Development and performance evaluation of a piston type hydraulically operated briquetting machine with replaceable moulds

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Abstract: This study focuses on the development and performance evaluation of a piston type briquetting machine with replaceable moulds. The properties of the briquettes produced from cornhusk (CH), cassava peel (CP), sawdust (SD) at different torrefaction conditions and particle size less than 1.18 mm were studied with cassava starch as binder. The fuel application of the feedstock for co-firing in coal engines was evaluated by combustion indices. This machine has a replaceable cylindrical or square mould that could be used interchangeably. The machine has the capacity to produce 576 briquettes on an 8-hours operation while the biomass material flow rate for densification is 1.58 L h^{-1}. The highest maximum density of 1.09 g cm^{-3} was attained for cylindrical CP briquettes torrefied at 300°C and water preconditioned at 10% moisture content, while the relaxed density, shatter index and compressive strength are 0.58 g cm^{-3}, 98.35% and 0.75 N mm^{-2} respectively. The calorific value and fixed carbon for the SD briquettes are better than those of CH and CP. The cylindrical briquettes have better physical properties than the square ones. The square shaped briquettes however would occupy less void space during storage. Conclusively, the machine is capable of producing quality cylindrical and square shaped briquettes for heating applications.

Keywords: Briquette, combustion indices, densification, machine capacity, ram press, replaceable mould.

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1 Introduction

Wastes from agricultural activities accounts for about 80% of the total primary energy consumed in Nigeria while oil accounts for 13%, natural gas (6%) and hydro (1%) (EIA, 2015). This qualifies agricultural wastes as an important and resourceful material for energy recovery (Al-Widyan et al., 2002; Guo et al., 2016a). Unfortunately, the direct burning of this waste in their loose form is rampant hence, posing environmental pollution and hazards (Oladeji, 2012; Akogun et al., 2020a). In addition, it contributes to global warming, yet wasting energy that could be converted into useful power. Majority of these residues in their raw state are bulky and of low energy value (Oladeji, 2010, 2012). These characteristics make it difficult to handle, store, transport or to be utilized in their raw form (Kaliyan and Morey, 2009; Pallavi et al., 2013).

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In the light of these challenges, one of the approaches actively pursued worldwide towards improved and efficient utilization of agricultural residues for fuel is torrefaction and their densification to produce briquettes (Li and Liu, 2000; Benavente and Fullana, 2015; Akogun et al., 2020b). Moreover, torrefaction improves the combustion properties of biomass while briquetting improves its handling property for variety of applications (Guo et al., 2016b; Akande and Olorunnisola, 2018).

Briquette making has the potential to meet the additional energy demands of urban and industrial sectors, thereby making a significant contribution to the economic advancement of developing countries. The opportunities are available for all scales of business to grow. The scales of business include: the biomass feedstock suppliers, the briquette machine fabricators, the briquette producers and the end-use consumers. Therefore, the adoption of briquette technology will create safe and hygienic ways of disposing wastes, turn into a cash rich venture by converting waste into energy and contributing towards a better environment (Omoniyi and Igbo, 2016). Fuel briquettes production in Nigeria could be used as supplements for petroleum-based fuels, coal or wood in boiler heating (for steam generation), dryer heating and home heating, if produced under appropriate briquetting conditions (Olorunnisola, 2007).

According to Obi et al. (2013; 2014), existing machines in rural communities solve the problem of biomass waste utilization for briquette production at the household and community levels. To achieve this, some researchers such as Olorunnisola (2007) have developed manual briquetting machines; Nordiana (2009) and Omoniyi and Igbo (2016) developed hydraulic piston press hollow briquette making machines, etc. to solve waste management problems. However, constraint in the advancement of biomass briquetting is associated with the development of briquetting press for local commercial manufacture. Some of the commercial limitations associated with the existing machines are low production capacity, development of only one mould and mould shape of briquette, inadequate electrical power for briquetting machine that operates on electricity, etc. The need at the moment is the development of an efficient, cost effective and easy to duplicate appropriate briquetting machine suitable for heating applications (Obi et al., 2014). Moreover, the need to produce briquette of other shapes such as the square shape briquette other than the popularly produced cylindrical shaped briquettes is essential. The thrust of this work is the development of briquetting machine that will address the identified problems.

The objectives of this study therefore were to design, develop and evaluate the performance of a low pressure hydraulic operated briquetting machine with replaceable moulds of cylindrical or square shapes and to characterize the briquettes produced from raw and torrefied cornhusk residue, cassava peel and sawdust in terms of compressed density, relaxed density, shatter index, calorific value and proximate analysis. The application of the briquette as fuel for co-firing in coal engines was also assessed by combustion indices including fuel ratio, combustibility index and volatile ignitability. These created an avenue for proper utilization, better logistics and end-use domestic and industrial application of CH, CP and SD wastes.

2 Methodology

2.1 Design calculations

The important features of the briquetting machine include the determination of the briquette size, frame design, thickness of the moulds and the ram press capacity.

2.2 Briquette size

For the circular briquette, a diameter and height of 50 mm and 100 mm were chosen in line with the work of Husain et al. (2002). Moreover, the square shaped briquette is 50 mm by 100 mm. It is considered that the briquettes would be suitable for use in convectional charcoal stoves.

2.3 Frame design

The frame of the briquetting machine was constructed to house the moulds, lower plates, ram press and pistons. Mild steel was used for constructing the frame. The augmented straightness, tolerance and physical strength of mild steel makes it a better choice for this project. The design of the frame involves the determination of length (L) and breadth (B) having the shape of a rectangle. What informs the length of the frame is the length of the ram press after compression (0.7 m), the height of the moulds and length of piston rod (0.1 m), thickness of top and bottom plates (0.005+0.005= 0.01 m) and clearance. The breadth of the frame on the other hand was affected by the dimension of the mould plate.

The area of the frame (A, m^2) was computed with the aid of Equation 1.

$$A = L \times B = 0.9 \times 0.4 = 0.36 \text{ m}^2 \quad (1)$$

2.4 Thickness of mould

The internal wall of a cylindrical or square shaped mould is subjected to internal pressure when subjected to shear stress. If this stress exceed the permissible limit, the mould is likely to fail by either splitting into two troughs or breaking into two cylinders (Khurmi, 2005). Therefore, appropriate thickness of the material is required for the construction of the moulds in order for the cylinders to withstand the shear stress that would be generated at the walls of the moulds. For this design, since the maximum design pressure required is 15 MPa, a thin-wall cylinder was selected. In order to determine the expected thickness of the cylindrical mould therefore, the circumferential and longitudinal stresses were determined according to Khurmi (2005) relationship.

Circumferential stress is set up in resisting the bursting effect of the applied pressure. As a result of the internal pressure, the mould has the tendency to split into two troughs along its circumferential axis. It can be determined using the following expression:

$$\sigma_c = \frac{P\,d}{2t} \quad (2)$$

where; t stands for the thickness of mould, mm; P stands for the internal pressure in cylinder , 15 MPa; d stands for the internal diameter of cylinder, 50 mm; σ_c stands for the circumferential stress, MPa.

Since ultimate tensile stress of 400 MPa and factor of safety of 5 was used for mild steel in line with Khurmi and Gupta (2005).

Circumferential stress $(\sigma_c) = \frac{\text{Ultimate tensile stress}}{\text{factor of safety}} = \frac{400}{5}$ = 80 MPa

To determine the thickness, t of the mould, the circumferential stress relationship was used.

$t = \frac{15 \times 50}{2 \times 80} \approx 5$ mm

Considering the fact that the internal pressure the feedstock is subjected to also has the tendency to break the cylindrical mould into two pieces along its longitudinal axis. The maximum thickness of the mould that will prevent breaking of the cylindrical mould along its longitudinal axis was determined using Equation 3 in line with Khurmi (2005).

$$\text{Longitudinal stress } \sigma_L = \frac{total\ pressure}{resisting\ section} = \frac{P \times d^2 \frac{\pi}{4}}{\pi d t} = \frac{P\,.d}{4t} \quad (3)$$

where; σ_L stands for the longitudinal stress, MPa.

Since longitudinal stress is the half of circumferential stress (Khurmi, 2005), the circumferential stress is two times the longitudinal stress. Hence, the permissible stress is less than the circumferential stress. Or in other words, the circumferential stress is not greater than the permissible stress. The longitudinal stress is calculated using

$\sigma_L = \frac{p\,.d}{4t} = \frac{1}{2} \times \sigma_c = 0.5 \times 80 = 40$ MPa

Ultimate tensile stress is 400 MPa. Factor of safety of 5 was used for mild steel in line with Khurmi and Gupta (2005),

Since longitudinal stress is half of circumferential stress,

Longitudinal stress $(\sigma_L) = \frac{80}{2} = 40$ MPa

$t \leq \frac{15 \times 50}{4 \times 40} \approx 5$ mm

The thickness of material obtained for the cylindrical material is applied for the square shape mould. This is because the volume of briquette in the square shape mould is the same as the cylindrical shape counterpart. It also requires the same material for construction.

The maximum shear stress was calculated using Equation 4.

$$\text{Maximum shear stress } \tau_{\max} = \frac{\sigma c - \sigma L}{2} \quad (4)$$

Substituting $\sigma_c = \frac{p.d}{2t}$ and $\sigma_L = \frac{p.d}{4t}$

$$\tau_{\max} = \frac{\frac{P\times d}{2t} - \frac{P\times d}{4t}}{2} = \frac{P\times d}{8t} = \frac{15\times 50}{8\times 5} = 18.75 \text{ N/mm}^2.$$

2.5 Ram press capacity

The machine is hydraulically operated because the ram press provides the mechanical force that moves the feedstock in the mould up through the piston compressing the feedstock in the compression chamber. The capacity of the ram press shaft used in carrying out the compression was determined using Nordiana (2009) procedures as follows.

The weight of the lower flat metal plate

Weight of twelve (12) pistons

Weight of moulds

The weight of briquettes in the mould.

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

2.5.1 Weight of lower compression flat metal plate

The lower compression plate is made up of mild steel of density 7860 kg m^{-3}. What informs the length and breadth of the lower compression plate is the dimension of the twelve (12) moulds while the thickness, t of the bottom plates was obtained using Equation 2. The dimensions of the plate was 400 mm × 350 mm × 5 mm corresponding to length, width and thickness respectively, the weight of the lower compression flat plate was calculated using Equation 5 in line with Nordiana (2009):

$$W_{lp} = l \times w \times t \times \rho \times g \quad (5)$$

where: W_{lp} stands for the weight of lower compression flat plate, N;l stands for the length of plate , 0.40 m; w stands for the width of plate, 0.35 m; t stands for the thickness of plate ,0.005 m; ρ stands for the density of mild steel, 7860 kg m^{-3} (Khurmi, 2005) and g stands for the acceleration due to gravity, 9.81 m s^{-2}.

$$W_{lp} = 53.98 \text{ N}$$

2.5.2 Weight of twelve pistons

The piston is a hollow cylindrical body with either circular head (top) or square shaped head which enters into the mould during compression.

Volume of piston head (Square) = $L^2 \times t$ *(where L and t are respectively the length and thickness of the piston head in mm)*

= (50 × 50 × 2) mm^3 = 5000 mm^3 = 5 × 10^{-6} m^3

Volume of piston head (circular) = $\pi r^2 t$, where t = 2 mm (thickness of circular piston head) and r is the radius of the piston head in mm

= 5000 mm^3 = 5 × 10^{-6} m^3

Volume of rod = πr^2h = 3.15 × 10^{-5} m^3 (Assuming, 10 mm for rod radius); h is the height of the piston rod in mm

Total volume, V = Volume of squared piston head + volume of rod = 3.65 × 10^{-5} m^3

Since the volume of the rod with square head is same as that with circular head,

Also, since density of mild steel, ρ = 7860 kg m^{-3}

Therefore, mass of piston, $\rho \times V$ = 0.287 kg

Total mass of piston = 12 × 0.287 kg = 3.44 kg

Weight of piston W_p = 3.44 × 9.81 = 33.77 N

2.5.3 Weight of moulds

This is an opening where compression takes place. There are twelve (12) moulds in this machine. After the feedstock has been poured into the mould, the compression of the moulds through the ram press against the piston forms the compressed products- briquettes. The weight of moulds was calculated using Equation 6:

The weight of moulds = weight of flat plate – weight of twelve (12) holes where the moulds were attached + weight of the mould (itself)

$$W_{fp} = l \times w \times t \times \rho \times g \quad (6)$$

Where: W_{fp} stands for the weight flat plate, N; l stands for the length of plate = 0.40 m, w = width of plate = 0.35 m, t = thickness of plate = 0.005 m, ρ = density of mild steel = 7860 kg m^{-3} and g = acceleration due to gravity = 9.81 m s^{-2}.

$$W_{fp} = 53.98 \text{ N}$$

To determine the weight of twelve holes:

W = $(\pi d^2/4)t\rho g = \pi\,(\frac{0.05^2}{4}) \times 0.005 \times 7860 \times 9.81$ = 0.76 N

To determine the weight of the mould itself:

For a squared mould, Length (L) of 50 mm and height (H) of 100 mm was chosen in line with Oladeji (2012) and Obi et al. (2013).

Area of mould (A) = L^2 = 2500 mm^2;

Volume of squared mould = $L^2 \times H$ = 250,000 mm^3 = 0.00025 m^3;

Mass of mould = density × volume;

Mass of mould = 7860 × 0.00025 = 1.965 kg;

Total mass of mould = 12 × 1.97 = 23.6 kg = 231.52 N.

If the volume of square shape mould = volume of cylindrical mould;

Volume of cylindrical mould = πr^2h

If the volume of squared mould = volume of cylindrical mould, radius of cylindrical mould,

r = 28.2 mm

$$Weight\ of\ mould\ components\ (Wm) = weight\ of\ flat\ plate - weight\ of\ 12\ holes\ for\ moulds + weight\ of\ mould$$

$$Wm = 53.98 - 0.76 + 231.52 = 284.74N$$

2.5.4 Weight of briquette

To calculate the mass of feedstock during compaction to form briquettes in the moulds;

Loose bulk density (LBD) of corn husk = 127 kg m^{-3}; LBD of cassava peel = 172 kg m^{-3}; LBD of sawdust = 149 kg m^{-3}.

Using LBD of cassava peel =172 kg m^{-3} for it will accommodate any of the three feedstocks,

Mass of briquette samples, M = vol. of the mould filled with the feedstock × LBD;

M = 0.00025 × 172 = 0.043 kg

Since the moulds are twelve in number; then, total mass of briquette samples = 12 × 0.043 = 0.516 kg = 5.06 N.

This indicate that less energy is required to compress biomass for briquette production.

2.5.5 Force required for compacting the loose biomass in the mould into briquette

Since the force required for compacting the loose biomass in the mould into briquette is the total weight to be exerted by the ram press, calculate therefore the total weight exerted by the lower flat plate, pistons, mould and the compressed biomass into briquettes using Equation 7.

$$Total\ weight, Tw = weight\ of\ lower\ compression\ flat\ plate + weight\ of\ pistons + weight\ of\ mould + weight\ of\ briquette \qquad (7)$$

$Tw = 53.98 + 33.77 + 284.74 + 5.06$ = 377.55 N

To calculate other weights; Assuming mass of other weight being exerted by the ram press = 37.76 N (10% of total weight).

Total weight to be exerted by the ram press is therefore = 377.55 + 37.76 = 415.31 N

The chosen ram press of 1 ton capacity is suitable to achieve compression.

2.6 Machine capacity

The capacity of the machine (C) was calculated using Equation 8 in line with Oumarou and Oluwole (2010).

$$C = \frac{60N}{t} \qquad (8)$$

where N is number of briquettes per operation and t is the time taken (in minutes) to complete one operation cycle.

2.7 Biomass material flow rate for densification

From preliminary study, cylinder stroke length at a calculated stroke time will give the stroke speed. The material flow rate was obtained in line with Dairo et al. (2018) using Equation 9.

$$Q = \frac{6AV}{\%v} \qquad (9)$$

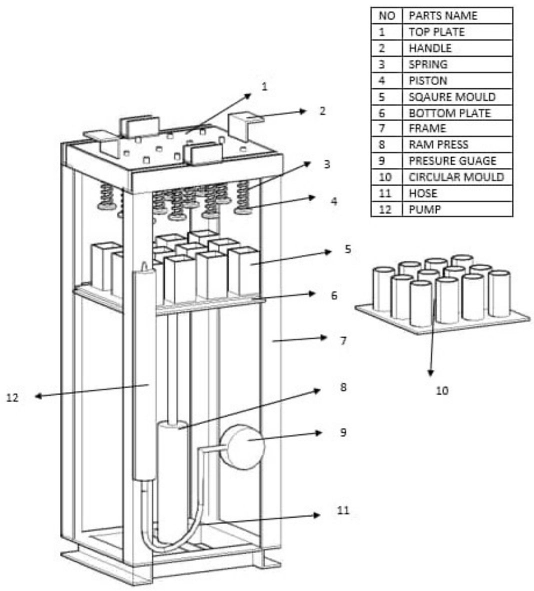
where, Q stands for the material flow rate required (L h^{-1}) , A stands for the Piston area and V stands for the Stroke speed, $\%v$ is volume efficiency (usually 95%)

2.8 Feedstock selection and pretreatment

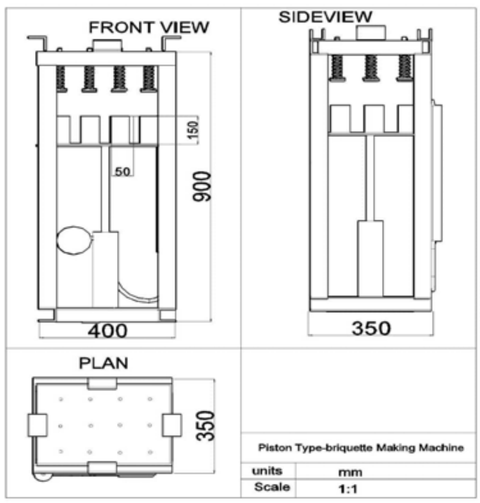
Three biomass materials used in this work are cornhusk (CH), cassava peel (CP) and sawdust (SD). The CH (the outer protective covering of a corncob and its grains) was obtained from waste dumps in Abeokuta metropolis. SD was obtained from Osiele sawmill in Abeokuta, while CP was obtained from Fami village, Alabata, Abeokuta, Nigeria. The CH samples were dried in an oven (model DHG 9030A, UK) at 104.5°C for 5 hours. At this period, it becomes crispy at the moisture content (MC) of 6.23% ± 0.83% (w.b.) making it ready and easier to mill. It was then subjected to hammer mill immediately due to its hygroscopic nature. The CP and SD were sun dried for three weeks. Dried samples were sieved using mesh size of 1.18 mm. Cassava starch was used as binder in this study. Torrefaction and water preconditioning of torrefied CH, CP and SD was carried out in line with Akogun et al. (2020b) and Waheed and Akogun (2020).

2.9 Mode of operation of the machine

Figure 1 shows the isometric drawing of the developed machine. The operation of the machine starts by lowering the ram press with the aid of a pressure relief valve. The bolts holding the top cover was unbolted to allow agricultural waste already mixed with the binder to be fed into the moulds. The top cover has twelve (12) piston rods with spring and flat plates attached to each. The rods are used to compress the feedstock in the individual moulds which are placed on a flat platform that is on the ram press. The top cover was then put back in place after loading the feedstock and bolted. After this, the valve was closed and the handle was inserted into the pump lever and actuated until the working pressure of 15 MPa was achieved. It was then allowed a holding time of 5 mins for the water to drain and enable the briquette to become well compacted. The moulds which contain the compressed feedstock were then hanged on the top frame when the ram press has pushed the mould upwards. The valve was then opened to allow the spring attached to each piston to push the compressed briquettes downward for ejection from the moulds. The wet briquettes are gently removed. The maximum density was determined immediately after ejection while the briquette was placed on a tray and dried under the sun. The whole process was repeated for new batches of briquettes to be produced.



(a)



(b)

Figure 1 The briquetting machine (a) isometric diagram (b) with dimensions

2.10 Performance Evaluation

Three raw briquette samples and those torrefied at 200°C, 250°C and 300°C were selected from each of CH, CP and SD briquette for evaluation. During the process of densification, the time for loading biomass into moulds, time for compressing the biomass and time for ejecting the biomass briquettes from the machine were taken and recorded. The production capacity of the machine and the material flow rate for densification was calculated. On ejection of the briquettes from the moulds, the mass and the dimensions to determine the volume of the briquettes were taken. The maximum density (MD), the density determined immediately after ejection, while the relaxed density (RD), density taken after drying for 21 days, were determined in g cm^{-3}.

Other characteristics of the briquettes were determined as follows:

The shatter index (SI) was determined in accordance with the procedure of Lubwama and Yiga (2017) and was expressed as shown in Equation 10

$$SI = \frac{weight\ of\ briquette\ that\ remain\ unshattered}{initial\ weight\ of\ the\ briquette} \times 100 \quad (10)$$

The compressive strength (CS) test was carried out in line with ASTM D21166-85 (2008) and was therefore calculated using Equation 11:

$$\mathrm{CS} = \frac{\text{The load at briquette failure}}{\text{Cross−sectional area of briquette}} \quad (11)$$

For the determination of combustion indices, briquettes were first analysed for proximate analysis in line with Akogun et al. (2020a). The calorific value (CV) of briquettes was measured by using a Gallenkemp bomb calorimeter in line with ASTM E711-87 standard (2004).

The combustion indices such as fuel ratio (FR), combustibility index (CI), and volatile ignitability (VI) measured in MJ kg^{-1} were determined in line with Ohm et al. (2015) and Akogun and Waheed (2019) to assess the torrefaction performance and fuel quality of briquettes. These indices were calculated using Equations 12-14.

$$FR = \frac{FC_{db}}{VM_{db}} \quad (12)$$

$$CI = \frac{CV_{db}}{FR} \times (115 - Ash_{db}) \times \frac{1}{105} \quad (13)$$

$$VI = \left[\frac{CV_{db} - 0.338FC_{db}}{VM_{db} + MC_{db}}\right] \times 100 \quad (14)$$

Other parameters such as FC and VM represents the fixed carbon and volatile matter content measured in percentage. The subscript db in the above Equations refer to dry basis.

3 Results and discussions

3.1 Mass yield of the feedstocks due to torrefaction

The resultant mass yield of the solid fuel and changes in mass yields with response to temperature is presented in Table 1.

Table 1 Mass yield of 100 g feedstock due to torrefaction

Temp. (°C)	Sawdust (g)	Cornhusk (g)	Cassava peel (g)
Raw	100.00	100.00	100.00
200	92.86	88.61	96.29
250	86.65	76.13	83.21
300	49.33	55.36	58.92

The results revealed that at relatively low torrefaction temperatures of 200°C, the mass loss was relatively negligible, whereas at a torrefaction temperature of 250°C and 300°C defined as mild and severe torrefaction respectively, the weight loss of the tested biomass becomes very pronounced. At close observation of the three tested biomass samples torrefied at 300°C, it was obvious that the weight loss was dependent on the nature of the biomass materials. Moreover, the rate of mass loss is between 49%-59% at the higher torrefaction temperature of 300°C.

Table 2 Analysis of variance for torrefaction condition and feedstock type

Source of Variation	SS	df	MS	F	P-value	F crit
Torrefaction condition	3569.996	3	1189.999	77.46933	3.45×10^{-5}	4.757063
Feedstock type	41.9822	2	20.9911	1.366528	0.324306	5.143253
Error	92.1654	6	15.3609			
Total	3704.143	11				

That is, only about 49%, 55% and 59% of mass were retained at this severe torrefaction temperature for SD, CH and CP respectively. Moreover, the analysis of variance (ANOVA) in Table 2 shows that the torrefaction condition has significant effect on the mass yield ($p < 0.05$). The raw and torrefied samples were grounded and sieved into particle sizes of less than 1.18 mm in order to improve the surface area of the material which improves on the samples' binding ability and strength.

3.2 Briquette production time, machine capacity and material flow rate for densification

The feedstock loading time, compaction time, the briquette ejection time and the total production time in percentage are presented in Table 3.

Table 3 Briquette production time.

Production time components	Time (secs)	Total production time in %
Biomass loading time	249	41.5
Biomass compaction time	300	50.0
Briquette ejection time	51	8.5
Total	600	100.0

For the cylinder stroke length of 0.1 m at a calculated stroke time of 10 sec gave a stroke speed of 0.01 m s^{-1}. Also, since piston area, A = 0.0025 m^2; stroke speed, volume efficiency %v = (usually 0. 95). The material flow rate for densification, Q = 1.58 L h^{-1}.

The capacity of the machine (C) was obtained as 72 briquettes per hour. This machine is capable of producing 576 briquettes on an 8 hours daily operation.

This piston type briquetting machine was fabricated at a cost of USD510.

3.3 Physical properties of briquettes

Figure 2 shows the maximum density (MD) of CP, CH and SD cylindrical- and square-shaped briquettes.

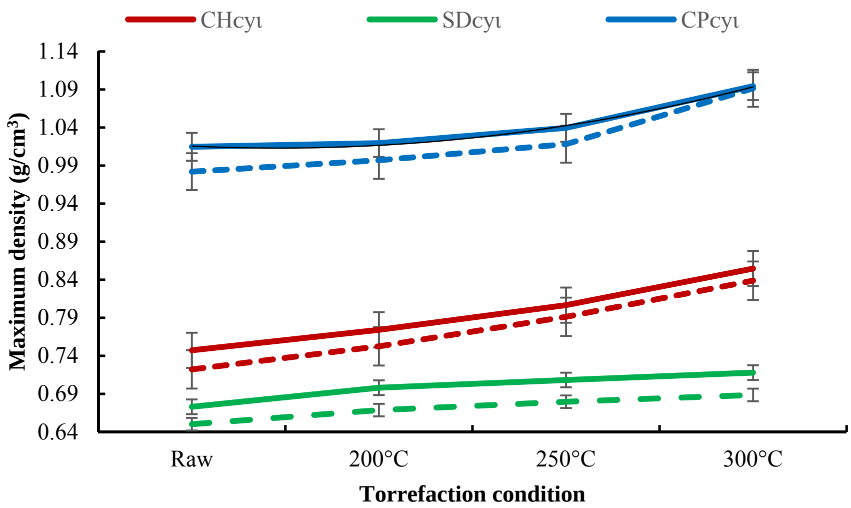


Figure 2 Effect of the torrefaction condition on the maximum density

The MD of raw cylindrical shaped briquette of CH, SD and CP were 0.75, 0.67 and 1.01 g cm^{-3} respectively. It can be seen from the figure that the MD for each feedstock increased with the increase in the torrefaction temperature which could be attributed to water preconditioning of the feedstock prior to torrefaction. The percentage increase in the MD of CH, SD and CP briquettes torrefied at 300°C over those of raw samples are 12.56%, 6.25% and 7.28% respectively. The MDs for square briquettes of CP, CH and SD are lower than those for cylindrical shaped briquettes which indicate that cylindrical briquettes are denser than square shaped ones. An increased trend was also obtained for RD of torrefied CH, SD and CP briquettes over that of raw briquettes as shown in Figure 3. There is an indication that the CP briquettes have higher MD and RD than those for CH and SD briquettes at all torrefaction conditions. This could be caused by the release of lignin component during devolatilisation of CP briquettes with higher binding effect than in CH and SD briquette. Chirchir et al. (2013) noted that the strong bonds generated by gluing result in minimal expansion of briquettes after withdrawal from the mould. Therefore, high values of MD and RD of the CP, CH and SD briquettes are synonymous to increased strength, decreased storage space and transportation cost and improved quality of the briquettes. The tacky nature of CP as described by

Arewa et al. (2016) could be responsible for its briquettes having higher values of MD and RD than the briquettes produced from CH and SD regardless of the shape.

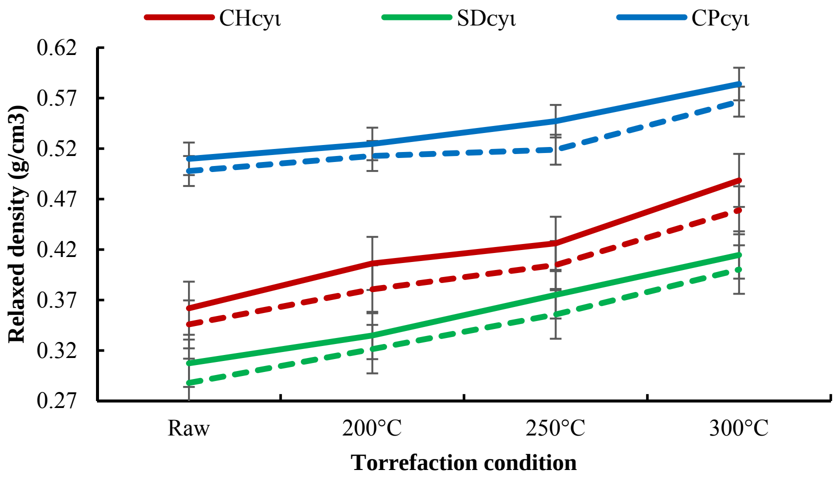


Figure 3 Effect of the torrefaction condition on the relaxed density

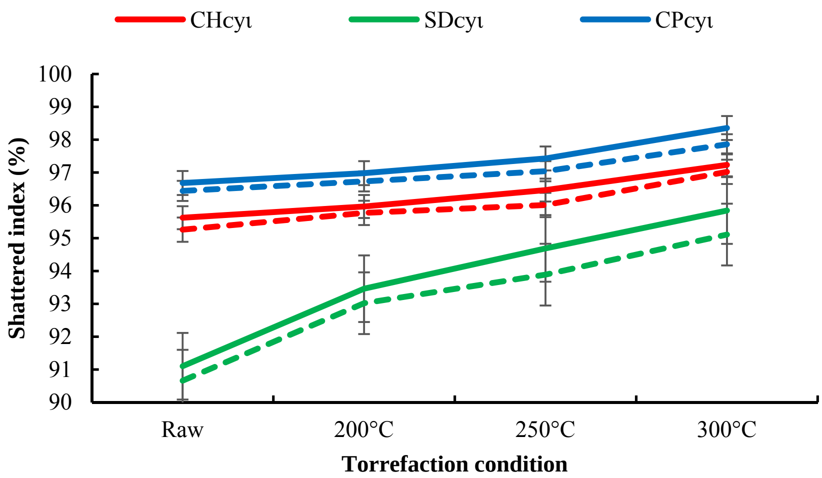


Figure 4 Effect of the torrefaction condition on the shatter index

Figure 4 shows that the shatter index (SI) of the CH, SD and CP cylindrical- and square-shaped briquettes at all torrefaction conditions were high (>90%). The SI for cylindrical shaped CH briquettes ranged from 95.6% to 97.2% at all torrefaction conditions. The SI for cylindrical briquettes produced from SD and CP ranged from 91.1% to 95.8% and 96.7% to 98.4% while that for square shaped briquette ranged from 90.66% to 95.11% and 96.44% to 97.86% respectively for the same feedstock. This showed a slight decrease in SI values of square briquettes from those of cylindrical briquettes. The torrefaction of the briquette samples at 300°C led to higher release of lignin, hence, a strong binding structure which yielded high SI. Chirchir et al. (2013) noted that the gluing causes strong bonding which is expected to reduce the SI of briquette with the increased in the lignin. The sprinkling of deionized water on this torefied samples prior to densification improved the SI (Bai et al., 2017). Yaman et al. (2001) predicted that the fibrous structure of CP would enhance the SI of briquettes. This could be the reason for the high value of SI in CP briquettes than in CH and SD for both shapes and at all torrefaction conditions. Olorunnisola (2007) obtained a value of 93%-98% for briquettes from waste paper and blends of coconut husks, which is within the values obtained in this work.

According to Blesa et al. (2001), one of the most important properties required in the preparation of good fuel briquette is compressive strength (CS). This property, according to the authors, has been extensively used as the selection criteria for most adequate briquettes and is closely associated with the amount and inherent organic composition of the raw materials. The CS is a criterion for briquette durability (Richard, 1990).

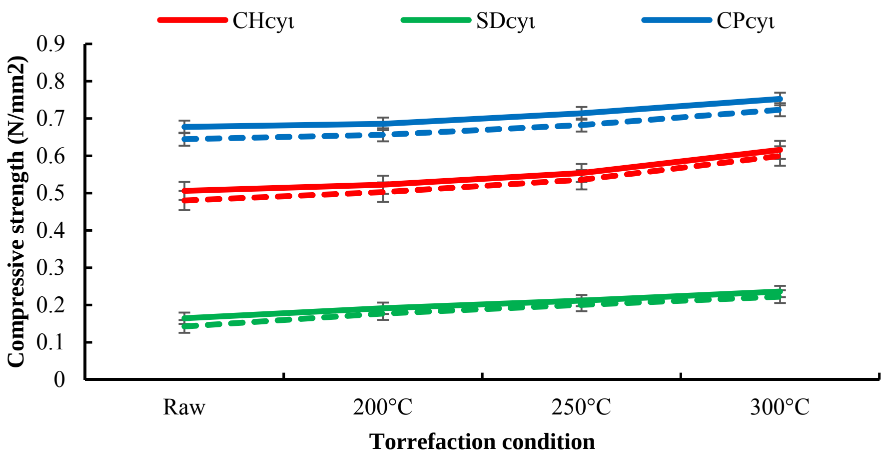


Figure 5 Effect of the torrefaction condition on the compressive strength

The CS for CH, CP and SD briquettes were plotted against the torrefaction condition in Figure 5. The results showed that for cylindrical briquettes, the CS increased from 0.51 N mm^{-2} for raw CH briquettes to 0.62 N mm^{-2} for that torrefied at 300°C indicating a 17.8% increase. Further observations showed that the CS for CP and SD also increased by 10% and 30.3% respectively. On the hand, the CSs for the square briquettes produced from the torrefied CH, SD and CP feedstock at 300°C are higher by 19.92%, 35.88% and 10.89% over those produced from raw CH, SD and CP feedstock respectively. In addition, the CP briquettes for both moulds generally has higher CS than those for CH and SD briquettes perhaps because of its morphology (Yaman et al., 2001) and its tacky nature (Arewa et al., 2016). The cylindrical shaped briquettes performed slightly better than the square briquettes in terms of the physical properties studied in this work. This could be due to a slight loss in cohesive strength of square briquettes at the four edges during compression and ejection during the briquette production process which eventually resulted to the decrease in the density and stability. However, the square shape briquette is better during storage because it occupies less void space in comparison with cylindrical briquettes. Fortunately, the values of the physical properties obtained in this study compared favourably with those reported in literature (Munir et al., 2009; Liao and Ma, 2010; Conag et al., 2017).

The result of the proximate analysis of briquettes produced from CH, CP and SD at different torrefaction condition is presented in Table 4. The volatile matter (VM) decreased from 70.5% for raw CH briquettes to 50.5% for that torrefied at 300°C. Similarly, the VM for CP briquettes ranges between 62.7% (for raw) to 41.3% (for the torrefied form) and for SD from 72.6% to 48.4%. The torrefied briquettes will burn longer than the raw biomass with little or no smoke when subjected to domestic or industrial applications due to its low VM. The fixed carbon (FC) content which predicts the heating value of a fuel briquette increased as a result of torrefaction. For instance, the FC of CH briquettes increased from 18.65% to 36.7% from its raw condition to that torrefied at 300°C. The same increased trend was also obtained in briquettes produced from SD (17.85%-39.50%) and CP (17.35%-36.65%). This implies that torrefied fuels with high FC such as that obtained in SD briquette will produced more heating energy when compared with its raw counterpart with low FC. Similarly, ash content (AC) increased slightly from 3.75% to 4.5% for CH briquettes produced for raw and that torrefied at 300°C respectively, 1.65% to 1.75% for SD briquettes and 9.85% to 14.95% for CP briquettes. This implies there will be need for more clearing of ash pits when CP briquettes are used, than CH and SD briquettes. However, the values obtained for AC is less than 20%, showing the suitability of the produced briquettes from the three feedstock considered. The calorific value (CV) obtained ranged from 12.27 to 16.23 MJ kg^{-1} for CH briquette produced for raw and treated briquettes torrefied at 300°C respectively, 14.70 to 20.95 MJ kg^{-1} for SD briquettes and 12.87 to 15.32 MJ kg^{-1} for CP briquettes with the values obtained at the same condition at which CH briquettes were subjected to. This showed that the three feedstock being considered in this work have low CV (≤ 15 MJ kg^{-1}) in their raw form. Its usage requires pre-treatment such as torrefaction and briquetting which improved their value upwards. The differences in the values of the CV obtained in this study from 17.36 MJ kg^{-1} for corncob and 19.4 MJ kg^{-1} for hardwood by Liu et al. (2015) and 17.47 MJ kg^{-1} for rice husk by Chen et al. (2012) may have been due to the variation in the type and concentration of binders, the species of the feedstock and torrefaction carried out on the feedstock. In addition, Table 5 shows that the torrefaction condition has significant effect on the proximate parameters except MC ($p< 0.05$). The feedstock type on the other hand has significant effect on the VM and FC.

3.4 Proximate analysis

Table 4 Proximate analysis for CH, SD and CP briquettes

Parameter	Raw	200 ℃	250 ℃	300 ℃
Volatile matter (%)				
CH	70.50	66.50	57.90	50.50
SD	72.60	63.60	61.00	48.40
CP	62.70	56.60	49.70	41.30
Ash content (%)				
CH	3.75	5.20	4.10	4.50
SD	1.65	1.50	2.50	1.70
CP	9.85	5.20	10.30	14.95
Fixed carbon (%)				
CH	18.25	22.10	27.60	36.70
SD	17.85	23.10	28.70	39.50
CP	17.35	24.60	28.90	35.65
Moisture content (%)				
CH	8.50	8.30	10.40	8.30
SD	8.90	11.80	8.80	10.40
CP	10.10	11.60	11.10	8.10

Table 5 ANOVA for proximate analysis of CH, SD and CP briquettes

Parameter	Source of Variation	SS	df	MS	F	P-value	F crit
VM	Torrefaction condition	206.5117	2	103.2558	43.07811	0.000276	5.143253
	Feedstock type	779.0358	3	259.6786	108.3374	1.29×10^{-5}	4.757063
	Error	14.38167	6	2.396944			
AC	Torrefaction condition	142.2754	2	71.13771	12.32904	0.007496	5.143253
	Feedstock type	14.78167	3	4.927222	0.853948	0.513565	4.757063
	Error	34.61958	6	5.769931			
FC	Torrefaction condition	2.557917	2	1.278958	0.773791	0.502378	5.143253
	Feedstock type	616.7942	3	205.5981	124.3902	8.62×10^{-6}	4.757063
	Error	9.917083	6	1.652847			
MC	Torrefaction condition	4.126667	2	2.063333	1.124092	0.384927	5.143253
	Feedstock type	5.349167	3	1.783056	0.971398	0.465582	4.757063
	Error	11.01333	6	1.835556			

3.5 Combustion indices

The application of briquette fuel from CP, CH and SD for co-firing in coal engines was evaluated with combustion indices such as fuel ratio, combustibility index and volatile ignitability. The fuel ratio (FR) for the raw CH, SD and CP briquettes is low while it increased as a result of torrefaction from 200°C to 300°C (Figure 6). The CP briquettes have higher FR than CH and SD briquettes at all treated condition. All torrefied briquette samples subjected to 300°C met the standard for FR in line with Ohm et al. (2015), Conag et al. (2017) and Akogun et al. (2020a).

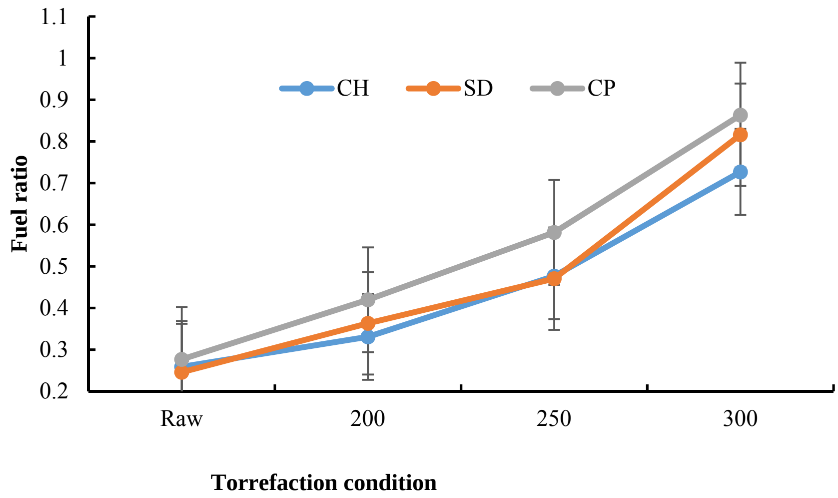


Figure 6 Variation of the fuel ratio with the torrefaction condition

The combustibility index (CI) for the torrefied CP briquettes at 300°C (17.28 MJ kg^{-1}) falls within the standard range of values. The value for CH briquettes (25.43 MJ kg^{-1}) and SD briquettes (24.97 MJ kg^{-1}) however are higher than 23 MJ kg^{-1} for CI (Figure 7).

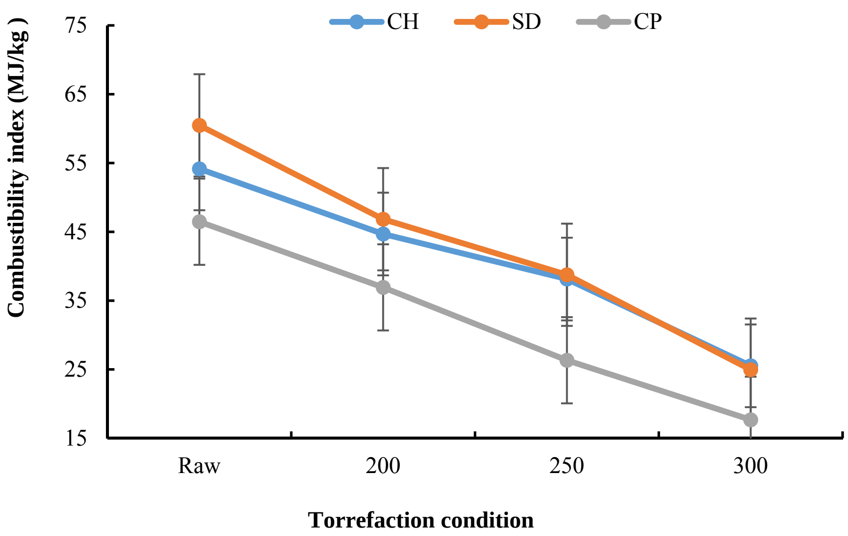


Figure 7 Variation of the combustibility index with the torrefaction condition

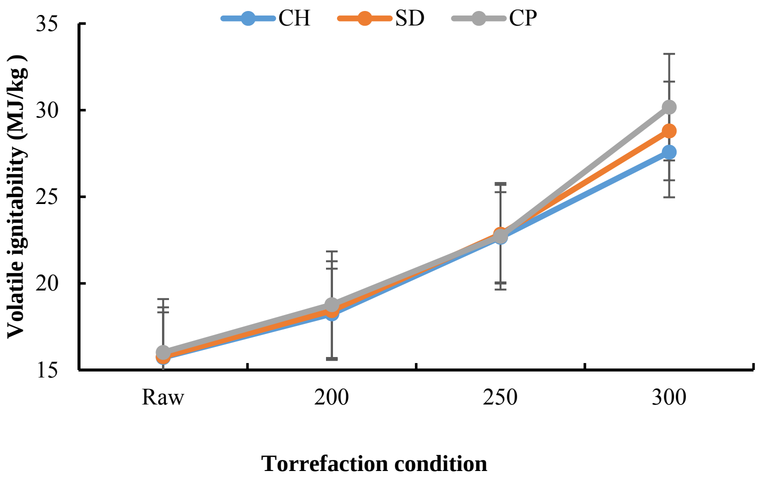


Figure 8 Variation of the volatile ignitability with the torrefaction condition

Volatile ignitability (VI) of CH, SD and CP briquettes torrefied at 300°C met the standard values, where the results obtained were greater than 14.5 MJ kg^{-1} (Figure 8). The improvements in the combustion indices could be attributed to the torrefaction temperature and time the biomasses were subjected to pretreatment prior to densification. These contributed to improvements in the proximate values and the CV of briquettes. The FR, CI and VI for the CP briquettes torrefied at 300°C fall respectively, within the prescribed values of $0.5\leq FR\leq 2.0$, $12\leq CI\leq 23$ MJ kg^{-1} and $VI\geq 14.5$ MJ kg^{-1} for mixed firing with coal in coal engines. The FR and VI for CH and SD briquettes torrefied at 300°C fall within the standard values while they are not within the range for CI. These briquettes (CH and SD) could however be blended together with each other or each with CP briquettes torrefied at 300°C in order to meet with the requirements for biomass briquette co-firing with coal.

4 Conclusion

In this study, a piston type briquetting machine with replaceable cylindrical- or squared- shaped mould was developed. The machine has the capacity to produce 576 raw and torrefied briquettes made from some agricultural wastes on an 8-hours operation while the biomass material flow rate for densification is 1.58 L h^{-1}. To achieve this, the properties of selected biomass from CH, CP and SD were determined and used in the design of the machine. At both raw and torrefied conditions, CP briquettes are better than SD and CH briquettes when MD, RD, CS and SI were determined. The cylindrical shaped briquettes performed better than square-shaped ones in terms of all the physical properties studied; however, square shaped briquettes will occupy less space during storage. Also, the SD briquettes performed better than the CH and CP in terms of the CV and FC. For combustion indices, CP briquette torrefied at 300°C met the standard for co-firing with coal in coal powered engines. The torrefied briquettes produced were found to have a significant value of CV, FC, SI, CS and density which is an indication that the briquettes produced are of good qualities for strength and heating applications. Finally, the machine is geared towards producing an end-product of better quality briquettes from all agro wastes and in the reduction of drudgery and labour intensiveness involved in briquettes production. This machine will also enhance and promote the establishment of economically viable small and medium scale briquette producing industries and create new employment opportunities in rural areas. Briquettes made from this machine using cornhusk, sawdust and cassava peel wastes, and other agricultural wastes could be an alternative source of domestic and industrial energy to charcoal, firewood, gas, coal and electricity if utilized.

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