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ORIGINAL RESEARCH

Design and fabrication of an improved low-cost biomass briquetting system for rural communities

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Abstract

This study was designed to develop a portable briquette mould to produce briquette and evaluated the performance of the briquette mould for household use in rural settings. Briquette mould was developed using engineering principles that satisfy the requirement of appropriate technology for rural dwellers. The biomass used for briquette production was *Cordia millenii*, and cow dung as a binder. The sawdust from Cordia millenii was screened to a particle size of 2 mm, washed with water, and mixed with cow dung at binder ratios of 15, 25, and 40 % by mass. The briquette mould was developed to be used in a press that was already constructed to provide low compaction pressure of 5 MPa. The physical, mechanical, and combustion characteristics of the briquettes such as water penetration index, compressed density, relaxed density, durability and burn rate were measured to evaluate the performance of the Briquette mould. The mould has a volumetric capacity of 1.76 x 10^6 mm^3, and a production capacity of 7.35 kg/hr. operating at a pressure of 2.5 MPa. Briquettes of the size 150 mm in diameter and 55 mm in height were produced. The result of the tests showed that the relaxed density ranged from 0.36 to 0.38 g/cm^3. The binder ratio had a significant impact on the relaxed density of the briquette. The durability varied from 56.81 to 68.85 %, with the 25 % binder ratio having the highest value. The calorific value varied from 27.84 to 28.01 $MJKg^{-1}$, increasing as the binder ratio increased.

Keywords: Briquette Mould, Briquettes, Cordia Millenii, Cow Dung, Low Compaction Pressure

Introduction

Briquettes are blocks of combustible biomass materials that can be used as solid fuel and for kindling fires in rural and urban households/industries such as food processing plants and Bakeries. According to the U.S. Energy Information Administration (2022), biomass provides a source of energy that can be harnessed in homes for heating and cooking. The chemical energy contained in briquettes can be obtained by burning the biomass. Biomass briquettes are made by densifying organic fibres at low to medium pressure after it has been mixed with a suitable binder (Wallace *et al*., 1991). The biomass used in the production of briquettes are renewable materials (fibres) obtained from plants and animals, they are obtained as waste or agricultural residue. The waste is in the form of sawdust, wood chips, and paper (Werther *et al*., 2000).

Biomass is one of the largest energy resources in the world. Kumar and Singh (2017), reported that biomass is the most prevalent source of cooking and heating energy for three-quarters of all people in developing countries, and accounts for 14 % of the total global energy use. According to Bajwa *et al.* (2018), biomass resources can be grouped in terms of properties (‘woody’ and ‘non-woody’ biomasses) or sourcing (agricultural residue and harvested natural materials). In developing countries, there is a high annual yield of biomass residue as by-products of the commercial forestry, agricultural, and industrial sectors. Between the year 2010 to 2011, agricultural and forest biomass feedstock was found to be 242 million tons (Mt) and it is estimated to increase to 281 million tons (Mt) from 2030 to 2031 due to the growing production of agricultural crops. Materials for the production of briquettes are readily available in large quantities. They include waste from wood, forest, and agricultural processes. These wastes usually constitute challenges to farmers, local sawmills and workshops. Hence, they can be locally sourced at little cost (usually transportation) and they require very minimal pre-processing operations. Cheap, clean and efficient fuel is needed for a wide range of domestic applications in homes, local bakeries and canteens such as boiling, heating, steaming and baking. The prices of cooking gas and kerosene are expensive and are not readily available in rural communities around the country. Briquette production is well advanced in Europe and Asia, and it is becoming accepted in many African countries because it addresses the challenges of very low thermal efficiency associated with the combustion of loose biomass materials (fibres), emission of smoky flames during the burning of firewood for domestic use, the rising cost of cooking fuel for domestic applications in developing countries, and wastage of wood fibres obtained as sawdust or wood chips in sawmills and wood harvesting areas. Briquettes are made using a screw press or piston press to apply the compaction pressure needed for densification. For the screw press compaction, the biomass is extruded by a rotating screw through a heated and taper die (Ravina *et al*., 2016). The piston press compacts biomass into the briquettes sequentially in a chamber with a pressing cylindrical or square-shaped piston. Briquettes are pressed in the pressing chamber and may be discharged through counter pressure (Križan *et al*., 2012).

These production processes are characterized by the high cost of production equipment, complex technologies not suitable for rural communities, and difficulty to manage. This work focused on the production of a low-cost briquetting system, easily adaptable in rural communities.

The aim of this work was to produce low-cost briquette production equipment and briquettes, using locally sourced materials, wood residues and animal waste. Sawdust was chosen as the biomass for briquette production because it is readily available at little or no cost and requires simple pre-processing. Sawdust used for briquette can be obtained from both hardwood and softwood species. According to Emerhi (2011), briquettes made from sawdust have a longer burning time and more energy efficiency than other biomass residues, (about 40 % more). The use of sawdust for briquetting usually requires the use of a binder due to the low binding force between the sawdust particles. The organic binders have good bonding,

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good combustion performance and low ash content, although it impacts poor mechanical strength (Guojie *et al*., 2018). The organic binder chosen for this study is Cow dung because of its availability and ready-to-use form. Therefore, this study sought to:

1) Develop a biomass briquetting system for rural communities,
2) Evaluate the performance of the briquette mould based on the physical properties and combustion characteristics of the briquette produced.

Materials and Methods

Materials collection and preparation

The materials used for the production of the briquette mould and briquettes were:

i. Mild steel sheet
ii. Iron rod
iii. *Cordia millenii* sawdust
iv. Cow dung
v. Water

The materials used for the fabrication of the briquette mould were locally sourced from a metal scrap market in Ibadan city of Nigeria. Mild steel was chosen because of its low-cost, suitability, mechanical strength, availability, high strength-to-weight ratio and easy joining. *Cordia millenii* sawdust was used in the production of the briquette. It was obtained from the wood workshop of the University of Ibadan. The sawdust was washed using water and left to air dry for 5 days, after which the moisture content was determined to be at 15 % using a moisture meter. Then it was screened using a sieve of 2 mm hole size. This was done to ensure the uniform size of the particles used for briquette production. The *Cordia millenii* saw dust served as the dry biomass as shown in Figure 1(a). Freshly deposited cow dung was obtained from the Teaching and Research farm, University of Ibadan. The dirt and solid particles contained in the cow dung were removed before it was mixed with the sawdust as shown in Figure 1(b). Pipe-borne water was also used in the preparation of the feedstock.

(a)

(b)

Figure 1 (a) *Cordia millenii* sawdust for briquetting, and (b) cow dung for briquetting

Briquette mould design and fabrication

General considerations in briquette mould design

The following considerations were made for the briquette mould:

i. Type of load and stress caused on the briquette mould: The various types of load and stresses acting on the Briquette mould parts were considered. These stresses determine the efficiency of compaction of the briquettes. It was required to be able to withstand stresses that would develop in its component parts.
ii. The motion of the parts of the Briquette mould: The parts responsible for the densification of the briquettes were adequately considered to give the required compaction. The motion required in this case was rectilinear motion. This motion ensures that the pressure applied is transmitted to all areas of the feedstock in the briquette mould.
iii. Selection of materials: Properties and behaviour of materials under workshop conditions were considered. Such characteristics include strength, durability, flexibility, weight, ability to be welded, machinability, etc.
iv. Convenient and economical features: Operating and managing features were considered, such as easy handling of briquetting materials and easy access to the finished products were provided.
v. Use of standard parts: Standard parts such as screws, supports, nuts, pins, bolts and studs were used.
vi. Assembling: Ease and time of assembling the briquette mould parts was also considered.
vii. Discharge Mechanism: The ease, timeliness and careful discharge of the briquette was also considered. The ease of discharge would determine the production capacity of the briquette-making machine.

Description of briquette mould parts

i. Mould cylinder: This is a cylindrical component of a calculated internal diameter and thickness. It produces the solid briquette form which has a specific dimension and volume. It also provides for compaction of the loose biomass material due to its unexpansive and rigid nature.
ii. Base plate: The base plate is a cylindrical disk of calculated thickness and diameter. Four studs of pre-determined sizes were attached to the base plate to create openings in the briquette for proper combustion.
iii. Briquette carrier: The briquette carrier is a circular disk of pre-determined thickness with slots that align with the vertical studs of the base plate. Its sole function is to ensure the effective discharge of the formed briquette fuel from the briquette mould.
iv. Compaction rod and plate: the compaction rod is a metallic bar of a calculated thickness and length, welded to a circular plate having a clearance with the mould cylinder and strength that would withstand the compaction force. It transmits the pressure of the cold press to the entire briquette.

Design of briquette mould

A. Briquette mould cylinder:

The mould cylinder is expected to resist axial and hoop stress due to the press, contain an adequate volume of briquette biomass that would burn for a stipulated time and is expected to ensure efficient compaction of the briquette biomass. The following steps were followed:

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i. Estimation of Briquette mould volume:
Briquette cross-sectional area, $A_1 = \pi r^2$ (1)
Briquette Volume, V_1=Area of Briquette x Height of Briquette (2)
Height of Briquette Mould (H) = 100 mm
Diameter of Briquette = 150 mm
Since the required diameter of the briquette is equal to the diameter of the mould,
Volume of Mould cylinder, V_2 = Areaa Briquette x Height of Briquette Mould (3)
V_2 =1,767,375 mm x 100 = 1,767,375 mm^3
The volume of the briquette mould cylinder is 1.76 x 10^6 mm^3

ii. Estimation of force exerted by the cold press:
Force of the cold press F = Pressure of press (P) x Area of comp. rod (A) (4)
Area of compaction Rod (A_2) = πr^2 (r = radius of rod = 15mm) (5)
A_2 = 3.142 x 15 x 15 = 706.95 mm^2 (~ 0.000707 m^2)

The pressure exerted by a cold press is dependent on the length of the lever that is attached to the screw, the pitch of the screw press, and the force applied to the lever. The pressure exerted is given as:
P = Circumference of swing (C) x Number of threads (N) x Force on Arm or Lever (F) (6)
$C = 2\pi R$ (7)
Where R= Radius of lever arm = 570 mm, N = 10 threads, and p = Pitch of screw = 65 mm
Therefore:

$$\text{Force on arm, } F = \frac{Qp}{2}\pi R \quad (8)$$

Where Q = reaction force of the mould chamber, and Force on arm, F = 0.5340 N

Substituting the values of the circumference, number of threads and force in lever into Equation (6), the pressure of the cold press is 19.122 N/m^2. Therefore, from Equation (4), The force exerted by the cold press is 0.0135 N.

iii. Determination of stress on the mould cylinder:
The thickness of the mould cylinder is expected to withstand the stresses that would result due to the pressure given as:

$$\text{Axial stress on mould } \sigma_z = \frac{Pd}{4t} \quad (9)$$

Where P = Internal pressure = 19.122 N/m^2 assuming that the same pressure is transmitted across all levels of the cylinder.
d = Internal diameter of cylinder = 150 mm (Expected to contain the briquette size), and t = Wall thickness (mm)
Assuming, a safety factor of 1.8,

$$\text{Axial stress} = \frac{\text{Yield stress}}{1.8} \quad (10)$$

From Table1, Yield tensional stress of mild steel = 250 MPa
Allowable Axial stress = 250 / 1.8 = 137.5 MPa ~ 137.5 x 10^6 N/m^2. Therefore, assuming the suitable thickness (t) to be 3 mm for the cylinder, the maximum axial stress (σ_z) can be obtained as follows:

$$(\sigma_z) = \frac{19.122 N/m2 \times 0.15m}{4 \times 0.003m} = 239.03\ N/m^2$$

According to Khurmi and Gupta (2005), the axial stress is half the hoop stress of the cylinder, and the design must be based on the maximum stress (i.e., hoop stress) given as:

$$\text{Hoop stress on mould } (\sigma_h) = \frac{PDm}{2t} \quad (11)$$

Given P = Internal pressure = 19.122 N/m^2,
D_m = outside diameter of cylinder = 154 mm, and t = Wall thickness = 3 mm

$$(\sigma_h) = \frac{19.122 N/m2 \times 0.15m}{2\times 0.003m} = 478.05\ N/m^2$$

Allowable yield stress of material = 137.5 MPa ~ 137.5 x 10^6 N/m^2. Therefore, since the hoop stress (478.05 N/m^2) <<< Yield stress (137.5 x 10^6 N/m^2) the design of the mould cylinder is sufficient for densification of the briquette.

b. Design of base plate and briquette carrier:
The base plate is required to resist load in bending, have a sufficient thickness that would support the briquette biomass load and have a diameter that would support the volume of the briquette. Four vertical studs were attached to create holes in the briquette for proper combustion.

Analysis of bending stress of base plate:
Allowable bending stress (σ_b) = 0.55 x yield strength (12)
= 0.55 x 250 *Mpa*
= 137.5 MPa
Assuming the force acts at the centre of the plate area:

$$\text{Stress} = \frac{p}{A} \quad (13)$$

Where:
A_3= Area of the disk, $A_3 = \pi r^2$
r = radius of base plate = 160/2 = 80 mm, and
A_3= 20,108.8 mm^2 ~ 2.01 x 10² m^2
Therefore, substituting the value of the area and force on acting on the plate:

$$\text{Stress} = \frac{0.0125kN}{20108.8m^2} = 0.671 kN/m^2$$

Allowable yield stress = 137.5 MPa ~ 137.5 x 10^6 N/m^2
Calculated Bending stress = 0.671 x 1000 N/m^2 ~ 671 N/m^2
Since the calculated value is far lesser than the allowable value, the design would hold conveniently (i.e., 671 N/m^2 <<<<< 137.5 x 10^6 N/m^2).

c. Design of compaction unit:
The compaction unit is required to have fixed and free end conditions, with the vertical rod welded to transmit the compaction force. It is also required that the critical load of the compaction members be greater than the applied load due to the screw press for the design to hold. The following steps were carried out:
According to Euler's buckling theory:

$$P_{cr} = \frac{\pi 2EI}{L2} \quad (14)$$

Where P_{cr} = Critical load that would cause buckling
E = Modulus of elasticity of Mild steel = 210 GPa
I = Moment of inertia of cylindrical rod cross-section
L = effective length of the rod = 100 mm (The length corresponds to the height of the briquette mould. This would prevent contact of the pressing surface with the vertical studs of the base plate)
The effective length factor for the rod's end condition k = 2.0
So, L = 2 x 100mm = 200 mm

$$\text{Moment of Inertia (I)} = \frac{\pi d4}{64} \quad (15)$$

$$I = \frac{3142}{64}$$

Therefore, substituting all the values in equation (14)

$$\text{Critical load } (P_{cr}) = \frac{3.142 \times 3.142 \times 210000000000 \times 490.93}{2004}$$

$$= 636108.56 \text{ N}$$
$$= 636.108 \text{ kN}$$

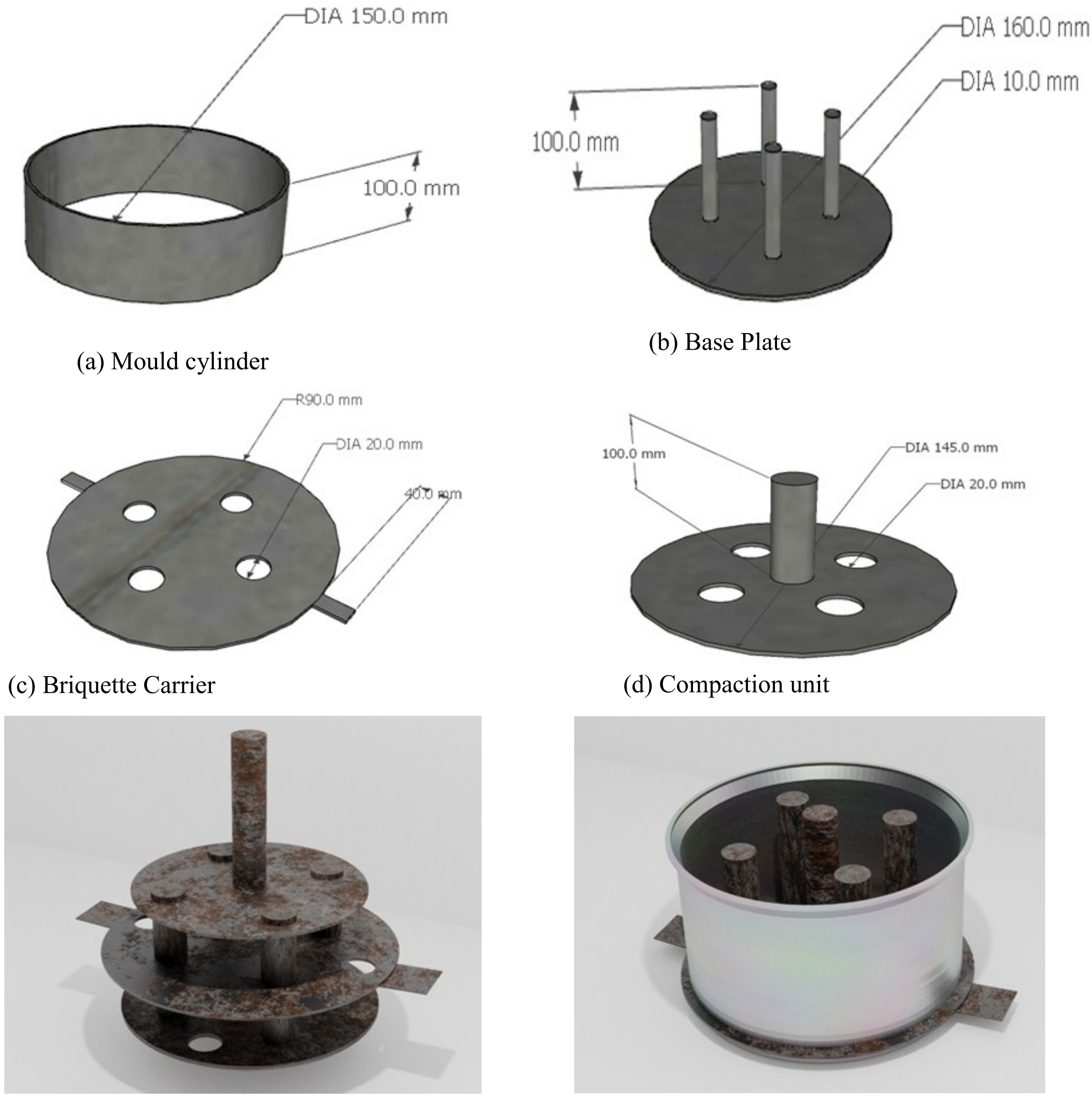
Since the applied load of 0.0061 kN is far lesser than the critical load at which failure would occur, the compression rod parameters is sufficient for the press. Hence, the critical load of the welded compaction rod and plate is 636.108 kN. The AutoCAD drawing, which was based on design analysis, is shown in Fig. 2(a) to 2(f).

Construction of Briquette mould

i. Construction of the Mould cylinder:
The mould cylinder was made of mild steel obtained from second-hand compressor cylinder of a refrigerator obtained from a local parts market in Ibadan. The compressor's cylinder was cut with oxy-ethylene flame after careful marking was done and ground with an abrasive disk grinder to ensure uniform level and height for the mould.

ii Construction of the base plate:
The base plate of the press was made of a flat circular mild steel plate and vertical studs were aligned at an equidistance of 50 mm from the centre of the base plate to the quadrant of the circle. The plate was cut using an oxy-ethylene flame and grounded with the abrasive disk grinder to ensure a uniform circular cross-section for the plate. The surface of the base plate was also smoothened to ensure uniform thickness of the plate. The vertical studs are made of Galvanized iron rod and it was cut from the standard size bar of 6 m into 90 mm length of studs.

iii. Construction of the briquette carrier disk:
The briquette carrier is a circular plate equipped with a handle on both sides for lifting the formed briquette from the base plate. It has four slots which allow for the vertical studs on the base plate to pass through.



(a) Mould cylinder (b) Base Plate

(c) Briquette Carrier (d) Compaction unit

(e) Rendered drawing of mould components (f) Assembly of Briquette mould

Figure 2 Images of the briquette mould

iv. Construction of compaction rod and plate:
The compaction plate is a circular plate cut from a mild steel sheet, it has a rod attached at the centre of the compaction plate by arc welding. Circular slots are drilled into the plates with the aid of the drilling machine to allow for upward and downward movement of the vertical studs on the base plates that would align with it. The compaction rod was made of mild steel. Fig 3(a) to 3(b) show the fabricated briquette mould parts. The materials used in the construction of the briquette mould are based on the properties and behaviour under the working conditions shown in Table 1, while the materials are shown in Table 2.

Biomass densification

The feedstock for the briquette mould was obtained by combining the binder and biomass in definite proportions by weight (15:85, 25:75 and 40:60). Cow dung was used as binders for the *Cordia millenii* sawdust (biomass). About 65 g, 108 g and 172 g of cow dung weighed on a digital weighing balance were combined with 366 g, 323 g and 259 g of *Cordia millenii* sawdust respectively. The feedstock was loaded into the mould according to the defined proportion, and then low-compaction pressure was applied to the feedstock in the briquette mould, so as to ensure that the loose biomass particles bond in a manner that the product would remain in a compressed state.

The average time for biomass loading, compaction and discharge was 3 minutes (in 5 samples). A dwell time of 3 minutes was allowed for each densification process. The average production time component of the briquette mould or die was recorded, as well as their percentages in the total production time and the corresponding average mass of briquette produced are shown in Table 3.

Performance evaluation of briquette mould

The performance of the briquette mould was evaluated based on the physical properties and combustion characteristics of the briquette produced.

Table 1 Properties of mild steel

S/N	Property	Value
1	Ultimate strength (MPa)	400
2	Yield strength (MPa)	
	a. Tensional	250
	b. Shear	145
3	Modulus of Elasticity (GPa)	210
	Modulus of Rigidity (GPa)	77.2
	Density of Mild steel (kg/m^3)	7860
	Coefficient of thermal expansion (GPa)	11.7

Table 2 Materials briquette mould components

S/No.	Components	Materials Used
1	Mould cylinder	Mild steel
2	Base plate	Mild steel
3	Briquette carrier	Mild steel
4	Compaction rod	Cast iron
5	Compaction plate	Mild steel


(a) Briquette mould cylinder


(b) Briquette base plate


(c) Briquette carrier plate


(d) Compaction unit

Figure 3 Briquette mould parts

Physical properties determination

(i) Bulk density

The bulk density of the sawdust sample was determined by weighing an empty cylindrical container of a known volume, and carefully filling it with the biomass sample. The container was filled to approximately 1/3 the height of the container with the sample and tapped on a wooden table approximately 10 times to allow the material to settle down. this was repeated three times until the container was filled. Then the mass of the containing sample was determined. The bulk density was determined as:

$$B.D_{sawdust} = \frac{W1 + W2}{V} \quad (16)$$

Where: W_1= Weight of Sawdust, g; W_2 = Weight of Con tainer, g; V = Volume of the container, cm^3

(ii) The compressed density:

The compressed density (density immediately after compression) of the briquette was determined immediately after discharge from the briquette mould. It is the ratio of the measured weight to the estimated volume of the briquette. It was determined as:

$$C.D_{briquette} = \frac{W}{Vi} \quad (17)$$

Where:
W= Weight of briquette, g
V_i= Initial Volume of briquettes, cm^3

(iii) Relaxed Density:

The relaxed density (density determined when dried) and relaxation ratio (ratio of compressed density to relaxed density) of the briquette were determined in the dry condition of the briquette after about 10080 minutes of sun drying (Olorunnisola, 2007). This served as a measure of the relative stability of the briquette after compression.

$$R.D_{\ briquettes} = \frac{W}{V_c} \quad (18)$$

Where:
W= Weight of briquette, g, and
V_f= Volume of briquette, cm^3

(iv) Briquette stability

It was measured in terms of its dimensional changes on exposure to atmospheric conditions (Sotande *et al*., 2010). The dimensional stability could be determined by measuring the height of the briquette at different time intervals. It was measured at 0, 30, 60, and 1440 min intervals (Sotande *et al*., 2010)

(v) Durability

This is the measure of the shear and impact stress that briquettes can withstand during transportation, storage, and handling (Adapa *et al*., 2009). The durability of the briquette was determined according to Suparin *et al*. (2008) following the shattered index method. The briquette sample was dropped repeatedly from a height of 1.5m onto a metal base. The portion of the briquette that remained was used as an index of briquette durability (Sah *et al*., 1980). The durability rating of the briquette was therefore expressed as a percentage of the mass remaining on the metal plate to the initial mass of the material. This gave an indication of the ability of the briquette to withstand mechanical handling. It is obtained as

$$Durability= \frac{wf}{wi} \ x1oo\% \quad (19)$$

Where: W_i= Initial mass of briquette, g; W_f = Mass of portion after shattering, g

(vi) Water resistance

The water resistance of the briquette was estimated by immersing the briquette fully in a container filled with warm tap water and measuring the time required for the dispersion to commence in water. The higher the water resistance time, the more stable the briquette is in terms of weathering resistance (Richard, 1990).

Combustion properties of briquettes

Proximate analysis was performed to determine the percentage of volatile matter, fixed carbon and ash content of a representative sample of the briquette. The proximate analysis was determined based on ASTM Standard method (ASTM standard, 2004). It includes the following:

a. Volatile Matter

The volatile matter was determined by measuring 1 g of the briquette sample and placing it in a crucible of known weight, after which it is oven dried to constant weight and heated to a temperature of 600 ^oC for 10 minutes. The volatile matter was estimated as the percentage loss in weight to the weight of the oven-dried sample.

b. Ash Content:

The percentage of ash content was determined by estimating the weight of ash residue left after burning the briquette, as a percentage of the original oven-dried weight.

c. Fixed Carbon:

The percentage of fixed carbon (FC) was calculated as;
FC = 100 - (% Volatile matter + % Ash content) (20)

(a) Biomass Loading (b) Pressure application (c) Biomass discharge

Figure 4 Biomass densification

The heating value for the sawdust briquette produced was calculated using the Gouthal formula given as:

$Hv = 2.326\ (147.6C + 144V)$ (21)

Where H_V is the heating value (MJ·kg-1), C is the percentage of fixed carbon, and V is the percentage of volatile matter (Obi *et al*., 2013).

Results and Discussion

The components of the Briquette mould which serves as the die are the mould cylinder, base plate, carrier disk and compaction unit. The briquette Mould assembly is shown in Fig. 5. The mould cylinder was fabricated using mild steel obtained from a second-hand compressor of a refrigerator. The internal diameter, thickness and height of the mould cylinder are 150 mm, 3 mm and 100 mm respectively. The mass and volumetric capacity of the component are 3 Kg and 1.76 x 106 mm^3. It contains the feedstock (organic fibre and binder) for densification and provides the counter pressure required to form the briquette.

The compaction unit is made of a 140 mm circular plate with a thickness of 3 mm and a 100 mm galvanized iron rod attached to it. It transmits the compaction force to the feedstock through alternative upward and downward movement initiated by the cold press. The compaction unit transmits the pressure of densification which other mould components counter-act to. The base plate was fabricated into a flat circular plate of 160 mm diameter and 3 mm thickness, with 4 vertical studs of 10 mm thickness aligned at an equidistance of 50 mm from the centre of the base plate to the quadrant of the circle. The vertical studs on the base plate serve to create holes in the formed briquette and allow for good airflow in the briquette. The base plate also provides the counter pressure that forms the briquette.

The carrier disk is a circular plate of 180 mm diameter with four 20 mm diameter slots located at four equidistant points to the centre of the plate. The carrier is responsible for the discharge of the formed briquette. The rectangular handle of 2 mm by 5 mm by 3 mm dimension helps with easy removal of the briquette in the mould.

Result of biomass densification

The process produced cylindrical briquettes of diameter 150 mm and height of 55 mm. The briquettes produced had a moisture content of 8.86 % after it was sundried for 7 days. The briquettes produced had an average mass of 431 g. The colour of the briquette was brownish black, although it became darker with increasing binder levels. The binder levels of 15, 25, and 40 % are presented as OB1585, OB2575, and OB4060 in Figure 6 (a) to (c) respectively.

Table 3 shows the average biomass loading time of 56 seconds, average biomass compaction time of 68 seconds, dwell time of 180 seconds, and average biomass discharge time of 66 seconds recorded respectively. The production capacity of the machine was about 7.35 Kg/hr (tested with Cordia millenii sawdust). The average production time for the briquette was 373 seconds, which was lesser than the average production time of 868.1 seconds reported by Adekoya (1998). Figure 7 shows the time of the various stages of production as a percentage of the total production time.

Physical properties of briquettes

The physical properties of the sawdust briquette are shown in Tables 4. The influence of binder level was evident in the physical properties of the briquettes produced. The bulk density of the loose saw dust particle was 0.4831 g/cm3, the compressed density ranged from 0.4303 to 0.4396 g/cm3 with the addition of 15 to 40 % of cow dung. The maximum compressed density of 0.4396 g/cm3 was reached at the 25 % binder level and it was significantly different from the value obtained at 15 and 40 % binder levels. The compressed density was also influenced by the pressure of compaction and dwell time. Higher pressure and dwell time reflected higher compressed density. It became apparent that there was a direct relationship between the compressed density and the relaxation ratio of the briquette, therefore higher compressed density indicated a higher relaxation ratio. The relaxed density variation with binder level is shown in Table 4.

The durability rating of the sawdust briquette ranged from 56.81 to 68.85 %. It was observed that the durability rating of the briquette has a direct relationship with the compressed density. The highest durability rating of 68.85 % was recorded for the sawdust briquette with a 25:75 binder-biomass mixture having the highest compressed density while 56.81% was recorded for the briquette with 15-85 binder-biomass mixture having the

Figure 5 Assembled briquette mould

(a) OB1585 (b) OB2575 (c) OB4060

Figure 6 Briquettes of different binder ratios least compressed density. This indicated that the durability was dependent on the compressed density of the sawdust. Table 4 shows the effects of the binder ratio proportion on the water penetration resistance of the briquette. It was observed that the water resistance of the briquette increased with an increase in the binder ratio. This could as a result of the hydrophobic nature of the binder. The water penetration ranged from 16.62 to 24.11 % after 5 minutes. The degree of resistance to water penetration was also observed to vary directly with the compressed density and the durability rating of the briquette.

Combustion properties of briquettes

The performance of the briquette mould was also evaluated based on the combustion characteristics of the Sawdust briquette produced. Table 5. shows the combustion parameters of sawdust briquettes made using the briquette mould. Proximate analysis was used to establish the briquette's combustion parameters. The binder amounts had a substantial impact on the briquette's combustion parameters ($P < 0.05$). The volatile matter concentrations measured varied from 67.28 to 67.44 % percent. These results were outside the acceptable limit for smokeless fuel, which is known to contain no more than 20 % volatile matter (Ivanov et al., 2003). The amount of ash in the samples ranged from 16.78 to 17.29 %. The highest value was obtained at the 25 % binder level, which results in an increase of combustion residual in the form of ash, lowering the heating value of briquettes. With a value of 15.86 %, the calculated fixed carbon was highest at the 40 % binder level. This also contrib-

Table 3 Briquette production time

Production Time Components	**Time (secs)**	**Proportion of total Production time (%)**
Biomass loading time (T1)	56	15.01
Biomass Compaction Time (T2)	68	18.23
Dwell time (T3)	180	48.26
Biomass Discharge Time (T4)	69	18.50
Total	373	100

Table 4 Effects of briquette binder ratio on the physical properties

S/N	Briquette Binder Ratio	Relaxed Density (g/cm^3)	Compressed Density (g/cm^3)	Water Penetration Index (%)	Resistance to Water Penetration (%)	Shatter Index (%)	Durability (%)
1	15:85	0.3846	0.4328	20.47	79.53	43.19	56.81
2	25:75	0.3809	0.4396	24.11	75.89	31.15	68.85
3	40:60	0.3635	0.4303	16.62	83.38	32.62	67.38

Table 5 Proximate analysis of sawdust briquettes

S/N	Briquette-Binder ratio	% Volatile matter	% Ash Content	% Fixed Carbon	Moisture content (%)	Calorific Value ($MJKg^{-1}$)
1	15:85	67.28	17.29	15.43	10.36	27.84
2	25:75	67.44	16.97	15.59	10.92	27.93
3	40:60	67.36	16.78	15.86	11.20	28.01

Table 6 Significance of Relaxed density on Calorific value

S/N	Relaxed density (g/cm^3)	Calorific value ($MJKg^{-1}$)
1	0.3846	27.84
2	0.3809	27.93
3	0.3635	28.01

Table 7 Cost of production of the Briquette mould

Materials	Specification	Quantity	Cost (N)
Mould cylinder	ϕ154mm	1 piece	200
Mild steel sheet	700mm x 700mm x 3mm	1 sheet	2000
Cast iron rod	ϕ23mm, 100mm	1 rod	200
Iron rod	Φ10, 100mm	4 rod	500
Electrode	Guage 12		2000
Oxy-ethylene gas		1 kg	2000
Total Cost			6900

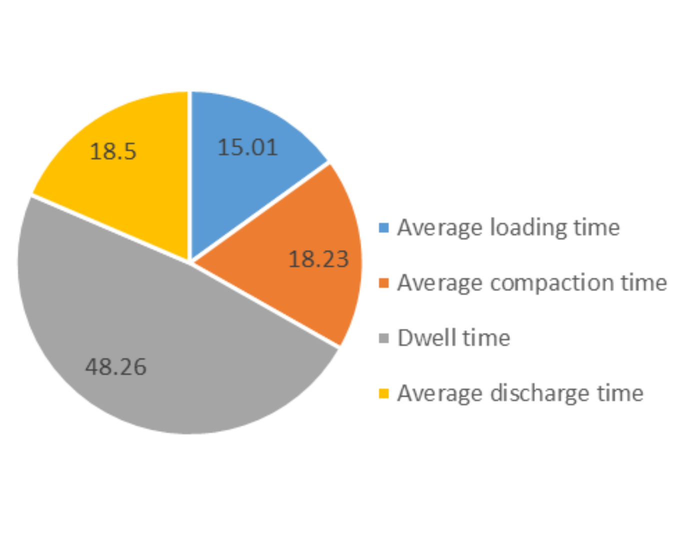


Figure 7 Distribution of briquette production time

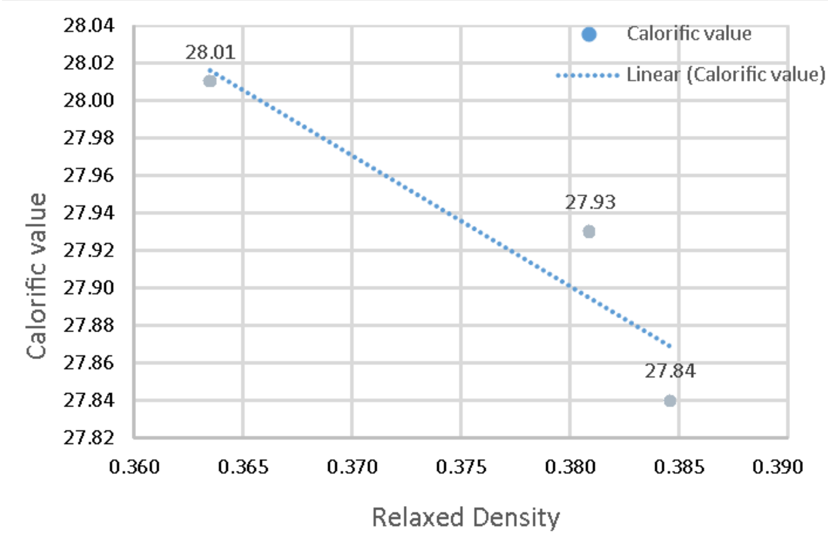


Figure 8 The effect of relaxed density on calorific value

uted to the smoky flame during the combustion of the briquette.

The most essential combustion feature for establishing a material's viability as a fuel is its heating value. It indicates the amount of fuel required to generate a given amount of energy. The heating value was between 27.84 and 28.01 $MJkg^{-1}$. The highest value was found at the 40 percent binder level, while the lowest was found at the 15 percent binder level. It is possible that the low heating value at the 15 % binder level is related to the significant ash content measured at that binder level. The highest heating value of 28.01 $MJkg^{-1}$ was found to be higher than 18.89 $MJkg^{-1}$ obtained in banana peel briquette (Wilaipon, 2008) and 14.1 $MJkg^{-1}$ obtained in maize cob briquette (Wilaipon, 2007), 24 to 27 $MJkg^{-1}$ for lignite with bio-binder (Ivanov, 2003), and 12.60 $MJ.kg^{-1}$ obtained in groundnut shell briquette (Musa, 2007), although it was lower than 33.08 $MJkg^{-1}$ obtained by (Sotande, 2010) for sawdust briquette. As a result, the sawdust briquette is a good potential fuel for domestic cooking. Table 6 and Figure 8 show the relationship between the relaxed density of the briquette and the calorific value. It can be seen that the calorific value varied inversely with the relaxed density. The cost of production of the briquette mould is shown in Table 7.

Conclusion

The development of the manually operated briquetting system provided a low-cost alternative for the production of briquettes for rural communities. The machine provides a daily production capacity of 176.4 kg/day at no extra running cost such as electricity. The stability, durability, and water resistance of the briquette indicated that the briquette production process was efficient as it was within range with known standards as defined by Suparin *et al*. (2008). It was also found that the relaxed density of the briquette significantly affected the calorific value of the briquette. The production process could easily be adapted in rural communities to provide a cheap heating source for domestic activities.

Conflict of Interest Declaration

The authors declare that there is no conflict of interest.

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