_2R_1$	2.1		23.8		74.1		16.52	
$P_1B_2R_2$	2.4	2.2	22.1	23.1	75.5	74.7	17.25	16.997
$P_1B_2R_3$	2.1		23.4		74.5		17.22	
$P_1B_3R_1$	3.8		17.5		78.7		14.65	
$P_1B_3R_2$	3.4	3.6	16.5	17.4	80.1	79.0	15.03	14.779
$P_1B_3R_3$	3.6		18.2		78.2		14.66	
$P_2B_1R_1$	2.1		23.8		74.1		17.26	
$P_2B_1R_2$	2.3	2.3	22.7	23.5	75.0	74.2	17.10	17.128
$P_2B_1R_3$	2.5		24.0		73.5		17.02	
$P_2B_2R_1$	2.3		22.4		75.3		16.30	
$P_2B_2R_2$	2.8	2.5	22.0	22.2	75.2	75.3	16.40	16.338
$P_2B_2R_3$	2.4		22.2		75.4		16.31	
$P_2B_3R_1$	2.1		19.1		78.8		15.63	
$P_2B_3R_2$	1.9	2.1	18.7	18.8	79.4	79.1	15.61	15.593
$P_2B_3R_3$	2.3		18.6		79.1		15.54	
$P_3B_1R_1$	1.2		26.2		72.6		19.24	
$P_3B_1R_2$	1.4	1.3	26.3	26.2	72.3	72.5	19.99	19.165
$P_3B_1R_3$	1.3		26.1		72.6		18.26	
$P_3B_2R_1$	1.7		22.0		76.3		18.20	
$P_3B_2R_2$	1.6	1.7	22.2	22.1	76.2	76.2	16.80	17.280
$P_3B_2R_3$	1.8		22.1		76.1		16.84	
$P_3B_3R_1$	1.6		24.5		73.9		16.65	
$P_3B_3R_2$	2.1	1.8	25.5	25.5	72.4	72.7	16.75	16.734
$P_3B_3R_3$	1.7		26.5		71.8		16.80	

Appendix C: Thermal Fuel Efficiency (TFE) of Sorghum-Stalk Briquettes

Treatments	Mean m_w (kg)	Mean m_e (kg)	Mean m_f (kg)	T_1 (K)	Mean T_2 (K)	c_p (kJ/kgK)	L (kJ/kg)	Mean E_f (kJ/kg)	Mean TFE (%)
P_3B_3	0.9787	0.0857	0.1242	303	370	4.2	2260	16734	22.57
P_3B_2	0.9794	0.1016	0.1242	303	371	4.2	2260	17280	24.66
P_3B_1	0.9788	0.0969	0.1241	303	371	4.2	2260	19165	20.96
P_2B_3	0.9787	0.0621	0.124	303	371	4.2	2260	15593	21.71
P_2B_2	0.9786	0.054	0.1241	303	357	4.2	2260	16338	16.97
P_2B_1	0.9788	0.0396	0.1038	303	364	4.2	2260	17128	19.14
P_1B_3	0.9787	0.0746	0.1241	303	372	4.2	2260	14779	23.73
P_1B_2	0.9789	0.0718	0.1243	303	373	4.2	2260	16997	21.30
P_1B_1	0.9787	0.0708	0.1241	303	373	4.2	2260	16883	21.37

Appendix D: Experimental Values of the Physical Properties of Millet-Stalk Briquettes

Treatments	Compressed density (kg/m^3)	Mean Compressed density (kg/m^3)	Relaxed density (kg/m^3)	Mean Relaxed density (kg/m^3)	Relaxation ratio	Mean Relaxation ratio	Shattered index (%)	Mean Shattered index (%)	Axial expansion (%)	Mean Axial expansion (%)
$P_1B_1R_1$	651.42		177.34		3.67		97.22		3.92	
$P_1B_1R_2$	792.84	724.58	191.32	184.58	4.14	3.92	98.64	98.37	5.98	1.03
$P_1B_1R_3$	729.50		185.09		3.94		99.25		4.78	
$P_1B_2R_1$	703.61		186.81		3.77		99.44		5.43	
$P_1B_2R_2$	685.37	700.46	192.85	191.70	3.55	3.66	99.42	98.72	3.09	1.80
$P_1B_2R_3$	712.39		195.43		3.65		97.29		1.89	
$P_1B_3R_1$	646.59		203.48		3.18		99.03		2.78	
$P_1B_3R_2$	626.68	638.19	182.59	188.44	3.43	3.40	97.65	98.85	3.58	0.94
$P_1B_3R_3$	641.29		179.26		3.58		99.86		1.70	
$P_2B_1R_1$	612.98		176.88		3.47		97.12		4.02	
$P_2B_1R_2$	639.27	627.98	188.15	181.90	3.40	3.45	98.35	97.48	3.86	0.52
$P_2B_1R_3$	631.69		180.68		3.50		96.98		3.05	
$P_2B_2R_1$	650.65		182.29		3.57		97.80		3.92	
$P_2B_2R_2$	628.01	620.05	193.66	185.39	3.24	3.35	96.20	97.56	2.35	0.86
$P_2B_2R_3$	581.50		180.21		3.23		98.68		3.76	
$P_2B_3R_1$	693.63		185.65		3.74		99.57		2.35	
$P_2B_3R_2$	640.76	672.68	184.86	189.74	3.47	3.55	97.88	98.34	3.05	0.46
$P_2B_3R_3$	683.63		198.70		3.44		97.56		2.18	
$P_3B_1R_1$	804.23		241.22		3.33		99.73		3.36	
$P_3B_1R_2$	787.58	787.62	232.50	235.04	3.39	3.35	99.26	99.38	3.55	0.10
$P_3B_1R_3$	771.06		231.40		3.33		99.14		3.40	
$P_3B_2R_1$	799.73		240.45		3.33		99.87		1.53	
$P_3B_2R_2$	803.22	801.59	226.78	231.05	3.54	3.46	99.28	99.44	2.16	0.64
$P_3B_2R_3$	801.82		228.31		3.51		99.16		2.80	
$P_3B_3R_1$	726.57		200.84		3.62		100.00		2.47	
$P_3B_3R_2$	871.62	854.01	218.07	209.14	4.00	4.07	99.75	99.65	1.27	0.74
$P_3B_3R_3$	963.84		208.51		4.62		99.20		2.61	

Appendix E: Experimental Values of the Thermal Properties of Millet-Stalk Briquettes

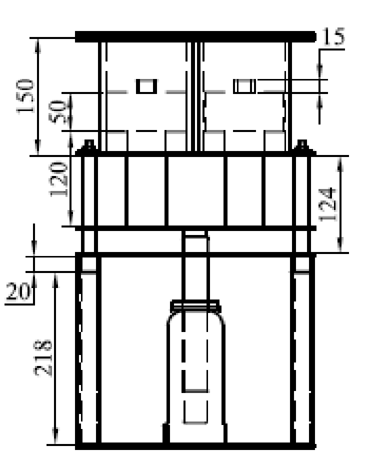
Treatments	Ash content (%)	Mean Ash content (%)	Volatile matter (%)	Mean Volatile matter (%)	Fixed Carbon (%)	Mean Fixed Carbon (%)	Calorific value (MJ/kg)	Mean Calorific value (MJ/kg)
$P_1B_1R_1$	2.3		26.1		71.6		17.08	
$P_1B_1R_2$	2.4	2.4	26.0	26.1	71.6	71.5	16.48	16.782
$P_1B_1R_3$	2.5		26.2		71.3		16.78	
$P_1B_2R_1$	3.4		25.1		71.5		15.65	
$P_1B_2R_2$	3.6	3.5	25.4	25.2	71.0	71.3	15.32	15.544
$P_1B_2R_3$	3.5		25.1		71.4		15.67	
$P_1B_3R_1$	3.7		22.8		73.5		16.52	
$P_1B_3R_2$	3.8	3.6	22.1	22.7	74.1	73.7	16.17	16.389
$P_1B_3R_3$	3.3		23.2		73.5		16.48	
$P_2B_1R_1$	2.1		25.3		72.6		16.04	
$P_2B_1R_2$	2.2	2.1	24.6	25.0	73.2	72.9	16.52	16.422
$P_2B_1R_3$	2.0		25.1		72.9		16.70	
$P_2B_2R_1$	3.8		27.1		69.1		16.73	
$P_2B_2R_2$	3.7	3.8	27.3	27.0	69.0	69.2	17.31	16.842
$P_2B_2R_3$	3.9		26.6		69.5		16.48	
$P_2B_3R_1$	2.5		26.5		71.0		16.43	
$P_2B_3R_2$	3.0	2.7	27.5	26.6	69.5	70.7	16.80	16.813
$P_2B_3R_3$	2.6		25.8		71.6		17.21	
$P_3B_1R_1$	2.3		23.2		74.5		17.00	
$P_3B_1R_2$	2.1	2.2	22.6	22.7	75.3	75.1	16.51	16.756
$P_3B_1R_3$	2.2		22.3		75.5		16.76	
$P_3B_2R_1$	3.7		24.6		71.7		16.90	
$P_3B_2R_2$	2.9	3.3	24.1	24.1	73.0	72.6	17.00	16.898
$P_3B_2R_3$	3.3		23.6		73.1		16.80	
$P_3B_3R_1$	3.0		23.2		73.8		16.31	
$P_3B_3R_2$	3.1	3.1	21.6	22.5	75.3	74.4	16.41	16.405
$P_3B_3R_3$	3.2		22.7		74.1		16.50	

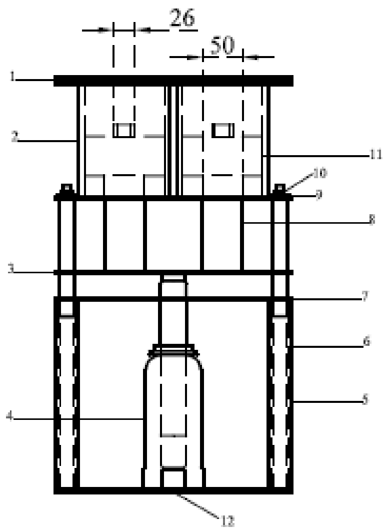
Appendix F: Thermal Fuel Efficiency (TFE) of Millet-Stalk Briquettes

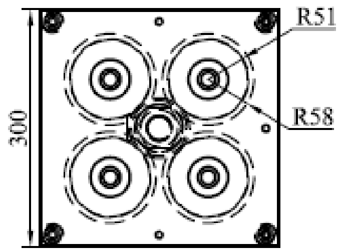
Treatments	Mean m_w (kg)	Mean m_e (kg)	Mean m_f (kg)	T_1 (K)	Mean T_2 (K)	c_p (kJ/kgK)	L (kJ/kg)	Mean E_f (kJ/kg)	Mean TFE (%)
P_3B_3	0.9787	0.1239	0.124	303	356	4.2	2260	16405	24.47
P_3B_2	0.9787	0.0512	0.124	303	369	4.2	2260	16898	18.47
P_3B_1	0.9787	0.0587	0.1244	303	372	4.2	2260	16756	19.97
P_2B_3	0.9787	0.0566	0.0874	303	372.5	4.2	2260	16813	28.15
P_2B_2	0.9787	0.0898	0.1242	303	373	4.2	2260	16842	23.46
P_2B_1	0.9787	0.091	0.124	303	372	4.2	2260	16422	24.03
P_1B_3	0.9787	0.0369	0.124	303	367	4.2	2260	16389	17.05
P_1B_2	0.9786	0.0615	0.124	303	373	4.2	2260	15544	22.14
P_1B_1	0.9789	0.0661	0.124	303	372	4.2	2260	16782	20.81

Appendix G: Mass of Ejected Sorghum-Stalk and Millet-Stalk Briquettes

Treatments	Mass of Ejected Sorghum-Stalk Briquette (kg)	Mass of Ejected Millet-Stalk Briquette (kg)
$P_1B_1R_1$	215.9	236.9
$P_1B_1R_2$	227.8	249.1
$P_1B_1R_3$	223.0	274.5
$P_1B_2R_1$	225.2	243.1
$P_1B_2R_2$	208.5	224.1
$P_1B_2R_3$	218.4	239.7
$P_1B_3R_1$	239.1	236.4
$P_1B_3R_2$	230.6	225.3
$P_1B_3R_3$	219.1	242.6
$P_2B_1R_1$	204.0	200.6
$P_2B_1R_2$	184.0	227.1
$P_2B_1R_3$	197.0	241.4
$P_2B_2R_1$	204.4	223.4
$P_2B_2R_2$	208.9	224.5
$P_2B_2R_3$	219.9	206.9
$P_2B_3R_1$	211.9	238.4
$P_2B_3R_2$	211.9	223.4
$P_2B_3R_3$	199.8	227.4
$P_3B_1R_1$	227.0	224.3
$P_3B_1R_2$	223.5	220.5
$P_3B_1R_3$	245.4	216.8
$P_3B_2R_1$	227.0	245.1
$P_3B_2R_2$	228.4	236.3
$P_3B_2R_3$	223.7	240.6
$P_3B_3R_1$	211.7	239.7
$P_3B_3R_2$	202.7	312.2
$P_3B_3R_3$	210.2	331.6







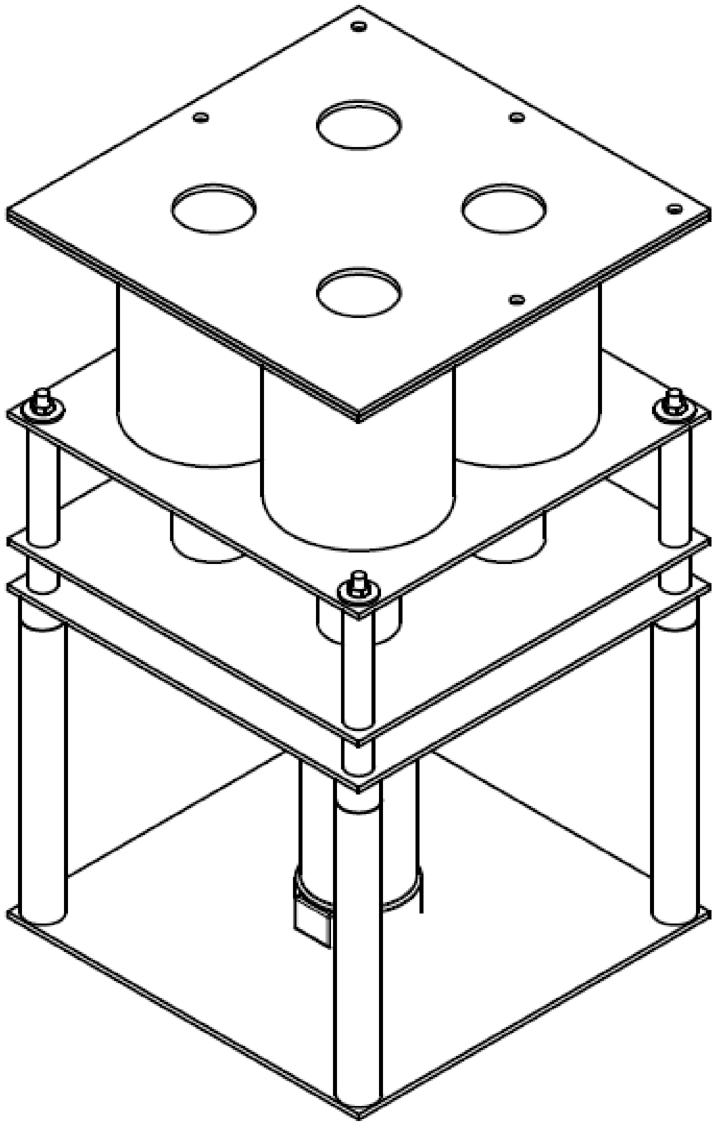
Details / Unit No.	DESCRIPTION	No. of	Materials	Remarks
12	Jack seat plate	1	Mild steel	Constructed
11	Piston head	4	Mild steel	Constructed
10	Nut	4	Mild steel	Standard
9	Washer	4	Steel	Standard
8	Connecting cylinder	4	Galvanized steel	Constructed
7	Bottom dead centre plate	1	Mild steel	Constructed
6	Rod stand	4	Mild steel	Constructed
5	Pipe stand	4	Mild steel	Constructed
4	5 tons Hydraulic Jack	1		Standard
3	Lower compression plate	1	Mild steel	Constructed
2	Mould	4	Galvanized steel	Constructed
1	Upper compression plate	1	Mild steel	Constructed

AHMADU BELLO UNIVERSITY, ZARIA
DEPARTMENT OF AGRICULTURAL ENGINEERING

DESCRIPTION: DEVELOPMENT AND PERFORMANCE EVALUATION OF HYDRAULIC PISTON PRESS BIOMASS HOLLOW BRIQUETTE MAKING MACHINE.

SCALE: 1:1
Dimensiona in 'mm'

	NAME	SIGNATURE	DATE
Drawn By:	Ajikashile Joshua		
Reg. No.:	MSC/ENG/30379/12-13		
Checked By:	Dr. M. ISIAKA		
	Dr. M. A. Gwarzo		
Approved By:	Dr. M. ISIAKA		02/05/2016



AHMADU BELLO UNIVERSITY, ZARIA DEPARTMENT OF AGRICULTURAL ENGINEERING			
DESCRIPTION: ISOMETRIC VIEW OF THE HYDRAULIC PISTON PRESS BIOMASS HOLLOW BRIQUETTE MAKING MACHINE.			SCALE: 1:1 Dimensiona in 'mm'
	NAME	SIGNATURE	DATE
Drawn By:	Ajikashile Joshua		
Reg. No.:	MSC/ENG/30379/12-13		
Checked By:	Dr. M. ISIAKA		
	Dr. M. A. Gwarzo		
Approved By:	Dr. M. ISIAKA		02/05/2016