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ENERGY CHARACTERIZATION AND OPTIMIZATION OF DENSIFIED SAWDUST BIOMASS WITH DIFFERENT TECHNIQUES

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ABSTRACT

Sawdust is a common biomass waste product, but its high moisture content and low bulk density make it difficult to handle, transport, store, and burn efficiently. By physically compacting the material into a consistent, high-density biofuel, densification procedures like pelletization and briquetting are used to get around these restrictions. The impact of different densification settings and methods on sawdust's mass-basis energy content (calorific value) and volumetric energy density is examined in this study. Several techniques were investigated, such as the incorporation of thermal pre-treatments and basic mechanical compaction with different pressures. The purpose of this sawdust densification study was to compare the screw press and piston press using identical electric motors (1 HP), driver/driven pulleys, v-belts, cylinders (barrels), and extrusion die. Because the densification presses were designed using the extrusion principle, a prototype of each press was made using locally accessible materials such as aluminium alloy, brass, mild steel, and galvanized sheet. The average calorific value (HHV) or mass energy density of the screw press's output briquettes was found to be 20048 KJ/kg. The average calorific value of the raw sawdust was 18682 KJ/kg, but the briquettes from the piston press had an average of 19244 KJ/kg.

1. INTRODUCTION

Biomass densification represents a set of technologies for the conversion of biomass into a fuel. The technology is also known as briquetting and it improves the handling characteristics of the materials for transport, storing etc. This technology can help in expanding the use of biomass in energy production, since densification improve the volumetric calorific value of a fuel, reduces cost of transport and can help in improving the fuel situation in rural areas. Raw materials for briquetting include waste from wood industries, loose biomass and other combustible waste products (Tanimu et al., 2013).

In most of Nigeria, biomass has maintained an all-time high level of acceptance for home cooking due to its affordability and accessibility. Nevertheless, there are limitations on using biomass as a direct fuel for power generation despite these advantageous characteristics. High particle wetness, low energy density, hydrophobicity, high oxygen content, and smoke production above the permissible limit for residential uses are a few of these. Due to its abundance and high energy content, biomass has become a viable alternative energy source in light of the growing expense, scarcity, and environmental risks associated with fossil fuels. (Bello et al., 2023)

One of the most important energy sources of mankind is biomass which is referred to all organic materials particularly wood and agricultural residues. It accounts for approximately 14% of total energy consumption in the world. It is widely accepted that fossil fuel shortage, fuel increase price, global warming including other environmental problems are critical issues. Therefore, sawdust energy has been attracting attention as an energy source since zero net carbon dioxide accumulation in the atmosphere from sawdust briquettes production and utilization can be achieved (Potomsok, 2007)

While biomass is a great renewable energy source, it is not a good fuel, because it typically contains more than 70% air and void space. This low volumetric energy makes it difficult to collect, ship, store and use. Densification is a relatively new process in which the air is squeezed out at high pressure to make briquettes (solid fuel) (Fapetu, 2000).

Fuel is defined as natural or artificial organic substance used as source of energy and raw material for domestic and industrial uses. Solid fuel for which bound or compressed sawdust (briquettes) belongs is grouped under the natural fuel origin (Gupta and Poonia, 2004). A fuel is any material that is burnt or altered to obtained energy. Fuel releases it energy either through chemical means, such as combustion or nuclear means, such as nuclear fission.

Sawdust is a common form of briquetting material. It is found throughout the world. In general anything that burns but is not found in an easy-to-use size can be used to make briquettes (Jekayinfa and Omisakin, 2005).

The availability of energy for domestic use in Nigeria continues to pose a formidable challenge, especially with the high cost of cooking gas and kerosene and the environmental problems associated with firewood. Alternative forms of energy need to be sourced. This has necessitated the need to improve on the use of biomass wastes such as sawdust as alternative energy (Oladeji, 2010).

The first step in briquetting is to collect a large amount of the material. Then the material is cut or crushed to make it smaller. Next it is combined with a small amount of water and a binder that keeps the material from falling apart when the pressure is taken away. Clay, mud, cement and starch are commonly used binders (Gary, 2004).

1.1 Densification Techniques

Densification techniques enhance the energy content of sawdust by increasing its volumetric energy density and improving its combustion properties. This is primarily because the process compacts the material, making it denser and more efficient for storage, transportation, and fuel use. While densification itself primarily improves physical characteristics like density and durability, pre-treatment steps like torrefaction can further increase the energy content per unit volume.

1.2 Effects of Densification on Energy Content

Increases volumetric energy density: Compacting sawdust into pellets or briquettes significantly increases its density, meaning more energy is packed into the same volume. Improves handling and storage: The higher density makes the fuel easier and cheaper to transport and store, which is a major advantage over low-density raw sawdust. Enhances combustion properties: Densification improves the fuel's durability and water-resistance, leading to more efficient and reliable combustion (Tanimu et al., 2013). Enables coal substitution: The improved energy density and properties make densified sawdust a viable alternative fuel that can be co-fired with coal in power plants.

High compaction technology or binderless technology consists of the piston press and the screw press. In the piston press technology, the biomass is pressed in a die by a reciprocating ram at a high pressure (Ojo and Mohammed, 2015).The piston press acts in a discontinuous fashion with material being fed into a cylinder which is then compressed by a piston into a slightly tapering die. However, in the screw press technique, material is fed continuously into a screw which forces the material into a cylindrical die (Tanimu et al., 2013); this die is often heated to raise the temperature to the point where lignin flow occurred (Grover and Mishra, 1996).

Densification technique will provide a means of reclaiming valuable secondary and high energy raw materials from process or production waste to achieve the following applications:

- Recycling
- Shredding
- Reduction of volume
- Making fuel “log”
- Removing water and oil
- Recovery of valuable materials.
- Gasification of biomass
- Compaction of filter dust

1.3 Objectives

The main objectives of this research are:

a) To determine the merits and demerits of the two densification techniques operated on the sawdust.
b) To establish a suitable and easier method of upgrading and converting wood residues into solid fuel for domestic and industrial uses thereby keeping the environment clean.

2. RELATED LITERATURES

2.1 The Energy Potential of Sawdust

Sawdust waste has been fired in boilers in a number of industries for many years both as means of waste disposal and of energy recovery (Gunn and Robert, 1989). But collection, transporting and firing the raw sawdust was a common problem. Europe had made every effort to further diversify its energy resources and to conserve energy, thus a significant energy potential was achieved from sawdust, e.g. the total net energy potential (after conversion) of forestry/wood residues was 3.33 x 10^8 GJ – 1.8 x 10^9 GJ (Bridgwater, 1997).

The compaction of loose combustible material for fuel making purposes was a technique used by most civilizations in the past, though the methods used were no more than simple bundling, baling or drying. Industrial method of briquetting dates to the second part of the 19^{th} century.

In 1865, a report was made on a machine used for making fuel briquettes from peat which is a recognizable predecessor of current machines (Grover and Mishra, 1996). Compacted biomass can be used as fuel in semi-urban and rural areas. Densification allows biomass resources to have a higher density and lower volume. Numerous studies on briquettes have shown an increase in the amount of densified sawdust or other biomass generated (Ikubanni et al., 2019).

Biomass is the world's third-largest source of energy among all renewable resources. Materials and lining materials can be biologically transformed into matter by biomass. Low-density biomass residues are difficult to handle, transport, store, and burn. A major factor in reducing the issue of large storage capacity and convenient transportation is densification/briquetting technology. The best way to use raw agricultural waste as a solid biomass fuel is with briquettes or pellets (Sunny et al., 2022).

3. MATERIAL AND METHOD

This research work was conducted by producing sawdust briquettes as solid fuel by using starch as a binder with the two densification techniques. Prototypes of the two briquetting machines were constructed tested, and their performances were determined. The following sequence was used (Tanimu et al., 2013).

3.1 Collection of raw sawdust and pre-processing of the raw sawdust:

There are many factors to consider before a biomass qualifies for use as feed stock for densification (briquetting). Apart from its availability in large quantities, it should have the following characteristics as feed parameters, these includes (Grover and Mishra, 1996):

(a) Effect of Moisture (Low moisture content, range of 10 - 15%)
(b) Effect of Particle size
(c) Effect of Ash content (Low ash content, range of 20 - 22%)
(d) Effect of Temperature of Biomass
(e) Effect of Temperature of the Die
(f) Effect of External Additives
(g) Hardness

3.2 The Briquetting Machines (Presses)

These are the cold extrusion equipment used in the production of the sawdust solid fuel as shown in Appendix I. They were fabricated with locally available materials like mild steel, galvanized sheet, aluminium alloy and brass after a careful material selection procedure.

3.2.1 Size of Cylinder (Barrel), Length of Stroke and Crank Plate Diameter:

The size of the briquettes produced were 40mm diameter, thus the piston sleeve of a Peugeot 504 car was used with an internal diameter of 84mm. The total length of the cylinder is 200mm, and then the length of stroke is 125mm. Therefore, the crank plate diameter is equal to 125mm equivalent to the length of stroke (Shah, 1965).

3.2.2 Size of Driven Pulley and Driven Pulley Speed:

The speed of the driven pulley was calculated (in ratio 1:5.6) and reduced to 250rpm from 1400rpm of the driver pulley (motor) speed. This enable the presses not to act as compressors especially the piston press, thus the diameter of the driven pulley was larger than the diameter of the driver pulley. This was calculated from; (Gupta and Poonia, 2004)

$$\textit{Driven}\,\text{pulley speed (rpm)} = \text{Driver pulley speed (rpm) x}\ \frac{\text{diameter of driver pulley}}{\text{diameter of driver pulley}}$$

With driver pulley diameter of 46mm, the driven pulley diameter was determined as 258mm and approximately in cm its (≈26cm)

3.2.3 Length of connecting rod and size of the piston:

The approximate analytical method was used to determine the velocity and acceleration of the piston with reference to the line diagram shown in figure 1; (Shah, 1965). This shows the arrangement of the piston-connecting-rod and crank mechanism as seen below (Figure 1).

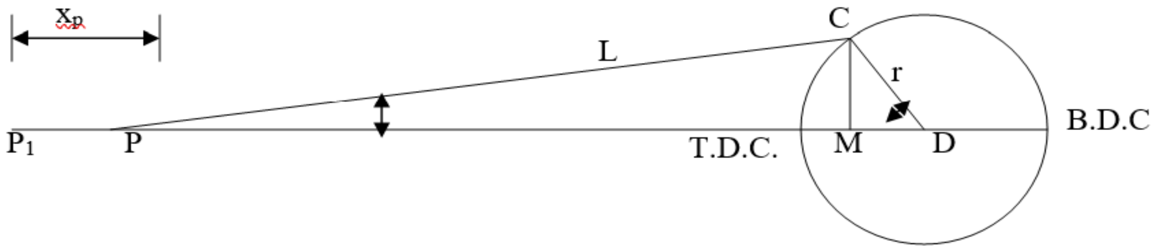

Figure 1. Piston – Connecting – Rod and Crank Mechanism

With reference to the known length of stroke of the piston, the length of cylinder, the crank diameter and the cylinder internal diameter, a line diagram of a link-mechanism consisting of the piston, crank and connecting rod was drawn. Knowing the initial position of the piston and the other parameters above, the length of the connecting rod was established as 175mm using link-mechanism construction on paper. The piston was casted to the size of ø83mm by 125mm to accommodate the required length of stroke (125mm) of the piston press.

3.2.4 The feed screw (Auger) on the screw press:

This is the prime transporter of the material for briquetting on the screw press. A mild steel flat bar of 2 mm thickness was notched with V-shaped through a length long enough to cover the screw shaft i.e. 160mm out of the 200mm length of the barrel. The distance between each flight of the auger is 30mm.The auger (screw feeder) runs with an equivalent speed of the driven pulley, which is 250rpm.

3.2.5 Extrusion Die:

These were produced in two numbers with all dimensions and features equal. They are the head of the densification presses whereby the briquettes takes and form the shape of the die (ø40mm) (Tanimu et al., 2013)

3.3 The Preparation and Production of the Sawdust Briquette

The first step in briquetting is to collect a large amount of the material. Then the material is crushed to make it smaller. Screening of feed material is essential for materials like sawdust which may contain many wooden cut pieces (Sheng, 2004). Next it is combined with a small amount of water and a binder that keeps the material from falling apart when the pressure is taken away. Clay, mud, cement and starch are commonly used binders (Gary, 2004).

The basic pre-processing steps are sieving-drying-mixing-densification & drying the briquettes. For every 3kg of screened sawdust, 1.5litres of starch was used for mixing. Starch was used because it's an organic binder, organic binders usually increase the heat value of wood briquettes and do not add to their ash content, thus briquettes made with some of these organic binders do not soften or disintegrate during combustion (Yahaya and Ibrahim, 2007).

3.3.1 Factors That Influence Energy Content

a) *Moisture content*: Lower moisture content in the raw material leads to higher compression strength and density, which correlates with higher energy content.
b) *Temperature*: Applying heat during the densification process improves the final product's physical, mechanical, and energetic characteristics.
c) *Pressure*: While pressure has some influence, its effect on strength is less pronounced than that of temperature or moisture content.
d) *Binders*: Adding binders can improve the physical and chemical properties, including the energy content, of the densified product.
e) *Pre-treatment (Torrefaction)*: Pre-treating sawdust with heat before densification like torrefaction can further increase its energy density and durability.

3.3.2 Economic Advantage in the use of Binders

The binding agency must produce a briquette of sufficient toughness to withstand exposure and the shocks of storage, transportation and stocking. Exposure to weather must not cause crumbling or excessive softening, and during combustion the exposure to heat must not cause disintegration (Yahaya and Ibrahim, 2007).

3.4 Instrumentations and Materials

3.4.1 Raw material:

Sawdust (Dried to 10 - 16% moisture content) and the use of Starch
(Locally made – wet)

3.4.2 Equipment used and their Manufacturers:

Stopwatch (GT4, Japan), Fabricated stove with Ash tray, Vanier Caliper, Thermometer (THERMEX), Digital Thermometer (0–2001range-comark, N.York), Weighing scale (Horse-race scale,U.S.A), Digital Scale (B303 College Digital balance), a standard pot (2.5 liters) and Bomb Calorimeter.

3.5 Briquettes Measurements and Comparison from Screw Press & Piston Press:

After the construction and fabrication of the prototype of the two presses, they were tested satisfactorily. The following were observed for their comparison, which are the two densification techniques. these includes wear of parts, noise, output from the machines, maintenance, density of briquette, homogeneity of briquette, friability, resistance to humidity, temperature of briquette and the combustion characteristics (calorific value).

4. RESULTS AND DISCUSSION

It was observed that the output briquettes from the screw press was continuous (12kg/hr –wet basis) while that of the piston press was in stroke (9kg/hr –wet basis). After sun drying the sample briquettes as shown in Appendix II, they were observed, measured and analyzed. On the dry basis the briquettes from the screw press have less diameter, greater mass and density but those from the piston press have greater diameter, greater volume, less mass and density.

Table 1. Density of Briquette from Screw Press

Sample	$\phi\,(\text{mm})$	$r\,(\text{mm})$	$h\,(\text{mm})$	$m\,(\text{g})$	$v\,(\text{m}^3)$	$\rho = \frac{m}{v}(g/m^3)$	$\rho\left(kg/m^3\right)$
1	37.5	18.75	69	30.30	76.22	0.398	$3.98\text{x}10^{-4}$
2	37.0	18.50	69.5	30.30	74.74	0.405	$4.05\text{x}10^{-4}$
3	36.5	18.25	70	30.24	73.25	0.413	$4.13\text{x}10^{-4}$
4	36.0	18.00	69.5	30.16	70.24	0.429	$4.29\text{x}10^{-4}$
5	37.0	18.50	69.5	30.24	74.74	0.405	$4.05\text{x}10^{-4}$
Total	184	92	347.5	151.24	369.19	2.05	$20.5\text{x}10^{-4}$
Average	36.8	18.4	69.5	30.25	73.84	0.41	$4.1\text{x}10^{-4}$

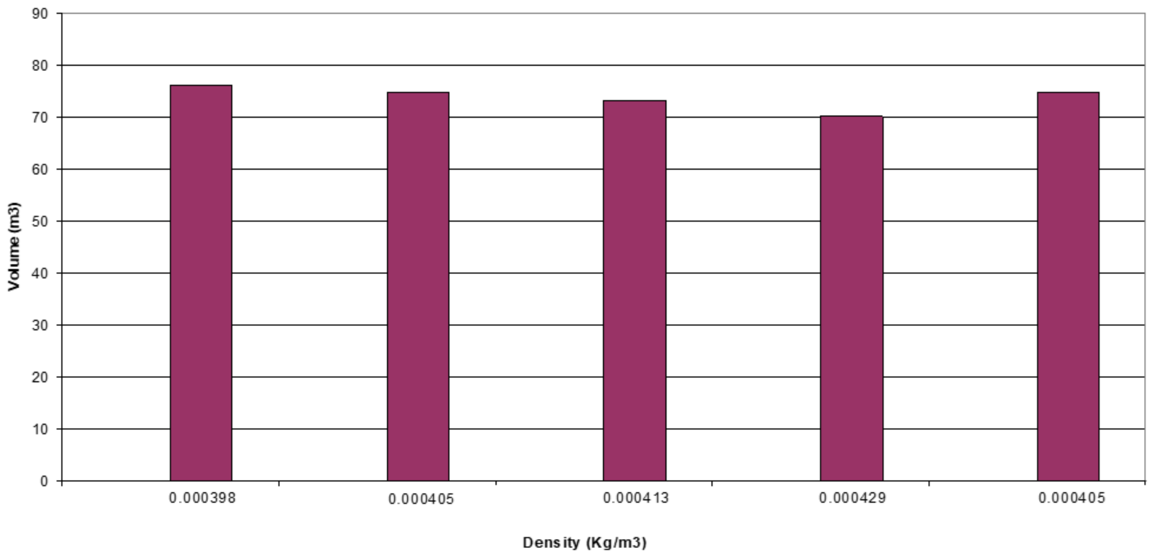

Figure 2. Volume against Density of Briquette from Screw Press

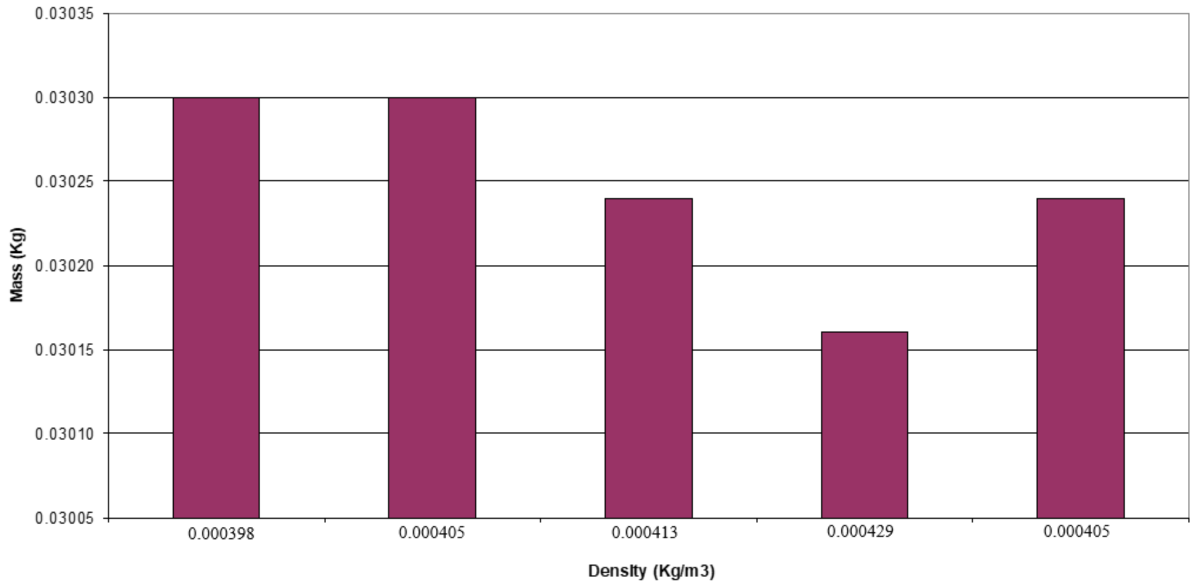

Figure 3. Mass against Density of Briquette from Screw Press

Table 2. Density of Briquette from Piston Press

Sample	ϕ (mm)	r (mm)	h (mm)	m (g)	v (m^3)	$\rho = \frac{m}{v}(g/m^3)$	$\rho\left(kg/m^3\right)$
1	38.70	19.35	69	29.50	81.17	0.339	$3.39x10^{-4}$
2	38.00	19.00	69.5	26.60	78.83	0.337	$3.37x10^{-4}$
3	38.50	19.25	68.5	26.65	79.76	0.334	$3.34x10^{-4}$
4	37.50	18.75	69	25.95	76.22	0.341	$3.41x10^{-4}$
5	38.50	19.25	69	26.70	80.84	0.332	$3.32x10^{-4}$
Total	191.2	95.60	34.5	133.4	396.32	1.683	$16.83x10^{-4}$
Average	38.24	19.12	69	26.7	79.3	0.34	$3.34x10^{-4}$

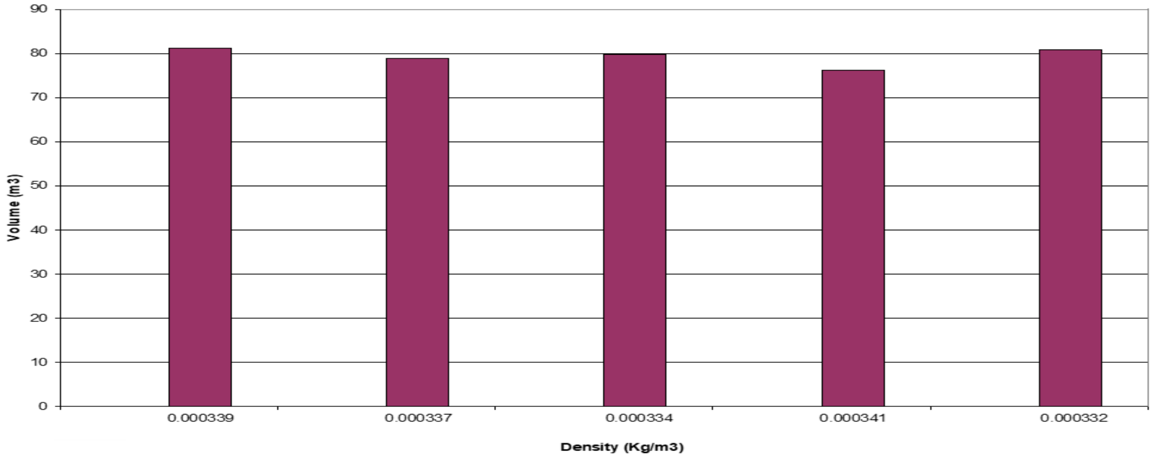

Figure 4. Volume against Density of Briquette from Piston Press

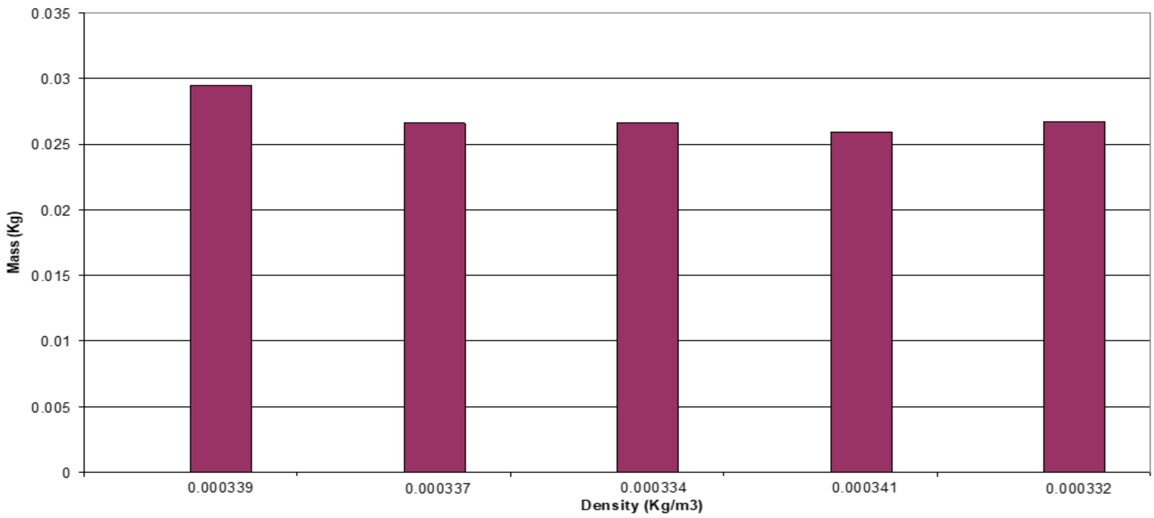

Figure 5.: Mass against Density of Briquette from Piston Press

4.1 Briquette Durability (friability) - (CRA, 1987)

Tests were done after samples of briquettes were dried.

Where H = 10ft = the chosen height for the test where the samples were dropped

= (10*0.3048) = 3.05m

a = briquette durability index

m_a = briquette remaining (g)

m_e = original wt. (g)

m_p = briquette wt. after the test (g)

Table 3. Durability of Briquette from Screw Press

Sample	$H(m)$	$m_e(g)$	$m_p(g)$	$m_a = m_e - m_\rho(g)$	$a = \frac{m_a}{m_e} \times 100(\%)$
1	3.05	30.25	29.87	0.38	1.26
2	3.05	30.30	29.99	0.31	1.02
3	3.05	30.16	29.86	0.30	0.99
4	3.05	29.98	29.63	0.35	1.17
5	3.05	30.30	30.29	0.01	0.03

Table 4. Durability of Briquette from Piston Press

Sample	$H(m)$	$m_e(g)$	$m_p(g)$	$m_a = m_e - m_\rho(g)$	$a = \frac{m_a}{m_e} \times 100(\%)$
1	3.05	25.86	25.38	0.48	1.86
2	3.05	26.72	26.24	0.48	1.80
3	3.05	27.02	27.00	0.02	0.07
4	3.05	26.60	26.05	0.55	2.07
5	3.05	26.65	26.29	0.36	1.35

4.2 Briquette Resistance to Humidity (CRA, 1987)

Where ϕ_i = initial briquette diameter (mm)

ϕ_f = final briquette diameter (mm)

T_e = elongation time (min)

e = elongation (mm)

Table 5. Resistance to Humidity of Briquette from Screw Press

Sample	ϕ_i (mm)	ϕ_f (mm)	T_e (mim)	$e = \phi_f - \phi_i$ (mm)	*Percentage* Elongation per min $(\%)$ $e/T_e \times 100$
1	36.6	40.0	15	3.4	22.7
2	37.2	40.2	15	3.0	20.0
3	37.5	40.9	15	3.4	22.7
4	36.5	40.1	15	3.6	24.0
5	36.0	39.9	15	3.9	26.0

Table 6. Resistance to Humidity of Briquette from Piston Press

Sample	ϕ_i (mm)	ϕ_f (mm)	T_e (mim)	$e = \phi_f - \phi_i$ (mm)	*Percentage* Elongation per min $(\%)$ $e/T_e \times 100$
1	38.1	42.2	15	4.1	27.3
2	37.9	41.9	15	4.0	26.7
3	38.5	42.9	15	4.4	29.3
4	38.0	42.4	15	4.4	29.3
5	38.6	43.1	15	4.5	30.0

4.3 The Water Boiling Test (WBT)

This modified version of the well-known Water Boiling Test is a rough simulation of the cooking process that is intended to understand how well energy is transferred from the fuel to the cooking pot. The modified version is WBT Version 3.0, Jan. 2007 (Rob, D. O., et al., 2007)

4.3.1 Percentage Ash Content

$$Percentage\text{ash content} = \frac{\text{Mass of ash}}{Total\text{ mass of fuel}} \text{ x } 100$$

Table 7. Briquette Percentage Ash Content

	Briquette from Screw Press			Briquette from Piston Press		
Test	Mass of Fuel Consumed (g)	Mass of Ash (g)	Ash Content (%)	Mass of Fuel Consumed (g)	Mass of Ash (g)	Ash Content (%)
WBT1	1200	57.6	4.8	1425	122.55	8.6
WBT2	1202	63.71	5.3	1405	123.64	8.8

4.4 Calculated results of the Piston Velocity

The piston velocity for the length of stroke was calculated at an interval of 45°.

$\underline{AT\ \theta = 0°}$

From this equation; (Shah, 1965): (a) $V_p = \omega r \left[\text{Sin}\ \theta + \frac{\text{Sin} 2\theta}{2\text{n}} \right]$

$$= 26.4 \text{ x } 62.5 \left[\text{Sin}\ 0 + \frac{\text{Sin}\ 0}{2 \text{ x } 2.8} \right]$$

$$= 1650\ (0 + 0)$$

$$= 0, \text{ e.t.c}$$

The results are presented in the following table below:

Table 8. Velocity of Piston for the Various Positions of the Crank Obtained

θ	0°	**45°**	**90°**	**135°**	**180°**	**225°**	**270°**	**315°**	**360°**
V_p **(m/s)**	0	1.46	1.65	0.87	0	-0.87	-1.65	-1.46	0

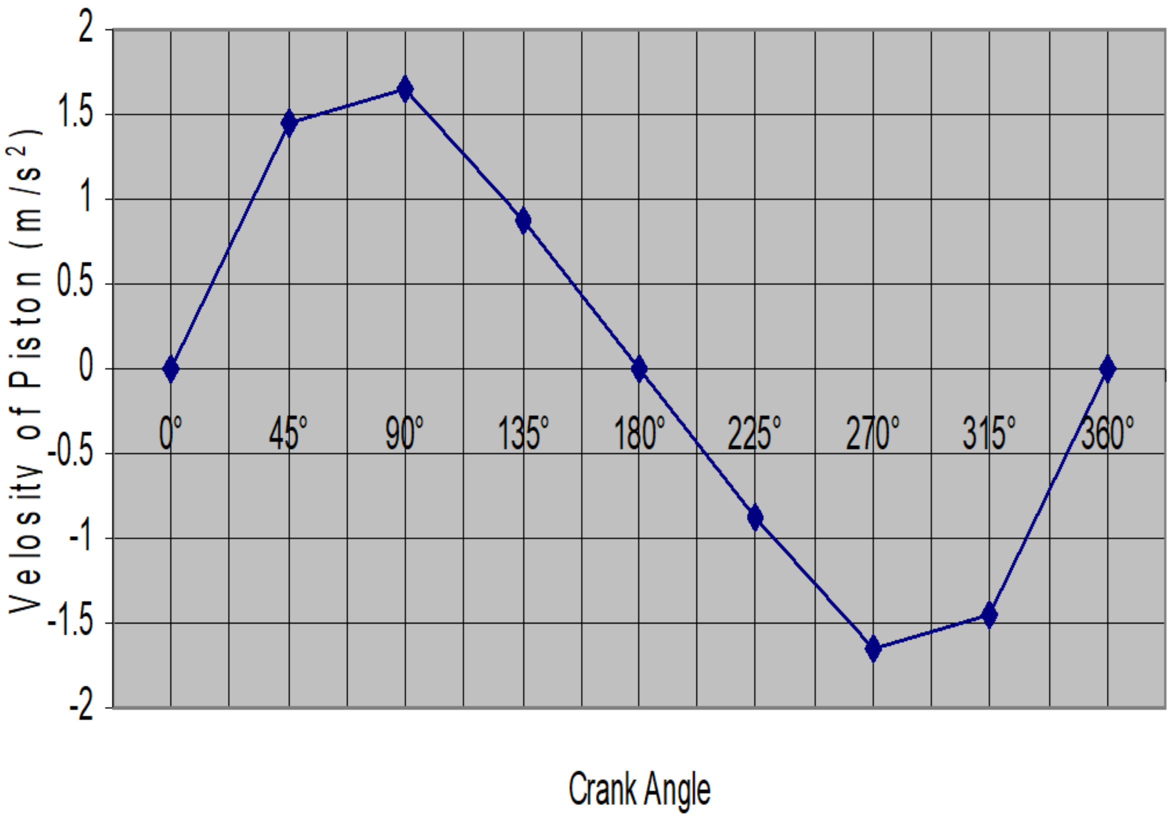

Figure 6. A Graph of Velocity of Piston Vs Crank Angle

Consequently, from the test conducted with the oxygen Bomb calorimeter, briquettes from the screw press were found to have a greater average Gross calorific value (HHV) or mass energy density of 20048 KJ/kg. The briquettes from the piston press have an average calorific value of 19244 KJ/kg while the raw sawdust had an average calorific value of 18682 KJ/kg. The friability of the briquettes from the screw press has an index of 1% while briquettes from piston press have an index of 1.35 – 2%. An acceptable value of briquette quality has an index of 0.5 – 1.5%, 0 index implies that the briquette is likely to disintegrate entirely with time. Also, the percentage elongation per minute is less on the briquettes from the screw press compared to that of the piston press. A figure of less than 50% is acceptable quality (CRA, 1987). Thus, the briquettes from the screw press have higher resistance to humidity.

Other results are summarized and tabulated as follows:

TABLE 9. Summary of the Comparison of a Piston Press and a Screw Press Densification Technique on Sawdust biomass.

S/No	Comparison	Piston Press	Screw Press
1.	Optimum Moisture Content of Raw Material	Can operate with 10-17%	10 – 15%
2.	Vibration/Noise	High	Low
3.	Maintenance	High	Low
4.	Combustion performance of briquettes	Not good	Very good
5.	Density of briquette	0.332 – 0.341 g/m^3	0.3908 – 0.405 g/m^3
6.	Mass of briquette	23.95 – 27.50 g	30.16 – 30.30 g
7.	Volume of briquette	76.22 – 81.17m^3	70.24 – 76.22 m^3
8.	Output from the machine	In stroke	Continuous
9.	Homogeneity of briquettes	Non-homogeneous	Homogeneous
10.	Wear of contact parts	Low in case of piston	High in case of screw
11.	Calorific value of briquette	Low	High

5. CONCLUSIONS

In conclusion, while mechanical densification primarily improves the physical properties and volumetric energy, pre-treatments like torrefaction or carbonization are necessary to enhance the specific mass-basis energy content of sawdust, creating a high-quality solid biofuel. Other advantages include;

i) In the application of sawdust as solid fuel, forming briquettes facilitates handling, storage and transportation.

ii) The densification techniques increase the net calorific value of sawdust per unit mass

iii) The briquetting process can help to solve the problem of wood residues disposal.

iv) The screw press densification technique produced stronger, uniformly-sized and dense briquettes which are recommended for carbonization. Although the carbonized charcoal produced are brittle.

v) The finished briquettes from the piston press need much protection from re-absorption of moisture than the briquettes from the screw press. This is because they are less dense and should be stored in dry areas. They need much careful handling to prevent crumbling.

vi) Densification of sawdust using the screw press can be easily employed to set up a small-scale factory. This is because its output is continuous and the briquette is uniform in size. The screw press also runs very smoothly without much noise, and the machine is light compared to the piston press because of the absence of reciprocating parts and crank plate.

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Conflicts of Interest
The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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APPENDIX I

Front view Photograph of the two Presses before painting

Front view Photograph of the two Presses after painting

APPENDIX II

Sample of Briquettes from Screw Press

Sample of Briquettes from Piston Press