Development and performance assessment of piston-type briquetting machine

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Abstract. Biomass residues can become effective and efficient for clean energy utilization in rural and sub-urban areas when compacted as briquettes. This process of compaction is known as briquetting. In order to compact biomass into solid fuels, a piston-type briquetting machine was developed in this study. Mild steel was majorly used for the construction of the parts of the machine. A prime mover of 1.5 hp electric motor was used to drive the machine. In order to evaluate the performance of the machine, sawdust and rice husk were mixed in the ratios 94:6, 92:8, 90:10 and pure sawdust was also used with the help of the urea formaldehyde (UF) that serves as binder. The efficiency and capacity of the machine were 85.7% and 68.56 kg/h, respectively. From the result of the physical properties, the density (820 - 870 kg/m³), moisture content (5.76 – 12.09 %), drop to fracture (8 – 20 times) and water resistance (93.75 – 94.24 %) increased as the rice husk particles increased in the briquette while porosity decreased with increased rice husk particles in the briquette. Based on the results obtained, quality of compacted solid fuels that could withstand handling, transportation and storage challenges can be produced using the machine.

1. Introduction

One of the most commonly as well as readily available renewable energy sources is biomass. It serves as feedstock for bio-energy which can be utilized to generate heat, electricity and various forms of energy [1-3]. Biomass has turned out to be a vital substitute to renewable energy because of its low greenhouse gas, low cost of production as well as low acidic gas emissions [4]. Biomass is bio-material that is traceable to plant or plant-based materials origin [5].

Agricultural wastes (biomass) are available in numerous quantities in most of the developing countries to be used as bio-fuels (solid bio-fuels). Wood and its wastes (such as sawdust of ‘Iroko’ tree, Teak tree, Melina tree etc.), agricultural crops residues (such as rice husks, corn cob, cashew nut shell etc.), animal wastes, municipal solid wastes and many others renewable sources have been identified by researchers [6 – 15]. As a result, various researchers have grown wide interest in bio-energy research. The unceasing reduction of several non-renewable energy resources available as well as the effects of...
greenhouse gases has been some of the reasons for the keen research focus and interests in renewable energy.

The production of solid bio-fuels in which biomass materials are compacted through densification of loose particles into rigid monolith for utilization as fuels for both rural and semi-urban dwellers can be termed briquetting [8, 16 – 17]. According to Mambo et al. [18], the effect of low bulk density, low thermal efficiency as well as the amount of excessive smoke generated due to burning hinders the usage of agricultural residues in their loose form as fuel. Therefore, for ecologically friendly, economically viable and sustainable usage of agricultural waste as solid biofuels, densification or compaction of the agricultural residues is paramount [18 – 19]. Furthermore, by means of densification, there could be increased biomass density [20 – 23]. Briquetting machines have been in existence for the conversion of wastes into solid fuel. [8, 10, 18, 24 – 31] among others have shown countless development such as manual and or electric powered, low pressure and moderately economical briquetting machine for biomass densification processing using several agricultural wastes such as sawdust, rice bran, rice husk, rice straw, corn cob, Melina tree sawdust, palm oil mill, sugarcane leaves, and many more [2, 4, 8, 12, 15, 32 – 34].

Mambo et al. [18] developed a manually operated hydraulic briquetting machine with 100 cylindrical molds. The machine production capacity was 122.928 kg/h. More so, the briquetting machine developed by Muhammad et al. [31] was incorporated with an external electric heater. The grinded biomass materials enter through the hopper, transported by means of power screw and then compressed through slotted tapper die that has been heated by externally attached electric heaters. Densification of biomass (sawdust and neem powder) using manually operated hydraulic pelletizer was employed by Rajaseenivasan et al. [11]. After the physical and combustion characteristics analysis, it was reported that there was an increment in the briquette strength with minute reduction in burning rate with the addition of the binding agent (neem powder). Furthermore, wood residues as well as other farm wastes (peanut shell, palm fruit fibers, rice husks, sawdust, coconut fibres and so on) have been densified with the utilization of piston-mold processes into solid fuels (briquettes) [35 – 36].

The outmost layer of paddy grain is the rice husk. Rice husk is very rich in silica and possesses other lignocellulosic constituents. It is naturally abundant in areas where rice grains are grown hence bio-fuels, particle board composites, electronics and so on have been produced from it. These products are highly valuable [32, 37 – 39]. More so, the residue obtained from processed woods can be referred to as sawdust. This is generated yearly in millions of tonnes and constitutes pollution to the environment if not well managed [15, 37, 40 – 42].

Due to the abundant nature and richness of rice husk and sawdust as biomass sources for solid fuel production, compaction of these two wastes at their pure states and with different ratios is important. This is to produce briquette with high strength as a result of increased physical properties such as bulk density, drop to fracture, water resistance index, porosity index and shatter index. The increased physical properties are paramount so as to enhance the easy handling, transportation and storage of the produced briquettes. Consequently, in this study a newly developed piston-type briquetting machine has been developed and evaluated for solid fuel (briquette) production from biomass for rural and sub-urban dwellers.

2. Methodology
The material choice for the production of briquetting machine is subject to the particular operation mode of the machine. In this study, the design analyses of the briquetting machine were done. Material determination for the component parts was done as well as describing the operating principle of the machine. The rectangular casing, square mold and frame are made of mild steel.
2.1 Design calculation

2.1.1 Design of the hopper. Through the utilization of Equation (1), the volume of the hopper was calculated.

\[ V = \frac{1}{3} \times h \times \left( A_1 + A_2\sqrt{A_1 \times A_2} \right) \]  \hspace{1cm} (1)

Where; \( V \) = volume of the hopper in (m\(^3\)); \( A_1 \) = area of the top in (m\(^2\)); \( A_2 \) = area of the hopper base in (m\(^2\)) and \( H \) = hopper height (m). The derived volume of the hopper was 0.0304 m\(^3\).

2.1.2 Volume of the rectangular casing. The rectangular casing volume was determined using Eq. (2).

\[ V_{hc} = L_4 B_4 H_4 \]  \hspace{1cm} (2)

Where; \( H_4 \) = rectangular casing height, \( L_4 \) = rectangular casing length and \( B_4 \) = rectangular casing breadth of rectangular casing where compaction of the briquette occurs.

The volume was calculated to be 0.0074 m\(^3\).

2.1.3 Design of the mould unit. Equation (3) was utilized to determine the volume of the rectangular mold

\[ V = LBH \]  \hspace{1cm} (3)

Where; \( V \) = volume of the mould, \( L \) = length of the mould, \( B \) = breadth of the mould and \( H \) = height of the mould.

The volume for the mould was obtained as 0.001 m\(^3\).

2.1.4 Force of compression determination. In order to determine the force required to compress the briquette, Eq. (4) was utilized;

\[ F = \frac{W \times \alpha}{A_0} \]  \hspace{1cm} (4)

Where; \( W \) = assumed weight of the biomass to be compressed, \( F \) = force applied on the plunger, \( \alpha \) = area of the rectangular casing and \( A_0 \) = area of the plunger.

2.1.5 Piston design. In the piston design, the following values were used. For piston shaft diameter, \( d \) (0.034 m), actual length of rectangular casing, \( L \) (0.608 m), extension of piston (Link) (0.418 m) and diameter of wheel (0.18 m).

However, as a result of large deflection which can be triggered by buckling, the least moment of inertia, \( I \) was determined using Eq. (5).

\[ I = AK^2 \]  \hspace{1cm} (5)

Where; \( A \) = cross-sectional area (m\(^2\)), \( K \) = radius of gyration of the cross-section area and \( I \) = moment of inertia (m\(^4\)).

The radius of gyration was determined using Eq. (6). Equations (7) and (8) were used to determine the moment of inertia and the cross-sectional area of the wheel, respectively.

\[ K = \frac{I}{A^{\frac{1}{2}}} \]  \hspace{1cm} (6)

\[ I = \frac{\pi d^4}{64} \]  \hspace{1cm} (7)

\[ A = \frac{\pi d^2}{4} \]  \hspace{1cm} (8)

Where; \( d \) = diameter of piston rod.

Hence, the radius of gyration (K) was evaluated to be 1.1 \times 10^{-2} m.

figures 1 and 2 display the orthographic views and isometric drawing of the piston-type briquetting machine, respectively.
2.2 Operation of the briquetting machine

For effective operation of the machine, the operator should be able to identify major parts and understand the working principle. The machine is powered by a gear motor. Biomass has to be mixed with the addition of a binder that serves as an adhesive to the mixture before it is introduced into the machine hopper. When the machine is switched on, the biomass mixture is poured into the hopper for compaction into briquette. The prime mover, which is the electric motor, drives a gear mounted on a shaft. The shaft then rotates and it is facilitated with a pillow bearing. The movement of the shaft enables the rotation of the wheel which in turns gives the link a reciprocating motion. Since the link is attached to the piston, it aids the forward and backward movement of the piston. As the piston moves forward, it presses the biomass
against the mold. With the force of the piston, the mixed biomass is rammed into the shape of the mold. As the piston returns to its initial position, the exit is opened for the briquette to be ejected from the casing.

2.3 Process of briquette preparation.

Rice husk, sawdust and organic binder (Urea Formaldehyde, UF) were the major biomass materials for the briquette production. Rice husk was gotten from a local rice milling industry in Oro, Kwara State. The sawdust was obtained from local saw mill industry in Omu-Aran, Kwara State. The rice husk and saw dust were initially sun-dried for three days to decrease moistness present in the materials. After this, the rice husk and saw dust were sieved to < 2 mm. To obtain the briquette of the desired quality, various mixtures were formed as shown in table 1. The mixtures of the two biomass materials were bonded using UF (binder). The mixture of the biomass was fed to briquetting machine for the production of the briquette. Four samples were produced for each of the composition stated in table 1.

Table 1. Mixing ratios (% wt.) of sawdust and rice husk for briquette production

| Sample | Sawdust (% wt.) | Rice husk (% wt.) |
|--------|-----------------|-------------------|
| A      | 100             | 0                 |
| B      | 94              | 6                 |
| C      | 92              | 8                 |
| D      | 90              | 10                |

Figure 3 displays some briquette samples produced from the developed piston-type briquetting machine.

![Figure 3. Briquette produced samples](image)

2.4 Performance evaluation of the machine

The briquetting machine was subjected to test based. The biomass materials were mixed based on the percentage weight ratios with the addition of binder as shown in table 1. The biomass mass input and briquette formed mass output were measured by means of a weighing balance. Using stop watch, the time of biomass processing to form briquette was obtained for each sample. The biomass loss was obtained using Eq. (9). The efficiency as well as the capacity of the machine was obtained using Eqs. (10) and (11a,b), respectively.

Biomass Loss (kg) = \( M_i - M_o \)  \hspace{1cm} (9)

Efficiency = \( \frac{M_o}{M_i} \times 100\% \)  \hspace{1cm} (10)

Machine Capacity (kg/h) = Briquette forming rate \( \times 1 \) hour \hspace{1cm} (11a)

However, Briquette forming rate = \( \frac{\text{Average mass of output briquette (kg)}}{\text{Average processing time (s)}} \)  \hspace{1cm} (11b)

Where; \( M_i \) and \( M_o \) are the mass of input biomass and mass of output briquette, respectively.
2.5 Physical properties evaluation

2.5.1 Bulk density. Evaluation of the density for each sample of the briquettes produced was carried out by measuring the weight of each sample using a Camry weighing scale. This was done in triplicate and the average was recorded. The volume of the briquette was obtained using the product of the length, breath and height. Therefore, the density of briquette was determined using Eq. (12).

\[
\text{Bulk density} (kg/m^3) = \frac{\text{weight of briquette} (kg)}{\text{volume of briquette} (m^3)}
\]

(12)

2.5.2 Drop to fracture. According to [43] and [44], continuous and repetitive release of each of the briquette sample from a fixed initial point of 2 m height into a concrete base until it got broken was done. The number of repetitive drops taken for each briquette sample to disintegrate into fragments was noted.

2.5.3 Water Resistance. The resistance to water penetration was measured as the percentage of water absorbed by briquette when submerged in water. This test is important so as to determine briquette response during rainy seasons or while in contact with water. Each briquette was submerged in 2.5 litres of water at a room temperature of 27○C for 30 seconds. Equations (13) and (14) were used to determine the water gained percentage as well as the percentage resistance to water penetration [14].

\[
\text{Water gained by briquette} (%) = \frac{w_2 - w_1}{w_1} \times 100
\]

(13)

\[
\%\text{Resistance to water penetration} = 100 - \text{water gain} \quad (%)
\]

(14)

Where; \( w_1 \) = Briquette initial weight (kg) and \( w_2 \) = Briquette final weight (kg)

2.5.4 Porosity index test. A degree of the water proportion absorbed by a briquette submerged in water is porosity index test. In this study, each briquette was submerged in 2.5 litres of water at 27○C for 30 seconds. The percentage water gain was calculated by using Eq. (15).

\[
\text{Porosity} = \frac{w_2 - w_1}{w_1} \times 100
\]

(15)

Where; \( w_1 \) = Initial weight of briquette before immersion (kg) and \( w_2 \) = Final weight of briquette after immersion (kg).

2.5.5 Shatter index test. It is used for determining the hardness of briquette when dropped on concrete floor from a height of one meter. The weight of the broken briquette was recorded. The percentage loss of the material was calculated by using the Eq. (16) [10].

\[
\text{Percentage of weight loss} = \frac{w_2 - w_1}{w_1}
\]

(16)

Where; \( w_1 \) = Weight of briquette before shattering (g) and \( w_2 \) = Weight of briquette after shattering (g).

2.5.6 Moisture content. The samples were dried in an oven (Uclear England, Model number: DHG-9053A) at 105○C until the samples arrived at a constant weight according to BS EN 14774-1 (2009) standard [45]. The values taken were measure in triplicates and the average value recorded for each briquette sample. Moisture content was calculated using Eq. (17).

\[
\text{Moisture Content} = \frac{W_b - W_d}{W_b} \times 100
\]

(17)

Where; \( W_b \) is the sample weight before oven drying and \( W_d \) is the sample weight after oven drying on a dry basis.
3. Results and Discussion

3.1 Performance evaluation of the machine.

The machine efficiency and the capacity were determined through the experimental tests as shown in table 2.

| Test | Pt (s) | Mi (kg) | Mo (kg) | Loss (kg) |
|------|--------|---------|---------|-----------|
| 1    | 45     | 1       | 0.82    | 0.18      |
| 2    | 46     | 1       | 0.83    | 0.17      |
| 3    | 49     | 1       | 0.84    | 0.16      |
| 4    | 48     | 1       | 0.86    | 0.14      |
| 5    | 43     | 1       | 0.85    | 0.15      |
| 6    | 45     | 1       | 0.87    | 0.13      |
| 7    | 44     | 1       | 0.87    | 0.13      |
| 8    | 45     | 1       | 0.88    | 0.12      |
| 9    | 46     | 1       | 0.86    | 0.14      |
| 10   | 44     | 1       | 0.85    | 0.15      |
| 11   | 42     | 1       | 0.86    | 0.14      |
| 12   | 43     | 1       | 0.89    | 0.11      |
| Average | 45 | 1 | 0.857 | 0.143 |

*Pt-Processing time; Mi-Mass of biomass input; Mo- Mass of briquette output

From table 2, the average mass of the briquette formed was 0.857 kg while the loss was 0.143 kg. Also, the average time of processing the biomass materials into solid fuel (briquette) by the machine was 45 s. The machine efficiency and capacity were evaluated to be 85.7% and 68.56 kg/h, respectively. The machine capacity of this study was found to be lower compared to the study of Muhammed et al. [31] and Mambo et al. [18] in which the machine capacities were 200 and 122.928 kg/h, respectively. This can be attributed to the enormous design nature of the machine as compared to this study. However, the machine efficiency in the study of Muhammed et al. [31] was not stated. Mambo et al. [18] obtained an efficiency that was higher than the machine efficiency as obtained from this study. Therefore, this machine can be redesigned to improve both the capacity and its efficiency.

3.2 Physical properties of briquette.

3.2.1 Bulk density. The physical quality of briquettes can be determined through density determination. Davies and Davies [14] stated that the higher the density, the better and higher is the energy/volume ratio. Figure 4 shows the bulk density of each briquette produced based on the percentage mixing ratios of sawdust and rice husk. From figure 4, the density was observed to be maximum at samples C and D (870 kg/m³) while the density of sample B was 860 kg/m³. The least density of 820 kg/m³ was obtained with sample A. Based on the study of Rajaseenivasan et al. [11], increment in briquette density lead to reduction in size; thereby improving combustion rate. Akowuah et al. [2] reported that high density briquette is said to have sufficient strength that can withstand failure and shocks during handling, transportation and storage. The densities of the briquettes obtained in this study were less when compared with the densities of sawdust-
charcoal briquette in the study of Akowuah et al. [2]. This might be as a result of better compaction between the mixture of the particles of sawdust and charcoal briquettes when compared to the briquettes of sawdust-rice husk particles. Charcoal particles are smaller than rice particle hence the pores are reduced in the sawdust-charcoal briquettes. It is suggested that for more compaction of the sawdust and rice husk, smaller particle sizes could be utilized.

![Figure 4. Density of different briquette samples](image)

3.2.2 Drop to fracture. The drop to fracture value for samples A, B, C and D are 8, 10, 16 and 20 times, respectively (See Figure 5). From experimental observation, briquette sample D gave the highest drop to fracture value. This implies that the presence of high rice husk quantity mixed with sawdust in the production of the briquettes give better strength when compared to the samples with a lower quantity of rice husk. Consequently, this means that the higher the percentage of rice husk the better the quality of the briquette. Furthermore, during transportation, utilization and storage, sample D will be able to resist damage more than other samples.

![Figure 5. Drop to fracture for different briquette samples](image)

3.2.3 Water resistance. To understand the behaviour of the briquettes in high humidity environment during storage or transportation, water resistance index (WRI) analysis was carried out and the results obtained are shown in Figure 6. The water resistance index for the samples increased from samples A to D with the values ranging from 93.75 - 95.24%. Based on the analysis, minimum value of water gained was obtained
from sample D. This implies that the sample D has the highest resistance to water penetration. This makes sample D the most desirable in terms of water resistance property when compared to other samples as revealed in the work of Davies and Davies [14] that the briquette with the least water absorption characteristics has the best hygroscopic property.

3.2.4 Porosity index. The porosity of briquette samples varied from 4.76 to 6.25% as shown in Fig. 7. Sample D has the least porosity index with 4.76% while sample A has the least with 6.25%. This implies that sample D has a lower absorption of water compared to the other three samples which makes it less porous. However, sample A is more porous due to high water absorption index. Decrease in porosity is a function of the increment in rice husk content in the sample (figure 7). According to Ikelle et al. [34], the sample with the least porosity index values implied that the biomass particles of the briquette exhibited good interfacial bonding. Sawdust could be said to have more coarse and loose particles than rice husk. The optimum porosity value is an indication that combustion rate will be faster in the sample.
3.2.5 *Shatter index.* Briquette strength is measured and known through the shatter index. To avoid distortion of briquettes during handling, it is important that the shatter index and impact resistance test be carried out [11]. Figure 8 shows the shatter index values obtained for samples A, B, C and D are 74.12, 76.19, 75.6 and 81.9%, respectively. Good shatter index with retention capacity of 81.9% of its weights on concrete floor was observed for sample D. Meanwhile, sample A has the percentage retention of about 74.12% observed to be the least among all the samples. The implication of this analysis is that sample D will be more resistant to damages during handling and transportation when compared to other samples.

![Figure 8. Shatter index of briquette samples](image)

Generally, in this study the higher porosity implies lower water resistance ability. Sample D has the highest water resistance thus lowest porosity. Although sample D has the lowest porosity, it has enough pores to allow oxygen in for combustion process though lower than that of sample A. The more the rice husk constituents in the biomass briquettes, the higher the density. The density of each sample has significant effect on the water resistance. As the density increased, the water resistance increased. More so, shatter index increased with increment in density but porosity index decreased as density increased.

3.2.6 *Moisture content.* Moisture content (MC) helps in determining briquette quality in terms of its burning properties [33, 46]. Table 3 shows the moisture content value of the produced samples. Low moisture content of briquettes could be indicative of ease of combustion of the biofuel. Drying is important for briquettes to reduce high moisture content that could induce high energy consumption for its initial drying rather than releasing immediate energy. Decomposition and disintegration of briquette can be prevented when there is low moisture content during handling, transportation and storage [33, 40, 47]. The moisture content values for all the samples are between 5.76 and 12.09%. These moisture content values were found to be within the range (not more than 15%) as recommended by Wilaipon [23] as well as Grover and Mishra [48] as reported by Akowuah *et al.* [2] for agro-waste briquettes.

| Sample | MC (%) |
|--------|--------|
| A      | 5.76   |
| B      | 6.67   |
| C      | 10.11  |
| D      | 12.09  |

Table 3. Moisture content of briquette samples
4. Conclusion
A piston-type briquetting was developed and evaluated using biomass (sawdust and rice husk) at different mixed ratios. The efficiency and capacity of the machine were 85.7 % and 68.56 kg/h, respectively. This study reveals that the machine developed is good for solid biofuel production for cleaner energy. The physical properties examined for the briquettes produced revealed that the briquettes possessed good physical qualities that could withstand damage during handling and transportation. The machine developed can be utilized in rural and sub-urban areas of developing countries for its dwellers.

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