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Development and Evaluation of Coffee Husk Biomass Briquetting Machine

Teka Tesfaye[1*] Adem Tibesso[2] Abduselam Aliyi[3]
Oromia Agricultural Research Institute, Jimma Agricultural Engineering Research Center,
Renewable Energy Engineering Research Team, P.O.Box 386, Jimma, Oromia, Ethiopia
Corresponding authors email: tekamen@yahoo.com, adamtibesso2007@yahoo.com, abduselam466@gmail.com

Abstract
The result of the direct burning of coffee husks biomass in a conventional manner is very low thermal efficiency and widespread air pollution. When they are made into briquettes, these problems are mitigated, transportation and storage costs are reduced, and energy production by improving their net calorific values per unit is enhanced. Aimed at minimizing the effect of coffee waste constitutes and turning them into an income generation source for the local communities through the development of biomass briquette machines. The experiment used different ratios of carbonized coffee husk and Clay Soil as a binder. The capacity of the machine, Physical and mechanical properties and thermal characteristics of the briquettes were evaluated. Throughput capacity and Degree of Densification of the machine, bulk Density, Resistance to water penetration, Shatter, and Tumbling resistance of the Briquette were increasing with the increase of clay binder ratio with a significant difference at alpha 0.05. The average minimum and maximum throughput capacity and Degree of Densification of the machine were 1.117 and 1.273 kg/min and 290.4 and 308.7%, respectively, at 0 and 25% clay binder ratios. Increasing the clay soil binder ratio increases the percentage of Ash content but decreases the fixed carbon percent and Calorific value. The minimum and maximum Calorific values, Fixed carbon, and Ash content were 3856.89 cal/g, 12.5%, 24%, and 5001.78 cal/g, 30%, and 36%, respectively. Both ignition and water boiling time increase by the increase of clay soil binder ratio with a minimum of 6.5 and 14.3 minutes and a maximum of 7.6 and 18.5 minutes, respectively. It was found that clay was the compatible binding material with coffee husk, where 5% is the optimal possible clay content with an optimal calorific value of 4848.39 Cal/gm and minimum ash content.
Keywords: Briquette, binder, coffee husk, clay soil, and development
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Abbreviations

Cal/g	Calorie per gram
cm	Centimeter
g	Gram
hr	Hour
hp	Horsepower
Kg	Kilogram
Kg/min	Kilogram per minute
Kg/m^3	Kilogram per cubic meter
masl	Above mean sea level
min	Minute
mm	Millimeter
rpm	Revolution per minute
s	Second

1. Introduction

Desertification is one of the world's biggest problems due to environmental changes and human abuse of forest resources as fuel and building materials (Abakr and Abasaeed, 2006). Forest is considered the primary source of fuel for most of the urban and rural population of our country, a population that is increasing at a fast rate. Although there are a lot of changes in living styles and standards, especially in urban areas, traditional cooking habits are still dominant. Most local dishes still depend on using wood directly from forests as the preferred fuel due to the availability and cheapness of wood (in most cases, people collect wood now from the nearby forests at no cost). This reliance on wood fuel significantly increases the rate at which the country's forest cover is shrinking and is associated with the adverse change in weather patterns and consequent climate variability experienced in the country (Miito and Banadda, 2017). This over-dependence on wood fuel is a significant cause of declining tree cover, loss of biodiversity, and aggravated consequences of global warming in response to the declining potential of carbon sequestration (Waswa, Mcharo and Mworia, 2020).

The coffee processing industry produces massive by-products since 30 to 50% of coffee fruit weight is waste. Due to the high production of coffee seeds, several reusing solutions have been proposed. Still, a win-win solution is needed to manage the considerable amount of coffee husk (Hoseini *et al.*, 2021).

In East Africa, especially in parts of Ethiopia, coffee husks are considered an economically useless by-product and are discarded in streams and fields with no significant utilization or treatment. This disposal of coffee husks wastes biomass energy and land resource and causes specific environmental harms, affecting soil and water quality. From 2007 to 2016, annual coffee production increased from 273,400 tons (t) to 469,091 t, while the planting area increased from 407,147 ha to 700,475 ha. Consequently, the coffee waste grew as processed coffee cherries increased. Thus, Ethiopia needs to use coffee husks for value addition, disposing of coffee waste, and reducing environmental pollution (Du *et al.*, 2021).

Southwest Ethiopia is known for its high coffee production, export, and disposable coffee by-products (coffee pulp, husk, and effluents). Yet, these wastes are disposed of in landfills or openly incinerated, causing water and air pollution and human and livestock health risks (Mamo *et al.*, 2021). Coffee husks have a low bulk density, which raises transportation and storage costs(Amertet, Mitiku and Belete, 2021). However, only a tiny proportion of biomass residues are utilized as fuel due to their high moisture, polymorphism, and low energy density. These troublesome characteristics increase transport, handling, and storage costs, making using biomass as a fuel impractical. Some of these drawbacks can be overcome if the biomass residues are densified into briquettes to provide more energy per unit volume and uniformity in shape and size (Suarez *et al.*, 2003).

In a developing country like Ethiopia, the direct burning of biomass in a conventional manner is associated with very low thermal efficiency and extensive air pollution. When they are made into briquettes, these problems are mitigated, transportation and storage costs are reduced, and energy production by improving their net calorific values per unit is enhanced. The essential advantages of Briquette are its low Sulfur content, the relative freedom of dust, ease of handling, and high calorific value.

Binders that act as glue to keep the particles together can densify biomass. Low-pressure densification is preferred because simple manual machines can be fabricated for making briquettes, and the rate of wear of parts of the devices is reduced. However, biomass densification is a complex process with a unique set of process variables for each biomass material to produce briquettes of desirable physical properties. The levels of factors to produce briquettes of optimum physical properties from coffee husks-clays mixtures are unknown (Okello, Kasisira and Okure, 2011).

Identification of suitable binder materials in low-pressure applications was rarely investigated. Binding agents must be supplied externally during ambient temperature processing. These binding agents can be made from a variety of materials. Waste or readily available materials are the best options for this application for economic feasibility.

The three individual machines in the existing briquetting system work together, including a hammer mill for grinding the carbonized; the fined charcoal and binder are thoroughly mixed at a predetermined mixing ratio and then transferred to a briquette machine to be extruded into briquettes. The briquettes are then cut and dried before being delivered to the store. The proposed design for a new briquetting system (a compact machine and one worker): carbonized material is transferred to a compact device, and the binder is added to the mixing container in which both grinding and briquetting take place. Briquettes are ejected from the die exit.

As a result, the study was conducted to determine the levels of process variables under which to produce coffee husk briquettes of optimum quality at the lowest pressure possible. So with clay soil as a binder, it aimed to minimize the environmental hazards that coffee waste constitutes in the coffee processing industry and turn them into income generation sources for the local communities.

2. Materials and Methods

2.1. Description of the study area

The study was carried out at the Jimma Agricultural Engineering Research Center in the Oromia region of Ethiopia, 353 kilometres southwest of Addis Abeba. The zone has a total area of 18415 km2 and is located between 7 ° 18′N and 8 ° 56′N latitudes and 35 ° 52′E and 37 ° 37′E longitudes. The area's main soil types are nitisol and comb soils, which receive an average annual rainfall of 1,467 mm per year (Elias, Muleta and Woyessa, 2016).

The zone has an elevation of 880 to 3360 meters (masl) above sea level. For 8 to 10 months receives an average annual rainfall of 1000 mm. The primary rainy season stretches from May to September, and there is a minor rainy season in February, March, and April. Jimma zone temperatures range from 8 - 28°C. The average temperature is 20°C annually. The study area agro-ecologies have a range of altitudes of 1000-1500 (lowlands), 1500-2500 (intermediate), and 2500-3360 masl (highlands) (Befikadu *et al.*, 2014).

2.2. Materials and Instruments used

Materials that are required for the manufacturing of the briquette machine were identified and selected based on the design specification. According to this, Sheet metals, Square pipes, Circular hollow pipes, a Bearing, a Screw shaft diameter of 35 mm, an Engine pulley diameter of 14 cm and Screw pulley diameter of 46 cm, an Engine motor of 10 hp, a Stopwatch, Oven dry, Thermometer, and Digital Balance were used.

2.3. Design calculations

2.3.1 Design of Extruder (the screw)

Diameter and pitch of last flight of compression zone

The volume of the last flight of the feeding zone, $V_f = \frac{\pi}{4}({D_1}^2 - {D_3}^2)$*pitch (2.1)

To calculate the pitch of the compression zone, assume the diameter of the last flight of the compression zone

$$V_c = \frac{\pi}{4}({D_1}^2 - {D_3}^2) * P_c \qquad (2.2)$$

2.3.2 Motor power required

Helix angle (α) of acme thread calculated as:

$$\tan\alpha = \frac{\text{pitch}}{\pi D} \qquad (2.3)$$

μ_1 = Virtual coefficient of friction

β = Angle of acme thread

$$\mu_1 = \tan\varphi_1 = \frac{\mu}{\cos\beta}$$

The force required overcoming friction at the screw,

$$F = W\tan(\alpha + \varphi_1) \qquad (2.4)$$

W = Axial load exerted by the screw

$$F = W\left[\frac{\tan\alpha + \tan\varphi_1}{1 - \tan\alpha * \tan\varphi_1}\right] \qquad (2.5)$$

Mean diameter of last flight of compression zone

$$d = D_2 - \frac{p_c}{2} \qquad (2.6)$$

The torque required overcoming friction at the screw

$$T = F * \frac{d}{2} \qquad (2.7)$$

The power required to drive the screw is

$$P = T * \omega \qquad (2.8)$$

2.3.3 Determination of the shaft speed

The transmission system is belt transmission via a pulley (specifically v belt selection) using a mechanical drive petrol engine or an electrical motor. Thus to calculate the shaft speed, the following parameters are used:

$$\frac{D_1}{D_2} = \frac{N_2}{N_1} \qquad (2.9)$$

$$N_2 = \frac{D_1}{D_2} * N_1$$

Where

N_1= Revolution of the smaller pulley, rpm.

N_2 = Revolution of the larger pulley, rpm.

2.3.4 Determination of the belt contact angle

The belt contact angle is given by

$$\sin\beta = \frac{(R - r)}{c} \qquad (2.10)$$

Where

R = radius of the large pulley, mm

r = radius of the smaller pulley, mm

The angles of wrap for the pulleys are given by

$$\alpha_1 = 180 - 2\sin^{-1}\left(\frac{R - r}{c}\right) \qquad (2.11)$$

$$\alpha_2 = 180 + 2\sin^{-1}\left(\frac{R - r}{c}\right) \qquad (2.12)$$

Where

α_1 = Wrapping angle for the smaller pulley, degree

α_2 = Wrapping angle for the smaller pulley, degree

2.3.5 Determination of the belt tension

Tangential load:

The belt tension was calculated using a Textbook by 'Khurrmi and Gupta formulas.

Maximum tension in a belt:

$T = SA$ (2.13)

Centrifugal tension in the belt

$T_c = mv^2$ (2.14)

$T_1 = T - T_c$

To get tension in the slack side, use the relationship below

$2.3 \log \left(\frac{T_1}{T_1}\right) = \left(\frac{\mu\alpha_1}{\sin\theta}\right)$ (2.15)

Where

T_1 = Tension in the tight side, N

T_2 = Tension in the slack side, N

θ= Angle of groove ranges

μ = coefficient of friction between the belt and the pulley

S = The maximum permissible belt stress, MN/m

The power required by the shaft is given by

$P = (T_1 - T_2)*V$ (2.16)

The torque at the main shaft is given by

$T = (T_1 - T_2)*V$ (2.17)

2.3.6 Design of mixing system

The volume of the cylinder:

$V = \pi r^2 L$ (2.18)

Where

V [mm^3], r = radius in [mm], L = length in [mm]

The volume of material, V_m [mm^3]:

$V_m = 0.2*V$

Mass of mixing trough, M [Kg]:

$M = V_m*\rho$ (2.19)

Where ρ [Kg/m^3] is the density of the design material.

2.3.7 Design of Shaft and Blade

Normal load acting horizontally:

$W_{nvx} = W_{nx}\cos\theta$, $W_{nvy} = W_{ny}\cos\theta$, $W_{nvz} = W_{nz}\cos\theta$ (2.22)

$W_{nhx} = W_{nx}\sin\theta$, $W_{nhy} = W_{ny}\sin\theta$, $W_{nhz} = W_{nz}\sin\theta$ (2.23)

$W_{tx} = \frac{2T_x}{D_x}$, $W_{ty} = \frac{2T_y}{D_y}$, $W_{tz} = \frac{2T_z}{D_z}$ (2.20)

Where Ti [Nm] is the torque on the blade and the subscript 'i' represents blades x, y, and z.

The normal load exerted:

$W_{nx} = \frac{W_{tx}}{\cos\theta}$, $W_{ny} = \frac{W_{ty}}{\cos\theta}$, $W_{nz} = \frac{z}{\cos\theta}$ (2.21)

Normal load acting vertically:

2.4. Machine description and Experimental procedure

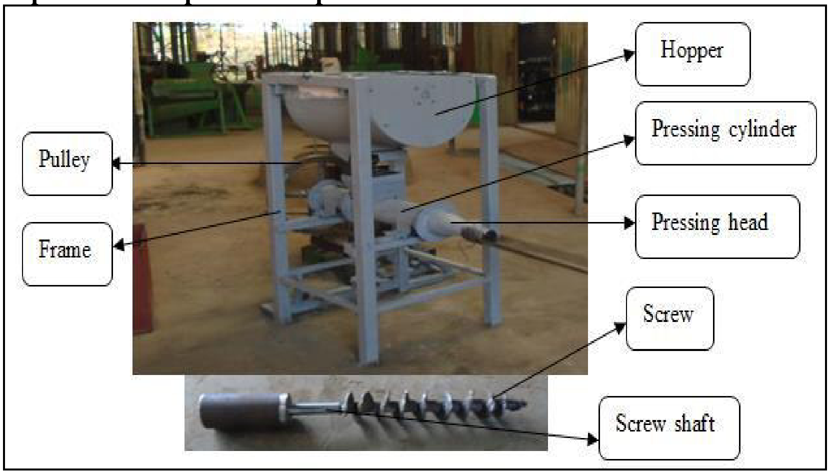

Figure 1. The detail components of the developed briquette machine

Table 1. Components specification of the briquette machine

Parts	Description
Overall size of the machine	126 cm×72 cm
Size of frame	60 cm×72 cm
Hopper	Concave 1.5 mm sheet metal
Pulley	D_o = 46 cm
Frame	4×4 square pipe 2 mm thickness
Pressing head	D_i = 5mm pipe
Pressing cylinder	D_i = 12 cm
Screw	6 cm pith diameter
Screw shaft	D = 35mm

Carbonized coffee husk and Clay Soil as a binder was used with a ratio of 100%, 95%, 90%, 85%, 80%, and 75% carbonized coffee husk and 0%, 5%, 10%, 15%, 20% and 25% clay soil respectively. Half of the weight of the ingredients (Carbonized coffee husk and Clay soil binder) water in a litre was added and mixed in the mixing chamber. Both Crushing and Extruding were done at the same time and within the extruding chamber. The experiment was done by adjusting the engine motor Speed to 1700 rpm using the fuel valve, causing the speed of the screw pulley to 518 rpm. The samples were weighed using a Model CTI200-s scale with capacities of 6 and 1.2 kg and precisions of 1 and 0.1 g, respectively. The moisture level is measured in this study using the drying oven method.

2.5. Performance evaluation parameters of the machine

2.5.1. Throughput capacity of the machine (C_t)

The machine throughput capacity was determined as the ratio of the briquette mass produced by the biomass briquette machine to the average time used in the briquette production (Fadeyibi and Adebayo, 2021).

$$C_t = \frac{m_b}{t_b} \qquad (2.24)$$

Where: Ct is the throughput capacity (kg/s), m_b is the mass of Briquette produced at time t (kg), and t_b is the briquette production time (s).

2.5.2. Physical and mechanical properties of briquettes

Bulk density: The bulk density of the produced fuel briquettes was determined by measuring the volume and weight of samples. The weighing was performed using the analytical balance, and the dimensions were measured using a Vernier calliper. The density was calculated by determining the material's ratio of mass and volume (TUATES, LIGISAN and CAPARIÑO, 2016).

$$\text{Bulk density (kg/m}^3\text{)} = \frac{\text{mass of biomass sample (kg)}}{\text{the volume of the measuring cylinder (m}^3\text{)}} \qquad (2.25)$$

Shatter resistance test:

This test was conducted to determine the hardness of the Briquette. The known weight and length briquette were dropped one meter on a concrete floor ten times. The percent loss of materials was calculated. The Briquette's shatter resistance was calculated using the following formula (Sengar *et al.*, 2012).

Percent weight loss = $\frac{w_1 - w_2}{w_1} * 100$ (2.26)

% shatter resistance = 100 % weight loss

Where W_1 = weight of Briquette before shattering, g

W_2 = weight of Briquette after shattering, g

Tumbling resistance test

The abrasive resistance test, also known as the tumbling test, measured the mechanical durability of densified products due to transport and handling processes. The Briquette was subjected to controlled shocks by a collision of fuel particles against each other and the walls of a rotating chamber. The tumbling process was conducted with a speed rate of 25 rpm for 5 minutes in a clockwise direction by referring to the standard of EN 15210-2. Sieving was required before and after tumbling for 30 s to remove the fines attached to the sample (Law, Gan and Gan, 2018). Then weight loss in the Briquette was noted, and tumbling resistance was calculated by using the following formula

Percent weight loss = $\frac{w_1 - w_2}{w_1} * 100$

%Tumbling resistance = 100 % weight loss

Where W_1 = weight of Briquette before tumbling, g

W_2 = weight of Briquette after tumbling, g

Resistance to water penetration:

It shows how the briquettes respond during rainy seasons or while in contact with water (Rajaseenivasan *et al.*, 2016). The percent of water gained was noted, and the following formula calculated water penetration resistance.

Water gained by Briquette = $\frac{w_1 - w_2}{w_1} * 100$

% Resistance of water penetration = 100 % water gained

Where,

W_1 = initial weight of briquette, g

W_2 = final weight of briquette, g

Degree of densification:-

The degree of densification is defined as the percent of the increase in density of biomass due to briquetting. The degree of densification represents the ability of materials to be bounded. It was calculated and recorded by using the equation below (Bhavsar *et al.*, 2018):

Degree of densification = $\frac{\text{the density of briquette} - \text{density of raw materials}}{\text{the density of raw materials}}$ (2.27)

2.5.3. Thermal characteristics of the briquettes

Proximate analysis

Analysis for moisture, volatile matter, ash, and fixed carbon contents was carried out on samples of Briquette at the Ethiopian Rural Energy Development and Promotion Center, Alternate Energy Technologies Design, prototype, and Testing Directorate Energy Efficiency Laboratory Unit. The calorific values of the samples were measured in a Bomb calorimeter apparatus (Zhu, Arsovska and Kozovska, 2020).

Ignition and water boiling time:

Five hundred grams of briquette sample was measured and put on a metal domestic briquette stove to boil 2.5 L of water using an aluminum pot. The time taken for the briquette sample to start burning uniformly and the time for boiling the water was recorded in minutes.

3. Results and Discussion

3.1. Throughput capacity and degree of densification of the machine

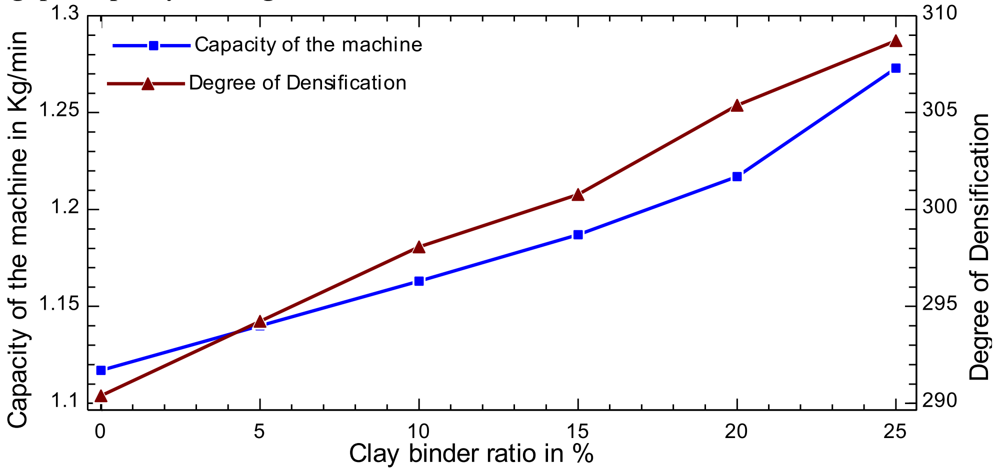

Figure 2. The result of throughput capacity and degree of densification of the machine

From figure 2, the machine's average throughput capacity and Degree of Densification increased with the clay binder ratio. The average minimum and maximum throughput capacity and Degree of Densification of the machine were 1.117 and 1.273 kg/min and 290.4 and 308.7%, respectively, at 0 and 25% clay binder ratios. The machine capacity of this study was similar at a 5% clay binder ratio compared to the study of (Ikubanni *et al.*, 2020), in which the machine capacities were 68.56 kg/h. But compared with the study (Fadeyibi and Adebayo, 2021), the capacity of 0.0055 kg/s, the result was much different, and this may be due to the power source being a 2.0 hp electric motor versus a 10.0 hp Acme engine. The result of the study (Srivastava *et al.*, 2014); the degree of densification of powdered vegetable market waste briquette was found to be 231, 203, 202 and 219 % for cauliflower + cabbage leaves, coriander stalk + leaves, field beans, and green pea pods, respectively. The difference may be due to its physical nature, which gave higher quality compaction of carbonized coffee husk.

3.2. Bulk density of briquettes and resistance to water penetration

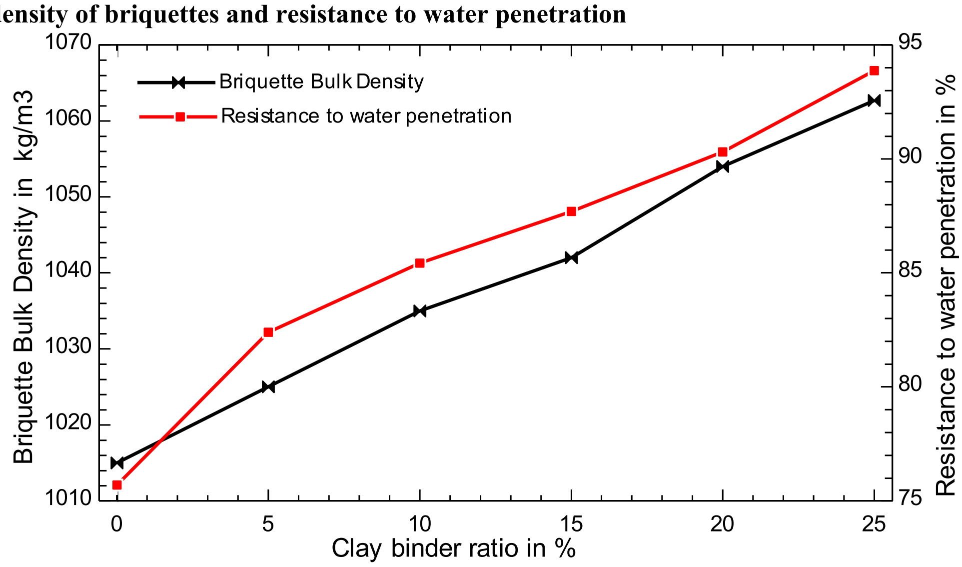

Figure 3. The result of bulk density and resistance to water penetration

As indicated in Figure 3, the bulk density and resistance to water penetration increase as the ratio of binder increases. The highest bulk density and resistance to water penetration were 1062.667 kg/m^3 and 93.867%, respectively. According to the study (Cubero-Abarca *et al.*, 2014), the bulk density of briquettes and pellets manufactured using coffee pulp was 1110 and 1300 kg/m^3. In the study (Meharu, 2019) on the Briquette of coffee husk at different particle sizes, the maximum bulk density at 25% clay soil binder ratio was 769.2 kg/m^3. The quantity and type of binder were discovered to be the most important factors influencing briquette density, followed by particle size. The combustibility of the same binding agent increases with increasing briquette density. Investigation results on the performance of sawdust briquette blending with neem powder resistance to water penetration ranged from 73 to 90% (Rajaseenivasan *et al.*, 2016). In this study, all the categories of briquettes fall within the acceptable quality value (>70%) based on the (Kpalo *et al.*, 2020) study.

3.3. Shatter and Tumbling resistance test

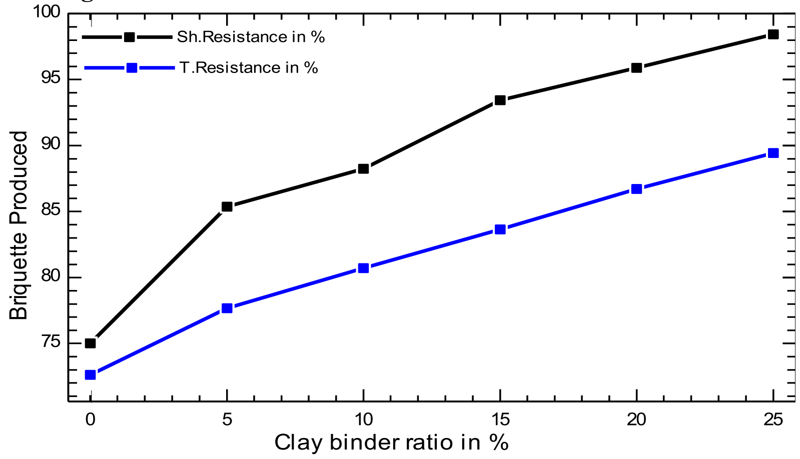

Figure 4. Shatter and Tumbling resistance

From figure 4, it was observed that both Shatter and Tumbling resistance increased with an increase in binder ratio. A quality briquette should fulfill the specifications by having ≥ 90 % shatter resistance, according to (Law, Gan and Gan, 2018). By taking this reference, the briquettes formed in the different binding ratios had shatter resistance from around 75 % to 98.4 %. The 15 to 25% clay soil binder ratio fell within the acceptance limit range. Thus they were considered quality briquettes. A tumbler test was carried out to check the durability index of the briquette fuel. The maximum (99.35%) and minimum (93.31%) tumbling resistance were observed in the study (Bhavsar *et al.*, 2018). The difference may be due to the type of biomass and binder used.

Table 2. The LSD test for treatments to see the effect of binder ratio at alpha: 0.05.

Treatments	Capacity kg/min	Bulk density kg/m3	Shatter Resistance in %	Tumbling Resistance in %	R.t. Water Penetration in %	Degree of Densification
Clay 25%	1.27[a]	1062.67[a]	98.43[a]	89.43[a]	93.87[a]	3.087[a]
Clay 20%	1.22[b]	1054.0[b]	95.88[b]	86.70[b]	90.3[b]	3.05[b]
Clay 15%	1.19[c]	1042.0[c]	93.43[c]	83.63[c]	87.7[c]	3.01[c]
Clay 10%	1.16[cd]	1035.0[d]	88.23[d]	80.69[d]	85.4[d]	2.98[d]
Clay 5%	1.14[de]	1025.0[e]	85.37[e]	77.66[e]	82.4[e]	2.94[e]
Clay 0%	1.12[e]	1015.0[f]	75.00[f]	72.61[f]	75.7[f]	2.90[f]
CV %	1.41	0.31	0.59	1.23	1.28	0.42

* Treatments with the same letter do not differ significantly.

3.4. Proximate Analysis

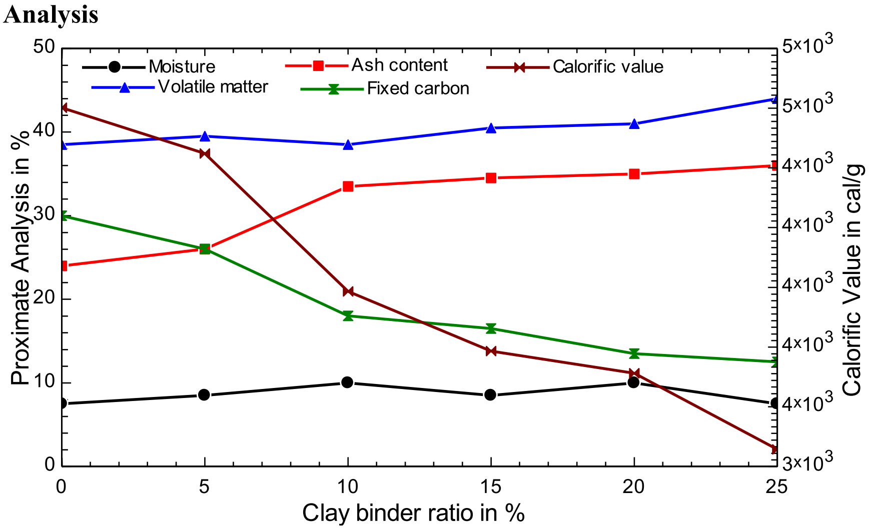

Figure 5. The proximate analysis results of the coffee husk briquette

As shown in the figure, increasing the clay soil binder ratio increases the percentage of Ash content but decreases the fixed carbon percent and Calorific value. Generally, high carbon content influences combustion behaviour, affecting ash fusion. Under the proximate analysis study, ash is the primary inorganic substance obtained after biomass combustion; ash typically contains calcium, potassium, magnesium, and phosphorus. Mineral deposition and agglomeration in ash melt is one issue that prevents the thermal process of biomass (Wang *et al.*, 2020). As a result, a higher fixed carbon content encourages more calorific energy in the charcoal produced. A higher fixed carbon content translates into a lower volatile matter content. As the Briquette enters the volatile combustion phase, its overall mass decreases. Increasing the hydrogen-to-carbon ratio augmented the combustion, although to a lesser extent, as the carbon ratio rises (Saeed *et al.*, 2021). The moisture content values (7.5 to 10%) comply with the range established for this categorei of product, i.e., 10 to 12%, according to the DIN 51731 standard (Deutsches Institute fur norming, 1996). An adequate moisture content level in briquettes allows sufficient heat and temperature in the chamber and reduces the amount of exhaust gas (Cubero, Roque and Filho, 2014). According to the study (Getu *et al.*, 2021), Briquette produced from bagasse clay as a binder in the ratio of 20:80 and molasses as a binder in the ratio of 10:90 were greater than the fixed carbon content of the charcoal briquette produced from sawdust briquette which was a fixed carbon content of 20.7%. Fixed carbon is the major quality measuring parameter that determines the energy behaviours in the production of densified biomass briquettes.

In the study (Kansai, Chaisuwan and Supakata, 2018), carbonized briquettes as a tool for adding value to waste from rain trees (Samanea Saman) and Coffee ground/Tea waste the physical properties, including volatile matter, ash content, and fixed carbon, were in the range of 27 to 37%, 14 to 33%, and 31 to 39%, respectively. High volatile matter results in easing ignition and enhancing combustion. Conversely, high ash content decreases the heating value. It increases the thermal resistance to heat transfer, as the study's report (Haddis, Alemayehu and Ambelu, 2014) on the potential of coffee husk and pulp as an environmentally friendly alternative source of energy. The average of the mean calorific values of the briquettes produced from coffee husks at both farms, i.e., the net average calorific value of the briquettes produced from Teppi and Limu coffee husks, amounted to 5041.1 cal/g.

As the study result of (Gebresas *et al.*, 2015) amount of clay binder increased from 15% to 25%, and the calorific value decreased from 4647 Cal/g to 3389 Cal/g. And the ash content increases from 25% to 40%. So the optimal calorific value of sesame stalk charcoal is 4647 Cal/gm with lesser ash content. One of the determinants of the quality of biomass charcoal is the ash content after burning. The ash content increases as the percentage of clay increases and is due to the ash content of clay which is about 90.1%. The percentage of fixed carbon in sesame stalk briquettes has decreased from 44.4% to 29.63% as the percentage of clay increases from 15% to 25%; this is due to the low carbon content of clay which is about 7.1% (Onchieku, Chikamai and Rao, 2012).
As shown in figure 5, as the percentage of clay increases from 5 % to 10 %, the rate of increment of ash content and rate of decrement of calorific value and fixed carbon content is high. As a result, 5% is the optimal possible clay content with an optimal calorific value of 4848.39 Cal/gm and minimum ash content.

3.5. Ignition and water boiling time

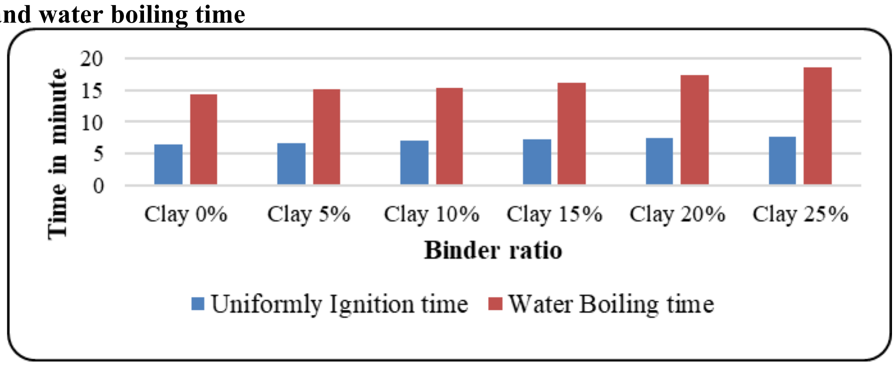

Figure 6. The effects of binder ratio on the ignition and water boiling time

As shown in the figure, both ignition and water boiling time increase by increasing the clay soil binder ratio with a minimum of 6.5 and 14.3 minutes and a maximum of 7.6 and 18.5 minutes, respectively. The ignition time increased with increasing binder concentration and compaction pressure. Increased compaction pressure automatically increased the density of briquettes and, consequently, delayed the ignition time of the briquettes. So this can be attributed to larger briquette pores allowing more air to support combustion. In the study (Kuhe, Terhemba and Iortyer, 2021), the ignition time ranged between 109 s and 140 s. but the values obtained from the different research were within the range of 19–186 s for bio-coal briquettes made by mixing the materials at various concentrations of 10–50% with coal. Water heated with rice husk-starch briquette took 15 min to boil 2 L of water compared to firewood, which took 21 min to boil the same quantity of water. Because of their higher burning rate, the shortest water boiling time was obtained from briquettes with higher calorific values. They were able to boil water faster than briquettes with low heating values.

The results (T.K., S and A. O. Y., 2016) from other biomass briquettes showed the shortest water boiling time, coal briquettes 26 minutes, cassava starch gel 18.05 minutes and Orange waste 15.00 minutes compared with the results of biomass used in this study. It can be stated that the briquettes produced are good enough for household cooking.

Figure 7. The final produced Briquette

4. Conclusion and Recommendations

The research reveals the potential to produce more than 67.02 kg charcoal per hour. The study has found that the binder ratio significantly affected the physical and combustion characteristics of briquettes produced from the carbonized coffee husk. The briquettes produced have sufficient density and degree of densification. The bulk density of the briquettes was 1015 to 1062.667 kg/m^{3,} which is higher than the residue materials, which is 150.73 kg/m^3. These translated into a 673.4 to 705.01% volume reduction. Therefore, high-quality and storable briquettes can be produced from the blend based on the results obtained. It is because the relaxed density and compressive strength of the briquettes produced are adequate; besides, the stored briquettes' length of time or service life proved satisfactory and acceptable stability even after some months of storage.

In addition, the combustibility test showed that biomass densification promotes better energy performance when compared to bulk biomass. It was found that clay was the compatible binding material with coffee husk, where 5% is the optimal possible clay content with an optimal calorific value of 4848.39 Cal/gm and minimum ash content. Moreover, the production of briquettes from coffee husk helps to increase the mechanism of carbon sequestration by reducing the deforestation rate as a result of providing renewable, clean, and sustainable energy as a substitute for fuel wood and charcoal. The briquette machines and the carbonizer are locally made in the research center workshop; thus, they can easily be made available in the local small and medium metal fabrication workshops in the region, which will have a positive effect on technology transfer and innovation that youngsters and women can do and bring change to their livelihood; hence, the technologies can be demonstrated if great attention is given. Using an electric motor instead of a fuel engine motor for sustainability and capacity improvement as a source of power where electric power is available.

Declaration of interests statement

The authors declare no conflict of interest

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