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Design and fabrication of biomass densification machine for teaching and research purposes

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Abstract

In developing nations, research output is limited due to factors like unreliable power supply and inadequate laboratory equipment. The high cost of purchasing completed laboratory equipment and the unavailability of accessories for imported equipment further contribute to this issue. A biomass densification machine was designed and constructed to address these challenges for teaching and research purposes. The machine was tested at five different compaction pressures (100, 200, 300, 400, and 500 kPa) using gelatinized cassava starch as a binder. The physical and mechanical characteristics of the produced fuel briquettes were investigated following ASTM standards and procedures reported in the literature. The results show that the physical and mechanical properties of the fuel briquettes increase with compaction pressure. The compressive strength, durability, and water resistance of the briquettes varied between 55 and 101 $\mathrm{kN{\cdot}m^{-2}}$, 89–99%, and 20–120 min, respectively, while the compressed and relaxed densities range from 0.780 to 1.220 $\mathrm{g{\cdot}cm^{-3}}$ and 0.670 to 0.990 $\mathrm{g{\cdot}cm^{-3}}$, respectively. The machine performed satisfactorily because the briquettes' characteristics were found to meet the specified ISO Standard (17225). The development of this machine will enable academic institutions, researchers, and students to harness the potential of biomass through the densification process without the challenges posed by imported equipment. The creation of the machine will also facilitate students' hands-on learning. By providing an easily accessible and reliable platform, academic and research institutions can integrate biomass solid fuel production experiments into their curricula, fostering a thorough understanding of renewable energy solutions and supporting sustainable practices. Therefore, it can be recommended for teaching and research in developing nations. Incorporating an electronic component, such as a digital pressure gauge and electric hydraulic jack, is recommended for future research to enhance the performance.

Keywords Briquettes · Compaction pressure · Laboratory equipment · Mechanical property · Physical property

Highlights

- Design and fabrication of biomass densification machine were carried out.
- The fabricated machine was tested by producing fuel briquettes using torrefied rice as feedstock.
- The physical and mechanical characteristics of the produced fuel briquettes were investigated, and the properties of the fuel briquettes increased with compaction pressure.
- The developed biomass densification machine performed satisfactorily and is recommended for teaching and research purposes in developing nations.

1 Introduction

In research and teaching, ultra-modern measuring instruments and laboratory equipment/apparatus play a crucial role in enabling scientific advancements and broadening horizons [1, 2]. However, the acquisition and use of such instruments recurrently present challenges, such as the

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need for highly experienced operators, high maintenance costs, and a dependence on overseas dealers for spare parts [3]. These challenges can limit the accessibility of essential equipment, cause poor performance, and slow research progress, including biomass densification research [4].

Biomass densification is the process of compressing biomass feedstock into high energy-dense solid fuels [5]. Biomass densification can be done with or without the application of heat [6, 7]. It can also be performed with or without using a binding agent [8–10]. The densification process includes briquetting, pelletizing, bailing, and cubing [11]. Pelletizing and briquetting are the most popular processes of biomass densification [5]. The product of briquetting and pelletizing processes are called briquettes and pellets, respectively. Biomass densification holds high potential as a sustainable and alternative energy solution. It provides several environmental advantages, such as reduced greenhouse gas emissions and a renewable energy option [12]. Additionally, it can be adopted as a waste management technique for converting forest, agricultural residues, industrial, and domestic wastes/residues into usable energy [13, 14].

Briquettes and pellets have expanded acceptance as sustainable and renewable substitutes to fossil fuels. They are generally used in domestic and industrial applications for power generation, cooking, and heating [15, 16]. A critical measure in ensuring that these solid fuels can be used consistently with good quality across different applications and commercial production is to ensure that they meet the criteria set out by the ISO Standard (17225) [17]. ISO standard specifies pellets as cylindrical and usually 6–25 mm and 3.15–50 mm in diameter and length, respectively [18]. In contrast, depending on the production processes, briquettes are often bigger (50–400 mm and 25–125 mm in length and diameter, respectively) and have diverse shapes [18]. The ISO Standard (17225) stipulates that the physical, chemical, and thermal characteristics of pellets and briquettes, such as ash content, moisture content, durability, and calorific value, must match specific standards. For instance, the moisture content of pellets and briquettes must be less than 10% of the total weight. Pellets and briquettes must have an ash content of less than 0.700% and 3%, respectively. Pellets and briquettes must have a minimum calorific value of 16.500 MJ/kg and 15 $\mathrm{MJ\cdot kg^{-1}}$, respectively. After mechanical processing and transportation, the durability of pellets shall be at least 97.500% and that of briquettes at least 85% [17, 18].

The effective deployment of biomass densification techniques depends significantly on the availability and accessibility of dedicated equipment and machinery. The biomass densification machines available in the market are expensive and unaffordable for educational and research institutions, particularly institutions in developing countries [3, 19]. Furthermore, the dependence on foreign suppliers for replacement parts and maintenance usually cause financial strains and delays [3].

Identifying the drawbacks caused by these challenges, this study presents the design and construction of a biomass densification machine precisely personalized for teaching and research purposes. The primary motivation for developing this equipment arises from the need to mitigate the challenges related to the importation and utilization of laboratory equipment. By designing and fabricating cost-effective equipment, the machine will empower researchers, students, and educational institutions to harness the potential of biomass through the densification process without the difficulties associated with imported equipment.

Research on developing equipment and machines for biomass densification has been recorded in developing nations. Jha and Yadav designed and fabricated briquetting machines on a laboratory scale to manufacture fuel briquettes using sawdust as feedstock [20]. The effect of binder and moisture content on the briquette produced was investigated. The fabricated machine produced briquettes at 7 kg/h.

The performance of the palm waste screw press briquettes molding machine was evaluated using different blends of the feedstock [21]. The machine was constructed using mild steel. The machine was capable of manufacturing briquettes for both domestic and industrial applications. A daily throughput of 1300 kg was achieved using the fabricated machine. Though an improvement in throughput was reported, there was no report on the pressure at which the machine was compacting the feedstock to produce the fuel briquettes. Similarly, a compression machine was constructed to make fuel briquettes from palm meat and fiber [22]. The machine compaction force was derived from a hydraulic system and electric motor. The machine's performance was evaluated using different feedstock, water, and binder blends. The compaction pressure varied between 108 and 196 kPa. The properties of the produced briquettes meet the established standard except for density.

A densification machine was designed and fabricated for biomass solid fuel production using vegetable residues as feedstock [23]. The machine compaction forces were derived from a 3-ton hydraulic jack. The performance of the machine was evaluated, and 96.300% efficiency was recorded with a maximum capacity of 0. 291 $\mathrm{kg\cdot h^{-1}}$. There was no report on the measurement of machine compaction pressure. Another briquetting machine was designed and fabricated to convert agricultural and forest residues to solid fuel [24]. The machine was tested using dry leaves and sawdust as feedstock. Wheat flour and coffee husk were utilized as the binder. The results show that briquette manufacture using wheat flour displayed better physico-mechanical and thermal properties than briquettes made from the coffee husk. The machine developer does not consider measuring the machine compaction pressure in the design stage. Tembhekar et al.

[25] designed a compact briquette machine for dry coconut biomass using molasses as the binding agent. The article focuses majorly on the design of the compaction systems, motor, and cutter. Transmission of power from the electric motor to the cutter was through a belt drive. There was no report on the fabrication of the machine. Analysis of the design machine revealed that measurement of the machine compaction pressure was not considered in the design.

Ikubanni et al. [26] designed, fabricated, and carried out the performance evaluation of a piston-type briquetting machine. The performance evaluation of the machine was carried out using a mixture of sawdust and rice husk as feedstock, while urea–formaldehyde was utilized as the binding agent. The physico-mechanical and combustion properties of the produced fuel briquettes were investigated. The capacity and efficiency of the constructed machine were 68.56 kg/h and 85.700%, respectively. The briquette characterization results showed that the machine produced briquettes of good quality. However, the measurement of the machine compacting forces was not considered in the design of the machine, and there was no report on pressure measurement during the performance evaluation. Sribalaji and Kumar [27] designed and fabricated a low-pressure biomass briquetting machine using a screw die technique. An electric heater was fixed at the outer surface of the die to raise the temperature of the die to about 300 °C. This was to enhance the combustion property of the feedstock and the binding property of the binder. The fabricated machine was reported to perform satisfactorily with an energy reduction of about 35%. There was no information on the pressure measurement during the construction, and testing of the machine.

The low research outcome in renewable energy through biomass densification in developing nations has been attributed to inadequate laboratory equipment [28–30]. This is due to the high cost of purchase and importation of foreign laboratory equipment. Also, the accessories of equipment manufactured abroad are unavailable locally, making maintenance and optimum utilization of imported equipment for teaching and research purposes difficult. Furthermore, the locally fabricated laboratory equipment must be improved to enhance research quality and accuracy. Therefore, biomass densification machine was designed and constructed in this study using locally available materials. The machine was developed with particular attention to affordability, easy maintenance and lower maintenance cost, and user-friendly operation. This study uses locally available components and materials to minimize reliance on foreign dealers and build self-sustainable teaching and research facilities for biomass densification studies in developing nations.

The development of a biomass densification machine would have a positive impact on the attainment of the United Nations' Sustainable Development Goals (SDGs) by 2030. Its implementation would specifically enhance access to research and technology in clean energy, including renewable energy and energy efficiency while encouraging investment in energy infrastructure and clean energy technology (SDG 7) [31, 32]. Additionally, the development of this machine aligns with the vision of the United Nations to expand infrastructure and upgrade technology for providing modern and sustainable energy services to all individuals in developing countries [31].

In many instances, agricultural and forest residues in developing countries are either discarded in open fields or burned openly, resulting in the emission of greenhouse gases and contributing to climate change [5]. This machine facilitates the conversion of agricultural and forest residues into energy that can be effectively utilized. As a result, developing nations can make strides towards accomplishing SDG 13, which seeks to diminish the occurrence and intensity of extreme weather phenomena caused by climate change [33]. The deployment of the biomass densification machine would advance research in renewable energy, promote mechanisms to enhance capacity for effective climate change-related research in the least developed countries, and ultimately reduce climate change impacts.

The novelty in the design includes the addition of a pressure gauge to measure the machine compaction pressure, the use of the different sizes of mold (the mold is detachable), producing four samples per sort, and using a semi-permanent assembly method. In addition, the developed machine is portable, simple to use, and less expensive.

2 Methodology

2.1 Materials

In this study, materials were selected based on availability, cost, strength, machinability, and suitability for constructing each part of the machine. The materials and standard parts selected include the front-fork pipe of a motorcycle, mild steel shaft, pressure gauge, hydraulic jack, tension helical spring, angle iron, metal plate, bolts, nuts, rice husk, and cassava starch. The hydraulic jack was bought at Ilorin, Kwara State, Nigeria. Rice husk was collected at a rice mill factory in Ganmo, Kwara State, Nigeria. Cassava starch was obtained at a cassava-processing factory, Gaa-Akanbi, Kwara State, Nigeria. The pressure gauge was bought at Iffy Tools, Taiwo-oke, Ilorin, Kwara State, Nigeria. The tension spring was obtained at Arimoore International, Taiwo-oke, Ilorin, Kwara State, Nigeria. All other components were obtained at Oko-Erin, Sawmill, Ilorin, Ilorin, Kwara State, Nigeria.

2.2 Design consideration

The design of the densification machine for developing nations considers elements like price, the use of standard parts, size, application, assembly, number of samples per sort, material availability, and robustness. Some parts of the machine were made cheaper by employing motorcycle and metal scraps, while others were made more affordable using standard interchangeable parts. The device was made specifically for lab or research use and was intended to be portable, strong, and long-lasting. The assembly technique was semi-permanent, and locally available materials were used to ensure simple part replacement. It was thought the samples for each type.

2.3 Design calculation of the hydraulic briquette press

2.3.1 Determination of the size of the mold

The mold comprises two main components: the sleeve and the piston. The front-fork pipe of a motorcycle was used for the fabrication of the sleeve. The pipe is made of stainless steel. It was surface treated with rust-proof oil plated to avoid corrosion. The internal and external diameters are 24 and 30 mm, respectively. The height of the sleeve was made to be 75 mm. The internal structure of the sleeve (space enclosed) forms the volume of the mold, while the height of the sleeve equals to the height of the mold. During densification, biomass feedstock occupies the space enclosed (internal diameter) by the sleeve (mold). And by extension, the inner diameter of the mold is approximately equal to the external diameter of the solid fuels produced using the machine. Therefore, the volume of the mold is calculated using Eq. 1 [23].

$$v = \frac{\pi d^2 h}{4} = 33,933.600\ \text{mm}^3 \tag{1}$$

where v is the volume of the mold, h is the height of the mold, and d is the internal diameter of the sleeve.

The mold was designed to generate 4 briquettes per sort; therefore, the total volume of the mold is calculated using Eq. 2.

$$V = 4 \times v = 135,734.400\ \text{mm}^3 \tag{2}$$

To ensure that the sleeve is designed and manufactured according to the appropriate specifications, it is recommended to utilize grade 442 (AISI 442) stainless steel alloy. This stainless steel possesses desirable characteristics such as a tensile strength within the range of 515–550 MPa, a maximum working temperature between 925 and 980 °C, and a melting point of 1065–1120 °C [34–36]. Moreover, grade 442 stainless steel exhibits excellent resistance against corrosion [35]. The biomass densification machine operates as a cold press type, meaning it functions at room temperature. The mold employed in this machine is expected to operate in a humid environment due to the inclusion of water during the biomass mixing process. However, grade 442 stainless steel is specifically manufactured to withstand corrosion. Consequently, the likelihood of mold (sleeve) failure resulting from corrosion and operating temperature is minimized through the use of grade 442 stainless steel.

Given that the ultimate tensile strength of stainless steel is 550 MPa and adopting a factor of safety of 5, the allowable tensile stress of the sleeve is calculated using Eq. 3 [34–36].

$$\delta = \frac{t}{f} = 110\ \text{MPa} \tag{3}$$

where t is the ultimate tensile strength of the mold material, f is the factor of safety, and δ is the allowable tensile stress.

According to Khurmi and Gupta, a cylindrical pipe can fail due to circumferential or longitudinal stress [36]. Therefore, neglecting the efficiency of the welded joints, the minimum thickness of the mold that would prevent failure due to circumferential and longitudinal stress is calculated using Eqs. 4 and 5.

$$T = \frac{p_c d}{2\delta\eta} \tag{4}$$

$$T = \frac{p_l d}{4\delta\eta} \tag{5}$$

T is the thickness of the sleeve; p_c is the pressure in the sleeve, considering circumferential stress; p_l is the pressure in the sleeve considering longitudinal stress; d is the internal diameter of the sleeve; δ is the allowable tensile stress; and η is the efficiency of the welded joint.

Considering failure due to circumferential stress,

$$p_c = \frac{2\delta\eta T}{d} = 45\ \text{MPa}$$

Considering failure due to longitudinal stress,

$$p_l = \frac{4\delta\eta T}{d} = 90\ \text{MPa}$$

Therefore, the pressure in the sleeve must be less than 45 MPa.

The machine was designed to consist of four sets of pistons. The pistons were fabricated from a solid shaft made of mild steel. Mild steel was used for easy turning of the material to the desired diameter. The initial diameter of the selected shaft was 25 mm. A clearance fit of 1 mm was provided between the sleeve and the piston so that the pistons could move freely in the sleeve without friction. The diameter of the shaft was reduced to 23 mm (diameter of the piston) using a CNC lathe machine at the Faculty of Engineering and Technology, University of

Ilorin, Nigeria. The length of the piston is the same as the height of the sleeve.

Considering the deflection of the piston due to buckling, the moment of inertia is calculated using Eq. 6 [26].

$$K = \sqrt{\frac{I}{A}}; I = \frac{\pi d^4}{64}; A = \frac{\pi d^2}{4} \tag{6}$$

where K is the radius of gyration, d is the diameter of the piston, I is the moment of inertia, and A is the cross-sectional area of the piston.

By computation, $K = 520$ mm

2.3.2 Selection of hydraulic jack and pressure gauge

The locally available hydraulic jacks were rated in tons. From the market survey, hydraulic jacks available were 3, 5, 10, and 20 bars. A 5-bar hydraulic jack was selected considering the cost and calculated pressure.

The maximum pressure generated by a 5-ton hydraulic jack is calculated using Eq. 7.

$$P = \frac{F}{A_j}; A_j = \pi r^2; F = ma \tag{7}$$

where F is the hydraulic force, A_j is the cross-sectional area of the hydraulic jack piston head, a is the acceleration due to gravity (9.810 $m{\cdot}s^{-2}$), m is the mass, and r is the radius of the hydraulic piston head.

The radius of the piston was measured to be 0.021 m using a Vanier caliper.

$$5 \text{ ton} = 5000 \text{ kg}$$

Therefore,

$$A = \pi r^2 = 0.001 \text{ m}^2$$

$$F = 59,050 \text{ N}$$

$$P = 35.035 \text{ MPa}$$

2.3.3 Pressure gauges

With careful modification, the pressure gauge was incorporated into the hydraulic jack. This was done by drilling a hole from the jack's center to connect with the gauge to measure the hydraulic pressure imparted by the jack, and this was measured in bars.

$$\begin{aligned} \text{Since } 1 \text{ bar} &= 0.100 \text{ MPa} \\ 35.035 \text{ Mpa} &= 350.350 \text{ bar} \end{aligned}$$

This implies that a pressure gauge greater than 350.350 bar must be selected to avoid damage to the pressure gauge. Therefore, 400-bar pressure gauge was selected for the design.

2.3.4 Design of the top and bottom plate

The top and the bottom plate are made of mill steel. This ensures that the frame can give the machine the required structural rigidity and support. The dimension of the plate is 300 × 300 mm. The bottom and top plate are subjected to a concentric load of 59,050 N. Assuming that the load is acting over a small plate area, the resulting direct stress and bending stress are determined using Eq. 8 [36].

$$\sigma_m = \frac{1.5P}{\pi t^2}\left[(1+v)\ln\frac{2b}{\pi e} + 1 - k_2\right] \tag{8}$$

Simplifying Eq. (8) gives Eq. 9.

$$t = \sqrt{\frac{1.5P}{\pi \sigma_m}\left[(1+v)\ \ln\frac{2b}{\pi e} + 1 - k_2\right]}; y_{m=}k_1\frac{Pa^2}{Et^3} \tag{9}$$

where $a = b$ is the length of the plate (mm) P is the concentrated load (N), v is the Poisson's ratio, E is the Young's modulus ($N{\cdot}mm^{-2}$), t is the plate thickness (mm), e is the radius of area with force applied (mm), σ_m is the maximum stress ($N{\cdot}mm^{-2}$), and y_m is the maximum deflection (mm).

The dimension of the top and bottom plate is 300 × 300 mm; therefore, $\frac{b}{a} = 1$. Therefore, k_1 and k_2 are 0.127 and 0.564, respectively [37]. The Poisson ratio, Young modulus, and ultimate tensile strength of mild steel are 0.303, 200 GPa, and 400 MPa, respectively [36, 38, 39]. With the aid of a Vernier caliper, the radius of the contact head of the hydraulic jack was measured to be 0.018 mm. The concentrated load is the hydraulic force, which is 59,050 N.

By computation, $t \approx 27$ mm.

2.3.5 Design of the tension spring

The tension springs were incorporated to force the piston of the hydraulic jack to the initial position after releasing the pressure valve. The available spring in the market had the following specifications:

$$\begin{aligned} &\text{Mean diameter of the coil } (D) = 16.500 \text{ mm} \\ &\text{Diameter of the wire } (d) = 1.500 \text{ mm} \\ &\text{Modulus do rigidity } (G) = 80 \text{ kN} \cdot \text{mm.}^{-1} \\ &\text{The spring index } (C) = \tfrac{D}{d} = 11 \end{aligned}$$

Therefore, Wahl's stress factor (K) is calculated using Eq. 10 [36].

$$K = \frac{4C - 1}{4C - 4} + \frac{0.615}{C} \tag{10}$$

The deflection of a tension spring is calculated using Eq. 11 [36].

$$\varphi = \frac{8w_j C^3 n}{Gd} \tag{11}$$

where φ is the deflection of the spring, w_j is the torsional load, C is the spring index, d is the diameter of the wire, n is the number of active turns, and G is the modulus of rigidity.

The maximum deflection of the spring is equal to the distance between the bottom of the hydraulic jack and the top of the mold, which is equal to 96.650 mm.

By simplifying Eq. 11, $n = \frac{\varphi Gd}{8w_j C^3} \cong 11$.

The maximum shear stress of the spring is calculated using Eq. 12 [36].

$$\tau_{max} = \frac{K8w_j C}{\pi d^2} \tag{12}$$

By computation, $\tau_{max} = 394.491$ MPa.

The free length (L_f) of the spring is determined using Eq. 13 [36].

$$L_f = n' d + \varphi + 0.15\varphi \tag{13}$$

For a tension helical spring,

$$n' = n + 1 \tag{14}$$

By computation, $L_f = 129.148$ mm.

2.4 Testing of the fabricated machine

The densification machine was tested using torrefied rice husk as feedstock. The feedstock was collected and sorted to remove unwanted materials. The sorted rice husk was torrefied at 260 °C at 30 min of residence time. There was no particle reduction process carried out on the feedstock. Solid fuel briquettes were manufactured using gelatinized cassava starch as a binder. The effects of compaction pressure were investigated on the produced fuel briquettes' physical and mechanical properties.

2.4.1 Operation of the machine

After adequately mixing the feedstock, the metal plate was placed at the base of the machine to cover the ejection space. The sleeve was placed on the metal plate, after which the feedstock was poured into the mold. The piston was made to align with the sleeve of the mold. The valve of the hydraulic jack was closed, and the jack was pumped using the pumping level. The pressure gauge displays the compaction pressure, and the piston was allowed to dwell on the feedstock for 4 min [40]. After dwelling time was reached, the valve of the jack was released. The mold was lifted to remove the metal plate covering the ejection space. The mold was returned while the valve of the hydraulic jack was closed. The briquettes were ejected through the opening created at the base of the machine by pumping the hydraulic jack. The valve of the hydraulic jack was released after ejection. The procedure is repeated for another round of the densification process. The produced briquettes were sun-dried for 7 days, after which they were kept in an air-tight bag for characterization. The sample of torrefied briquettes is shown in Fig. 1(a), while Fig. 1(b) and (c) show non-torrefied briquettes produced using the developed machine.

2.4.2 Characterization of the produced fuel briquettes

The green (briquettes immediately after ejecting from the mold) and relaxed (dried briquettes) densities of the produced briquette were determined using Eq. 15.

$$Density = \frac{mass\ of\ the\ briquette}{calculated\ volume\ of\ the\ briquette} \tag{15}$$

The resistance of the briquettes to compressive load was determined through investigation of the strength property according to ASTM D2166-85 standard using a Universal Testing Machine [41]. Also, the durability, which is the resistance of the briquettes to impact and rubbing load, was investigated by dropping briquette samples 4 times repeatedly from a height of 1.85 m onto a solid base [42]. Equation 16 was adopted for calculating durability. The relaxation ratio and water resistance of the briquette were calculated using Eqs. 17 and 18, respectively.

$$Durability = \frac{weight\ of\ briquette\ in\ plate\ after\ 4\ drops}{the\ initial\ weight\ of\ the\ sample} \times 100\% \tag{16}$$

$$Relaxation\ ratio = \frac{compressed\ density}{relaxed\ density} \tag{17}$$

$$Water\ resistance = time\ taken\ in\ seconds\ for\ the\ briquette\ to\ collapse\ in\ water \tag{18}$$

3 Results and discussion

3.1 Testing and specification of the fabricated machine

The biomass densification machine was designed and fabricated for teaching and research purposes. The machine was tested using torrefied rice husk as feedstock at different compaction pressure (100, 200, 300, 400, and 500 kPa). Four samples were

Fig. 1 The briquettes produced using the fabricated machine: **a** torrefied briquettes and **b** and **c** non-torrefied briquettes

produced per sort. Four samples were utilized for every test conducted. Through the densification process, it was observed that the gelatinized cassava starch, used as a binder, also functions as a lubricating agent. This property aid the smooth flow of biomass feedstock through the mold. This observation aligns with the findings reported by Sermyagina et al. [43], who confirmed that gelatinized starch also serves as a lubrication agent. The machine allows the use of different molds, provided that the height of the mold is not greater than 180 mm. The length and diameter of biomass solid fuel briquette range between 50–400 mm and 25–125 mm, respectively, as set out by ISO standard (ISO 17225) [17]. The length of the briquette produced using the developed machine is 64 mm. The diameter of the briquette (approximate diameter of the mold) in the study is 24 mm, which is less than the 25-mm minimum diameter set out by ISO standard. This is because the mold was fabricated using a standard material (front-fork pipe) manufactured at a specific diameter (24 mm). However, the mold of the machine is detachable, and the machine allows the utilization of mold with different geometric. Another mold of 60-mm diameter and 150-mm length was used, and the briquettes generated are shown in Fig. 1(c).

Depending on the type of mold used on the machine and the quantity of feedstock poured into the mold, it can be argued that the geometry of the briquettes manufactured using the developed densification machine meets the criteria of ISO standard. Furthermore, the operation of the machine and the characteristics of the briquettes produced describe the suitability of the biomass densification machine for teaching and research purposes, as it will facilitate practical learning experiences for students. By offering an accessible and reliable platform, educational and research institutions can incorporate biomass solid production experiments into their curriculum, promoting an in-depth knowledge of renewable energy competence and encouraging sustainable practices. The developed machine presents a significant potential to advance progress in the energy field and contribute to expanding sustainable energy solutions in developing countries.

A detailed analysis of the quality assessment, including the impact of compaction pressure on the density and durability of the briquettes produced with the developed machine, can be found in the works of Ibitoye et al. [40, 44]. It is worth noting that the biomass densification machine operates as a cold press type, functioning at room

Table 1 Specification of the fabricated biomass densification machine

S/N	Parameters	Specification
1	Diameter of the sleeve	24 mm
2	Diameter of the piston	23 mm
3	Maximum compacting force	59,050 N
4	Capacity of pressure gauge	40 MPa
5	Number of samples per sort	4
6	Size of the machine	300 × 300 × 550 mm

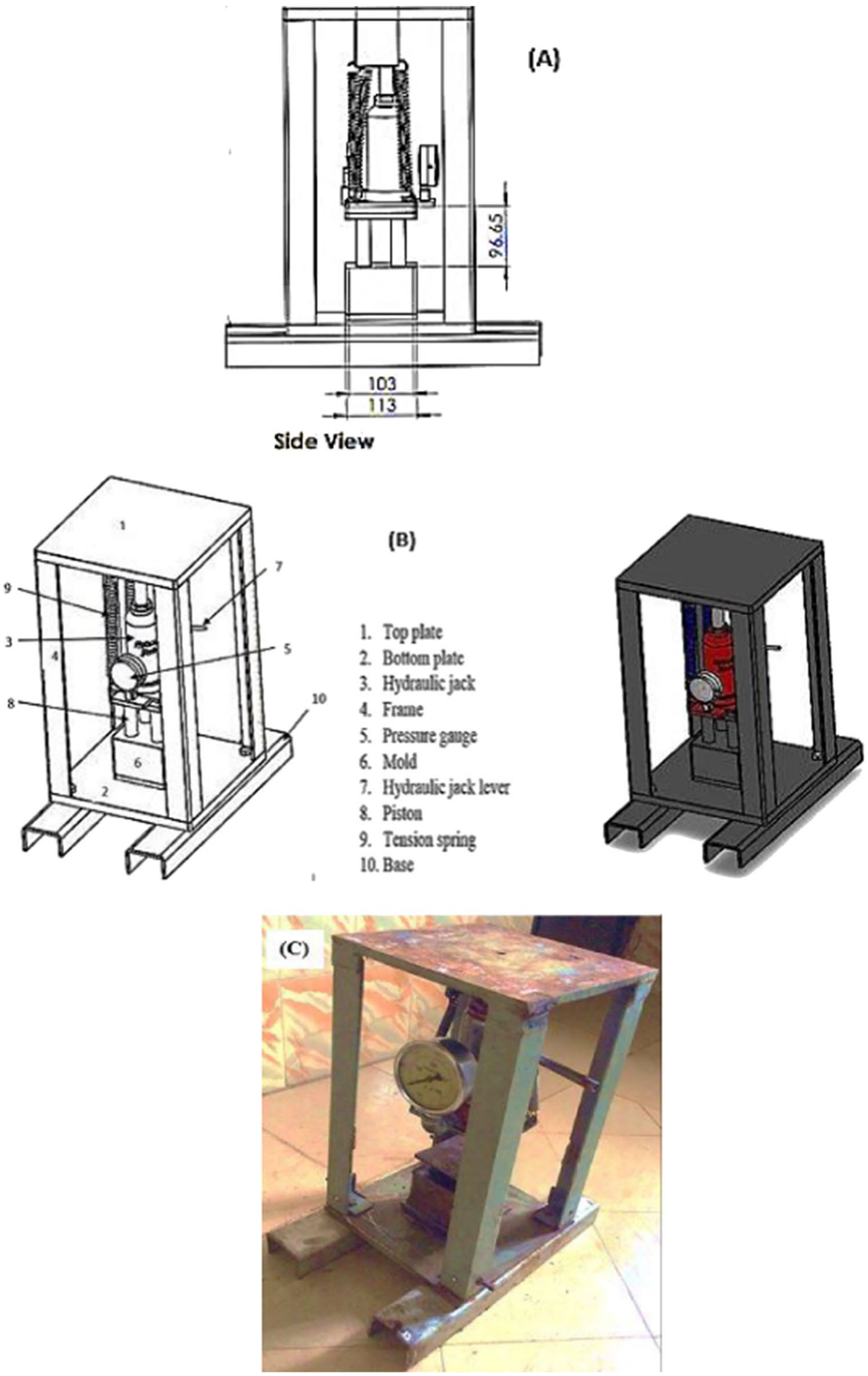

Fig. 2 Autographic (**A**) and isometric (**B**) views of the designed and fabricated (**C**) biomass densification machine

temperature. Therefore, investigating the influence of operating temperature on the performance of the machine may not be necessary. The specification of the fabricated machine is presented in Table 1. Figure 2 shows the designed and fabricated densification machine.

3.2 Characterization of the produced fuel briquettes

Figure 3 shows the effect of compaction pressure on compressive strength, durability, and water resistance. The

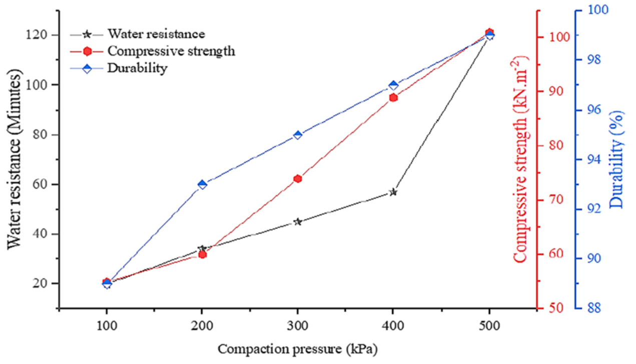

Fig. 3 Effect of compaction pressure on compressive strength, durability, and water resistance

compressive strength, durability, and water resistance of the briquette varied between 55–101 kN·m^{-2}, 89–99%, and 20–120 min, respectively. All the briquette properties investigated were found to increase with compaction pressure. This is because the applied pressure enhances the intermolecular bonding of briquette particles. This makes the adjacent particles interlock, improving the compressive and durability of the briquettes [45]. Higher compaction reduces the pore space between the particle. This reduces water percolation and capillary action, increasing the water-resistance characteristics of the produced briquettes. The observed trend agreed with the findings of Fehse et al. [46], who suggested in their study that the quality of briquettes improves as the compaction pressure increases. Similar observations were made by Ajimotokan et al. [11] while assessing the physico-mechanical properties of briquettes made from corncobs and rice husks. They also found that higher compaction pressure leads to enhanced physico-mechanical properties. However, it is worth noting that the optimum durability and compressive strength reported by Ajimotokan et al. were higher (99.13% and 111 kN·m^{-2}, respectively) than the values recorded in the current study. This difference could be attributed to the blend of biomass utilized in briquette production. The study indicated that blending different biomass feedstock can result to fuel property compensation and improve fuel quality.

Research has shown that increased compaction pressure results in better durability properties of biomass solid fuel [47]. Further, when the property of the briquette produced in this study was compared with the briquettes made by Ikubanni et al. [26], it was found that the briquettes manufactured in this study displayed better durability. However, the compressive strength of the briquette is less than the value reported by Sellin et al. [48]. The Sellin et al. briquettes were manufactured at a pressure higher than the pressure used in this study. Therefore, the significant difference in compressive strength could result from variations in the compaction pressure used to produce the briquettes.

The effect of compaction pressure on relaxed and compressed density is presented in Fig. 4. The compressed and relaxed densities range from 0.780 to 1.220 g·cm^{-3} and 0.6700 to 0.99 g·cm^{-3}, respectively. Analysis of the results on density revealed that relaxed and compressed densities increase as the densification pressure increases. As the compaction pressure increases, the calculated volume decreases at constant mass, which increases density [49]. The maximum compressed density obtained in the study is in agreement with the maximum density (1.212 g·cm^{-3}) reported by Chen et al. [6]. The maximum density by Chen et al. was achieved at 152.6 °C densification temperature, while the solid fuel produced in this study was manufactured at room temperature. Considering that the developed machine does not require an external heating device to produce high-density solid fuel, it is more economical compared to the pelletizing device developed by Chen et al. [6]. The density of the briquettes produced by Ikubanni et al. [26] is within the range of the briquette manufacturers using the developed machine. Furthermore, a study conducted by Yang et al. [44] discovered that the density of manufactured fuel briquettes rises as the compaction pressure increases. They also reported that a continuous increase in pressure leads to

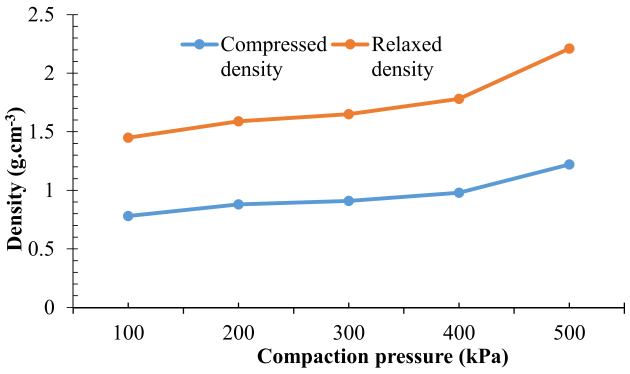

Fig. 4 Effect of compaction pressure on relaxed and compressed density

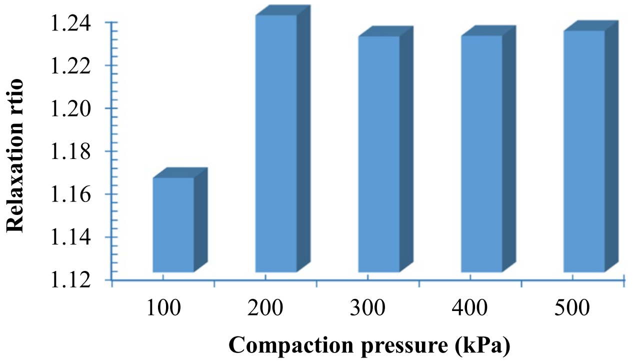

Fig. 5 Effect of compaction pressure on relaxation ratio

higher energy consumption — the findings of Yang et al. align with the trend observed in the present study. Additionally, it was observed in this study that higher compaction pressure necessitates more physical energy from the operator.

The relaxation ratio of solid fuel briquettes reveals how stable the briquettes will be during the storage period. This characteristic is important for transportation packaging and storage of the fuel briquettes. The smaller the relaxation ratio, the more stable the briquettes are during storage. A smaller relaxation ratio indicates large-volume displacement. The examination of the findings demonstrated that the relaxation ratio also rises as the densification pressure increases. This observation aligns with the results reported in the literature [50]. Figure 5 presents the variation of the relaxation ratio with the compaction pressure.

4 Conclusion

The biomass densification machine was designed, fabricated, and tested for teaching and research purposes in developing nations. The machine was tested at different compaction pressures and four samples were generated per sort. The machine enables the utilization of various molds as long as the height of the mold height does not exceed 180 mm. The geometry of the briquettes produced using the developed densification machine meets the criteria outlined in the ISO standard (ISO 17225). The compressive strength, durability, and water resistance of the produced briquettes exhibited a range of values, with compressive strength varying between 55 and 101 $kN \cdot m^{-2}$, durability ranging from 89 to 99%, and water resistance spanning 20–120 min. The compressed and relaxed densities range from 0.780 to 1.220 $g \cdot cm^{-3}$ and 0.6700 to 0.99 $g \cdot cm^{-3}$, respectively. All the properties of the briquettes investigated in this study increase with compaction pressure. The characteristics exhibited by the produced briquettes highlight the biomass densification machine's suitability for teaching and research purposes. It enables practical learning experiences for students, allowing them to gain hands-on knowledge in the renewable energy field. The developed machine holds significant potential to drive advancements in the energy sector and contribute to the expansion of sustainable energy solutions, particularly in developing countries.

5 Challenges encountered and recommendations for future research

A few challenges were encountered during the testing and operation of the machine. One challenge involves operating the machine at higher compaction pressures, particularly when densification is required at pressures exceeding 20 MPa. Running the machine beyond this threshold demands a significant amount of physical energy from the operator. This limitation becomes especially significant when the operator lacks the physical strength to compress at higher pressures.

This research has taken an initial stride in confirming the viability of a developed biomass densification machine. It has presented evidence of adherence to some criteria outlined in the ISO 17225 standard, thereby establishing its suitability. It is suggested to incorporate or replace certain mechanical components with electrical and electronic counterparts to enhance the performance and precision of the densification process. For example, the manually operated hydraulic jack could be replaced with an electric hydraulic jack. Additionally, using a digital pressure gauge would improve the accuracy of measurements. Automation of the briquetting process is recommended for future research. Furthermore, enhancing the capability of the machine can be achieved by upscaling the hydraulic jack and pressure gauge. The design and construction of mold with a heating device using locally available materials are suggested for future studies. This would expand the research capability of the machine.

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Data availability All the data and material pertinent to this manuscript are included in the manuscript. The Federal Republic of Nigeria Patent Publication granted the machine a patent under the patent number NG/P/2022/194. Therefore, additional details required for replicating the machine can be obtained by making a request to the relevant authorities through the corresponding author.

Declarations

Ethical approval Not applicable.

Competing interests The authors declare no competing interests.

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