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# Characterisation of briquettes from forest wastes: Optimisation approach

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**Abstract:** Waste from a forest environment constitutes an enormous quantity of renewable energy resources. In this study undesirable forest materials, such as jatropha seed shells (JSSs) and *Eucalyptus camaldulensis* wood shavings (EcWSs) were used in the production of briquettes with *Acacia senegal* as the binder using mixing proportions of 0 : 100, 25 : 75, 50 : 50, 75 : 25 and 100 : 0 while the binder was varied from 50, 60, 70, 80 to 90 g. Some physical properties, such as the density, moisture content, water resistance and shatter index, were optimised using the response surface methodology at these mixing proportions. The outcome of the production showed the briquettes to have mean values of 0.66 kg·m$^{-3}$, 11.51, 91.12 and 99.7 % for the density, moisture content, water resistance and shatter index, respectively. The optimum mixing ratio and binder quantity of 75 : 25 and 60 g, respectively, would result in a briquette having a 0.70 kg·m$^{-3}$, 10.88, 98.11 and 99.86% density, moisture content, water resistance and shatter index, respectively. It has been revealed that the JSS and EcWS are potential organic wastes which could be used as a feedstock for the production of briquettes. It could be concluded that the variation in the mixing proportion of the JSSs, EcWSs and *A. senegal* significantly affected the properties of the produced briquettes.

**Keywords:** binder; eucalyptus; jatropha seed shell; properties; wastes; wood shaving

Energy is one of the basic necessities of life. It is needed to enhance ecosystems and increase the comfort for humanity. There are several sources of energy which could serve as a preferable replacement for non-renewable energy sources, such coal and other fossil fuels (Brožek 2015). Biomass as a veritable source of energy is gaining research interest in both developing and developed countries (Brožek et al. 2012; Santhosh and Sreepathi 2018). Biomass remains a renewable source of energy which can reduce greenhouse gas emissions compared to fossil fuels, which have detrimentally contributed to global warming (Plíštil et al. 2004). In the last decade, there have been ongoing, aggressive global afforestation programmes in many countries of the world in a bid to alleviate the impact of greenhouse gas emissions. In the nearest future, it is inevitable that there will be large quantities of waste from the forest reserves which could be useful in production of solid fuels. This waste could serve as a feedstock for the production of solid fuels, such as briquettes (Gwenz et al. 2020; Kpalo and Zainuddin 2020). Briquettes have been produced from agricultural waste, such as corn cobs (Muazu and Stegemann 2017), tea waste (Demirbas 1999), rice bran (Olugbade and Mohammed 2015), corn stalks, cotton stalks, wheat straw,

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lignite (Gürbüz-Beker et al. 1998; Yaman et al. 2001; Lepersa et al. 2015), fruit branches, sugar cane waste (bagasse), and palm kernel shells (Chou et al. 2009; Zhongqing et al. 2015; Oke et al. 2016) to mention but a few. Moreover, in Nigeria, several projects have been embarked upon on the use of jatropha for the production of biodiesel (Fadele et al. 2012). Biodiesel production from jatropha fruit includes the decortications, shelling, oil extraction and transesterification processes. The by-products from these processes include the pods, shells and cakes which are toxic in nature and, at same time, could contribute to the environmental pollution (Openshaw 2000; Pandey et al. 2012; Aremu et al. 2015). It is most likely that a great deal of waste would be generated. In containing the waste generation from urban centres, Lori et al. (2016) proffered the conversion of waste (which are mostly organic) from the urban centre to a solid fuel through a densification process. Similarly, Krueger et al. (2019) reported the production of briquettes from faecal sludge and agricultural waste as means of solid waste management. Furthermore, Antwi-Boasiako and Acheampong (2016) studied some properties of sawdust briquettes produced from various tropical hardwoods in relation to their densities. Gwenz et al. (2020) produced briquettes from a mixture of coal dust, plastic waste and sawdust; its calorific value was found to have a range of 26.5 to 33.8 MJ·kg$^{-1}$ and the best mixing proportion was a mixture ratio of 50% coal dust, 40% plastics and 10% sawdust. Moreover, some organic and synthetic materials, such as cassava starch (Grover and Mishra 1996), molasses (Israelsen et al. 1981), microalgae (Zhang et al. 2018), bentonite, corn straw, rice dust (Rahaman and Abdul Salam 2017), sawdust (Emerhi 2011), clay, paper pulp, lignin (Demirbas 2003), etc have been used as binder in the production of briquettes with little or no information on the application of *Acacia senegal* (L.) Willd. as a binder in the briquette production (Olugbade and Ojo 2021). Previous studies on the production of solid fuels revealed that organic waste is a potential feedstock for the production of briquettes. The aim of this work was to optimise the briquette production from forest waste, such as jatropha seed shells (JSSs) and *Eucalyptus camaldulensis* Dehnhardt wood shavings (EcWSs) with *A. senegal* as the binder in relation to some of its properties.

## MATERIAL AND METHODS

**Sample preparation.** Within the briquette production process, some forest and agricultural waste, such as JSSs recovered from the jatropha seed shelling process and EcWSs, were collected from within the Federal College of Forestry Mechanisation and Trial Afforestation Research Station Kaduna, Nigeria. The waste was cleaned by removing any other agricultural materials, other than JSSs and EcWSs. The JSSs and EcWSs were pyrolyzed separately in an improvised kiln. The bio-chars recovered from the kiln were screened using a sieve having an aperture of 1.7 mm to obtain finer bio-char particles as shown in Figure 1. The bio-chars recovered were cooled and kept in polythene sacks at room temperature (28 ± 2 °C). The binder selected for the briquette production was *A. senegal*; also known as the gum arabic tree (Figure 1). It was purchased from the Kawo market Kaduna, Nigeria. This was comminuted using a pestle and mortar. A total mass of 1 200 g of JSSs and EcWSs were blended together using the mixing proportions of 0 : 100, 25 : 75, 50 : 50, 75 : 25 and 100 : 0, while the binder was varied from 50, 60, 70, 80 and 90 g as shown in Table 1.

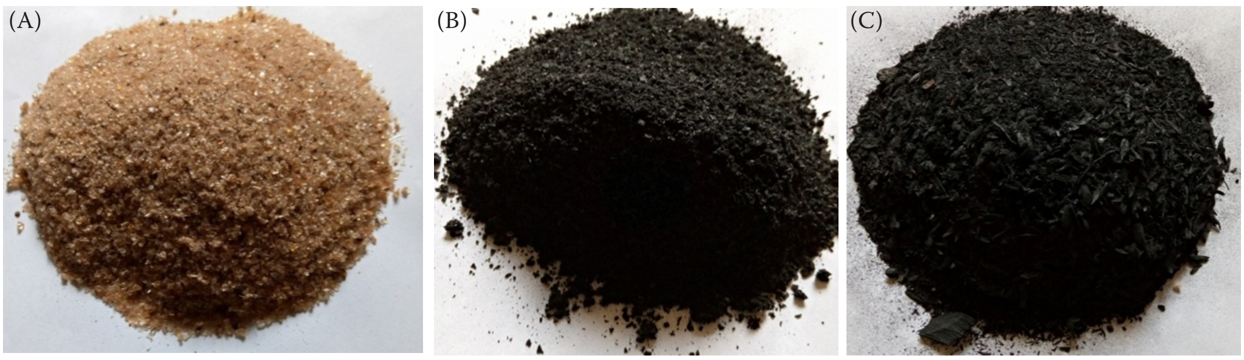


Figure 1. Constituents of the briquette (A) *Acacia senegal* wax, (B) jatropha seed shells and (C) *Eucalyptus camaldulensis* wood shavings

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Table 1. Experimental design for the jatropha-cum-*Eucalyptus camaldulensis* and the binder mixing ratios

| Factors | Levels | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Mass of binder (g) | 50 | 60 | 70 | 80 | 90 |
| Jatropha: *Eucalyptus* | 0:100 | 25:75 | 50:50 | 75:25 | 100:0 |

The produced briquettes have a height of 75.4 mm with external and internal diameters of 70 mm and 60 mm, respectively.

**Determination of some physical properties of the JSS-EcWS briquette.** Some physical properties which are important in the characterisation of the briquette were determined; these include the density, moisture content, water resistance and shatter index for the briquettes produced by applying the mixing proportions of 0:100, 25:75, 50:50, 75:25 and 100:0 for the JSSs and EcWSs with the *A. senegal.*

**Determination of the density.** The density of the briquettes was found by applying ASTM D2395-17 (ASTM 2017). The density of the briquette was evaluated from its mass and the corresponding volume as expressed in Equation (1). The volume was calculated from the diameters (both the inner and outer) and the height of the briquette as expressed in Equation (2) while the mass was measured using a digital weighing balance (Notebook Series Digital Scale, China) (Antwi-Boasiako and Acheampong 2016).

$$\rho = \frac{M}{V} \tag{1}$$

where: $\rho$ – density of the briquette (kg·m$^{-3}$); $M$ – mass of the briquette (kg); $V$ – volume of the briquette (m$^3$).

$$V = \pi H\left(R^2 - r^2\right) \tag{2}$$

where: $H$ – height of the briquette (m); $R$ – outer radius of the briquette (m); $r$ – inner radius of the briquette.

**Determination of the moisture content.** The moisture content (on a wet basis) of the briquette was determined at a temperature range of 120 to 130 °C by the oven-drying method according to ASTM D2444-16 (ASTM 2016) for 9 hours. The initial mass of the briquette was weighed before the oven-drying, while the final mass of the briquette was determined until a constant mass was obtained consistently at two-hour intervals. The moisture content was computed on a w.b. applying Equation (3).

$$MC = \frac{M_i - M_f}{M_i} \times 100 \tag{3}$$

where: $MC$ – moisture content on a w.b. (%); $M_i$ – initial mass of the briquette before oven-drying (g); $M_f$ – final mass of the briquette after oven-drying (g).

**Determination of the water resistance.** The water resistance test was carried out by weighing the initial mass of the briquette and then hydrating it in a water bath for two minutes; after which the final mass of the briquette was weighed. The percentage of the water absorbed by the briquette was calculated using Equation (4), while the resistance of the briquette to water was determined applying Equation (5) (Davies and Davies 2013a; Kpalo et al. 2020).

$$W = 100 \times \frac{M_h - M_i}{M_i} \tag{4}$$

where: $W$ – percentage of the water absorbed by the briquette (%); $M_h$ – mass of the hydrated briquette (g); $M_i$ – initial mass of the briquette before hydration (g).

$$W_r = 100 - W \tag{5}$$

where: $W_r$ – water resistance.

**Determination of the shatter index.** The shatter index of the briquette was determined following the ASTM D440-86 (ASTM 2002) procedure. This involved taking the initial mass of the briquette before subjecting it to a gravitational fall from a height of 2 m and, thereafter, the sample was passed through a sieve having an aperture of 2.36 mm. The mass of the briquette retained on the sieve was recorded (Kpalo et al. 2020). This procedure was replicated three times. The shatter index was calculated by applying Equation (6).

$$S_i = \frac{M_s}{M} \tag{6}$$

where: $S_i$ – shatter index, $M_s$ – mass of briquette after shattering (g); $M$ – mass of briquette before shattering (g).

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**Statistical analysis.** The optimisation of the mixing ratio and binder quantity was carried out applying experimental design plan in Table 1. The experimental design plan is comprised of two independent factors, i.e., the JSS-EcWS proportions from 0 : 100, 25 : 75, 50 : 50, 75 : 25 and 100 : 0% with the binder from 50, 60, 70, 80 to 90 g. The response surface methodology (RSM) was applied for the optimisation of the briquette production. The plan of experiment, as shown in Table 2, was generated using the statistical package Design-Expert (version 10) by applying a central composite rotatable design. The data obtained was subjected to an ANOVA test and the mathematical relationships between the independent and response parameters were established.

## RESULTS AND DISCUSSION

**Effects of the variation in mixing ratio and binder on density.** The influence of the variation in the mixing proportion and quantity of the binder in the JSS-EcWS briquette is established in this section. The density of the briquette was found to have a mean value of 0.662 kg·m$^{-3}$ with a range of 0.535 to 0.809 kg·m$^{-3}$ at the corresponding mixing ratios of 25 : 75 and 100 : 0, while the quantity of the binder in each mixing ratio was 60 and 70 g, respectively. The optimum density of the briquette was found to be 0.70 kg·m$^{-3}$ at a mixing ratio and binder quantity of 75 : 25 and 60 g. The values of the density are commensurate with what is obtainable in the literature (Prasityousila and Muenjina 2013; Gwenzi et al. 2020; Olugbade and Ojo 2021). The variation in the mixing ratio and quantity of the binder in the briquette has a significant impact on the density of the briquette as depicted in Table 3. The density of the briquette follows an increasing trend with both the quantity of binder and the JSS-EcWS mixing ratio as shown in Figure 2, which is in agreement with briquettes produced from municipal waste (Prasityousila and Muenjina 2013; Thabuot et al. 2015).

Table 2. Plans of the experimental design for the mixing ratio

| S. No | JSS-EcWS (%) | Mass of Binder (g) | Responses | | | |
|---|---|---|---|---|---|---|
| | | | density (kg·m$^{-3}$) | moisture content (%) | water resistance (%) | shatter index (%) |
| 1 | 50 : 50 | 70 | 0.67 | 11.60 | 97.25 | 99.41 |
| 2 | 50 : 50 | 70 | 0.64 | 11.72 | 92.36 | 99.59 |
| 3 | 75 : 25 | 60 | 0.69 | 10.56 | 96.18 | 99.88 |
| 4 | 75 : 25 | 80 | 0.72 | 12.41 | 97.45 | 99.81 |
| 5 | 50 : 50 | 70 | 0.66 | 10.54 | 96.95 | 99.84 |
| 6 | 50 : 50 | 90 | 0.72 | 12.31 | 96.86 | 99.79 |
| 7 | 25 : 75 | 60 | 0.54 | 11.59 | 72.04 | 99.22 |
| 8 | 50 : 50 | 70 | 0.65 | 11.29 | 94.02 | 99.72 |
| 9 | 50 : 50 | 70 | 0.67 | 10.74 | 95.27 | 99.84 |
| 10 | 0 : 100 | 70 | 0.57 | 12.17 | 75.00 | 99.75 |
| 11 | 100 : 0 | 70 | 0.81 | 11.09 | 96.24 | 99.77 |
| 12 | 25 : 75 | 80 | 0.65 | 12.29 | 84.28 | 99.73 |
| 13 | 50 : 50 | 50 | 0.64 | 11.32 | 90.60 | 99.72 |

S. No – serial number; JSS – jatropha seed shells; EcWS – *Eucalyptus camaldulensis* wood shavings

Table 3. Analysis of variance for the relationship between the density and the briquette constituents

| Source | Sum of Squares | *df* | Mean Square | *F*-value | *P*-value |
|---|---|---|---|---|---|
| Model | 0.0480 | 2 | 0.0240 | 36.77 | < 0.0001 |
| Mixing ratio (%) | 0.0410 | 1 | 0.0410 | 62.33 | < 0.0001 |
| Binder (g) | 0.0073 | 1 | 0.0073 | 11.21 | 0.0074 |
| Residual | 0.0065 | 10 | 0.0007 | | |
| Lack of fit | 0.0057 | 6 | 0.0010 | 4.95 | 0.0718 |
| Pure error | 0.0008 | 4 | 0.0002 | | |
| Correlation total | 0.0540 | 12 | | | |

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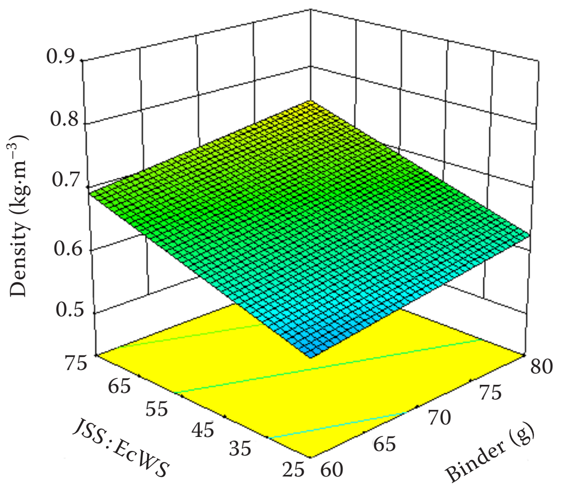


Figure 2. Density against the quantity of the binder and the JSS : EcWS mixing ratio

JSS – jatropha seed shells; EcWS – *Eucalyptus camaldulensis* wood shavings

This observation is also similar to the findings reported by some researchers (Singh and Singh 1982; Park et al. 2014; Rajaseenivasan et al. 2016). The increase in the density of the briquette with the proportion of the binder could be as a result of the improvement in its compactness due to the agglomeration of the JSS-EcWS bio-chars in the presence of the binder. The proportion of JSS-EcWS also increased with the increase in the density of the briquette as shown in Figure 3. This could be due to the porous nature of the JSS bio-char as well as the large surface area of the EcWS. Equation (7) shows the mathematical relationship that exists between the density and the mixing proportion of JSS-EcWS with the mass of the binder.

$$\rho = 0.373 + 0.00233A + 0.00247B \quad (R^2 = 0.88) \qquad (7)$$

where: $A$ – JSS-EcWS mixing proportions (%); $B$ –mass of the binder (g).

The model $F$-value of 36.77 implies the model is significant as shown in Table 2. There is less than 0.01 % chance that an $F$-value this large could occur due to noise. The lack of fit for an $F$-value of 4.95 implies that the lack of fit is not significant relative to the pure error. There is 7.18% chance that a lack of fit $F$-value this large could occur due to noise. A non-significant lack of fit is good since it shows that the observed data fit the model. The $R^2$ obtained was found to be 0.88. This shows that the variation in the mixing proportion and quantity of the binder in the briquette accounts for 88% of the total responses in the density of the briquette.

**Effects of variation in the mixing ratio and binder on the moisture content.** The effect of variation in the mixing proportion and quantity of the binder on the moisture content of the JSS-EcWS briquette was established; the moisture content of the briquette was found to have a mean value of 11.51% with a range of 10.54 to 12.41% at the corresponding mixing ratios of 50 : 50 and 75 : 25, while the quantity of the binder in each mixing ratio was 70 and 80 g, respectively. The optimum moisture content of the briquette was found to be 10.88% at a mixing ratio and binder quantity of 75 : 25 and 60 g. The range obtained for the moisture content of the JSS-EcWS briquette is similar to that of sawdust and wheat-straw briquettes, lignite briquettes, and charcoal dust briquettes (Wamukony and Jenkins 1995; Olugbade and Ojo 2021; Tanui et al. 2018). The optimum moisture content range for the briquette raw material was reported to be 12–20%. A low moisture content indicates the poor durability of the briquette (Resch and Hoag 1988; Olugbade and Ojo 2021). Briquettes with a low moisture content tend to crack and breakdown with time. More so, it has been reported that a moisture content that is less than 4 or 5% will reduce the stability of the briquettes, thus increasing its burning rate (Missagia et al. 2011; Tumuluru et al. 2011; Ahmad et al. 2018). The relationship between the moisture content and the mixing ratio with the quantity of the binder in the briquette was established to be significant as depicted in Table 4. The moisture content of the briquette follows an increasing trend with the quantity of binder which has also been reported for briquettes produced from recycled charcoal dust (Tanui et al. 2018). However, it increased with a decrease in the JSS-EcWS mixing ratio as shown in Figure 3.

The increase in the moisture content of the briquette with the quantity of the binder could be a result of its hygroscopic nature. The more the quantity of binder in the briquette increases, the more its tendency to absorb moisture from its immediate environment. Equation (8) shows the mathematical relationship that exists between the moisture content ($MC$) of the briquette and the mixing proportion of the JSS-EcWS briquette with the mass of binder.

$$MC = 9.38 - 0.0102A + 0.0378B \quad (R^2 = 0.50) \qquad (8)$$

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The model *F*-value of 4.53 implies that the model is significant as shown in Table 4. There is less than a 3.98% chance that an *F*-value this large could occur due to noise. The lack of fit for an *F*-value of 1.03 implies that the lack of fit is not significant relative to the pure error. There is a 51.32% chance that a lack of fit *F*-value this large could occur due to noise. A non-significant lack of fit is good since it shows that the observed data fit the model. The $R^2$ obtained was found to be 0.50. This shows that the variation in the mixing proportion and quantity of binder in the briquette accounts for 50% of the total responses in the moisture content of the briquette.

**Effects of variation in the mixing ratio and binder on the water resistance.** The water resistance test is a measure of the degree of response of a material to moisture when it is in contact to water (Davies and Davies 2013b). The influence of the variation in the mixing proportion and quantity of the binder on the water resistance of the JSS-EcWS briquette was established; the water resistance of the briquette was found to have a mean value of 91.12% with a range of 72.04 to 97.45% at the corresponding mixing ratios of 25 : 75 and 75 : 25, while the quantity of the binder in each mixing ratio was 60 and 80 g, respectively. The optimum water resistance of the briquette was found to be 98.11% at a mixing ratio and binder quantity of 75 : 25 and 60 g. Rajaseenivasan et al. (2016) reported similar values for a neem and sawdust briquette. The relationship between water resistance and the mixing ratio with the quantity of the binder in the briquette was established to be significant as depicted in Table 5. Davies and Davies (2013b) reported the effects of a binder on the water resistance of a water hyacinth briquette to be significant. The water resistance of the briquette follows an increasing trend with both the quantity of the binder and the JSS-EcWS mixing ratio as shown in Figure 4. The increase in the water resistance with the quantity of the binder could be due the small particle size of the pyrolyzed JSS and EcWS which enhanced its inter-particle bonding with negligible pore spaces.

The applied binder could also enhance the resistance of the briquette to water absorption when exposed, which may be the reason for its high water resistance capacity. Equation (9) shows the mathematical relationship that exists between the water

Table 4. Analysis of variance for the relationship between the moisture content and the briquette constituents

| Source | Sum of Squares | *df* | Mean Square | *F*-value | *P*-value |
|---|---|---|---|---|---|
| Model | 2.50 | 2 | 1.25 | 4.53 | 0.0398 |
| Mixing ratio (%) | 0.79 | 1 | 0.79 | 2.85 | 0.1222 |
| Binder (g) | 1.71 | 1 | 1.71 | 6.21 | 0.0319 |
| Residual | 2.75 | 10 | 0.28 | | |
| Lack of fit | 1.67 | 6 | 0.28 | 1.03 | 0.5132 |
| Pure error | 1.08 | 4 | 0.27 | | |
| Correlation total | 5.25 | 12 | | | |

Table 5. Analysis of variance for the relationship between the water resistance and the briquette constituents

| Source | Sum of Square | *df* | Mean Square | *F*-value | *P*-value |
|---|---|---|---|---|---|
| Model | 759 | 5 | 152 | 7.83 | 0.0087 |
| $A$ | 531 | 1 | 531 | 27.36 | 0.0012 |
| $B$ | 56 | 1 | 56 | 2.91 | 0.1317 |
| $AB$ | 30 | 1 | 30 | 1.55 | 0.2532 |
| $A^2$ | 140 | 1 | 140 | 7.23 | 0.0312 |
| $B^2$ | 5 | 1 | 5 | 0.23 | 0.6439 |
| Residual | 136 | 7 | 19 | | |
| Lack of fit | 119 | 3 | 40 | 9.47 | 0.0274 |
| Pure error | 17 | 4 | 4 | | |
| Correlation total | 895 | 12 | | | |

*A* – jatropa; *B* – binder

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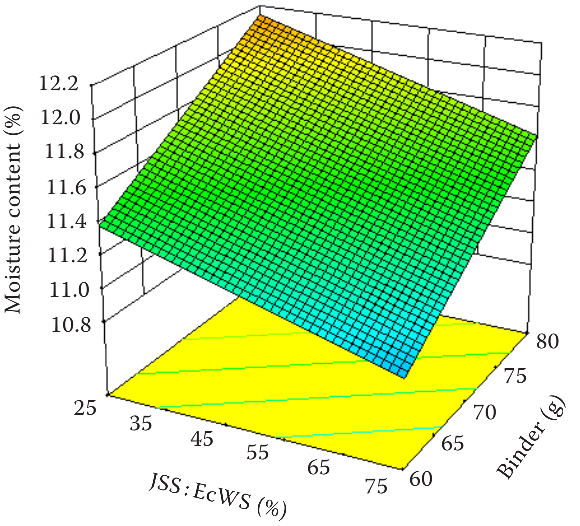


Figure 3. Moisture content against the quantity of the binder and the JSS : EcWS mixing ratio

JSS – jatropha seed shells; EcWS – *Eucalyptus camaldulensis* wood shavings

resistance of the briquette and the mixing proportion of the JSS-EcWS briquette with the mass of the binder.

$$W_r = -4.70 + 1.429A + 1.387B - 0.011AB - 0.00396A^2 - 0.00444B^2 \quad (R^2 = 0.85) \tag{9}$$

The model *F*-value of 7.83 implies that the model is significant as shown in Table 5. There is a 0.87% chance that an *F*-value this large could occur due to noise. The lack of fit for an *F*-value of 9.47 implies that the lack of fit is significant relative to the pure error. There is only a 2.75% chance that a lack of fit *F*-value this large could occur due to noise. The $R^2$ obtained was found to be 0.85. The $R^2$ shows the variation in the mixing proportion and quantity of the binder in the briquette accounts for 85% of the total responses in the water resistance of the briquette.

**Effects of variation in the mixing ratio and binder on the shatter index.** The shatter index test is a measure of the briquette's strength. A high shatter index is an indication of a briquette's good handling and strength properties, which are necessary in avoiding any damage (Rajaseenivasan et al. 2016; Olugbade and Ojo 2021). The impact of the variation in the mixing proportion and the quantity of the binder on the shatter index of the JSS-EcWS briquette was established; the shatter index of the briquette was found to have a mean value of 99.7% with a range of 99.22 to 99.88% at the corresponding mixing ratios of 25 : 75 and 75 : 25, while the quantity of the binder in each mixing ratio was 60 g respectively. The optimum shatter index of the briquette was found to be 99.86% at a mixing ratio and binder quantity of 75 : 25 and 60 g. These values were above the recommended value of 90%, thus indicating the ability of the briquette to retain their form after being subjected to an impact force (Borowski 2007; Borowski and Hycnar 2013; Gwenzi et al. 2020). The range obtained for the shatter index of the JSS-EcWS briquette is similar to that of a sawdust briquette blended with neem powder (Rajaseenivasan et al. 2016) and a corn cob and oil palm trunk bark briquette (Kpalo et al. 2020). The relationship between the shatter index and the mixing ratio with the quantity of the binder in the briquette was established to be insignificant as depicted in Table 6. Kpaloet al. (2020) reported the effects of the mixing ratio and waste paper pulp on the shatter index of a corn cob and oil palm trunk bark briquette to be insignificant. Antwi-Boasiako and Acheampong (2016) also show the effect of the mixing proportion on the shatter index of sawdust briquettes from some tropical hardwood to be insignificant.

The shatter index of the briquette follows an increasing trend with both the quantity of the binder and the JSS-EcWS mixing ratio as shown in Figure 5. The increase in the shatter index with the quantity of the binder could be due the agglomeration of the constituting materials, which resulted

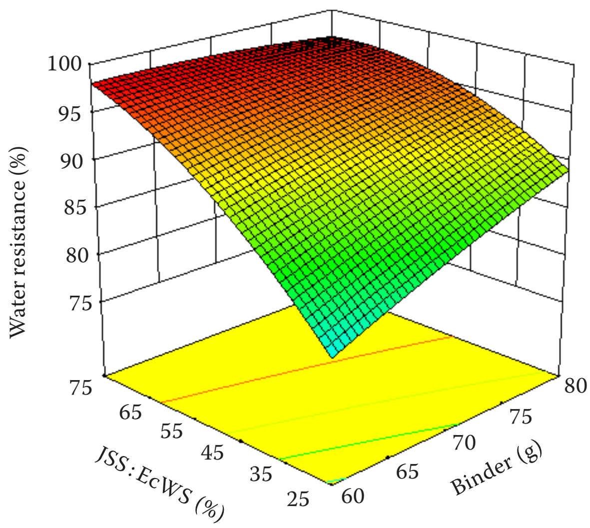


Figure 4. Water resistance against the quantity of the binder and the JSS:EcWS mixing ratio

JSS – jatropha seed shells; EcWS – *Eucalyptus camaldulensis* wood shavings

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in the strong bonding of particles. A similar result was obtained for briquettes produced from blending lignite with paper waste (Yaman et al. 2001).

The particle size of the pyrolyzed jatropha shell and *E. camaldulensis* wood shavings could also enhance the strength of the briquette. Equation (10) shows the mathematical relationship that exists between the shatter index of the briquette and the mixing proportion of the JSS-EcWS briquette with the mass of the binder.

$$S_i = 97.19 + 0.0432A + 0.0339B - 0.00058AB \quad (10)$$

($R^2$ = 0.38)

The model $F$-value of 1.87 implies that the model is insignificant as shown in Table 6. There is a 20.50% chance that an $F$-value this large could occur due to noise. The lack of fit for an $F$-value of 0.79 implies that the lack of fit is not significant relative to the pure error. There is a 60.60% chance that a lack of fit $F$-value this large could occur due to noise. A non-significant lack of fit is good since it shows that the observed data fit the model. The $R^2$ obtained was found to be 0.38. This is very low for a model. The $R^2$shows that the variation in the mixing proportion and quantity of the binder in the briquette accounts for 38% of the total responses in the moisture content of the briquette.

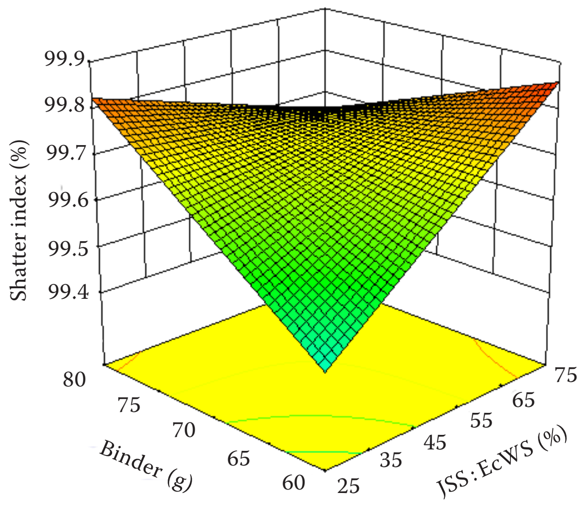


Figure 5. Shatter index against the quantity of the binder and the JSS:EcWS mixing ratio

JSS – jatropha seed shells; EcWS – *Eucalyptus camaldulensis* wood shavings

## CONCLUSION

Some of the properties of briquettes produced from forest waste were determined, while the effects of the mixing ratios and binder quantity on the briquette were also established. The density, moisture content, water resistance and shatter index ranged from 0.54 to 0.81 kg·m$^{-3}$, 10.54 to 12.41, 72.04 to 97.45 and 99.22 to 99.88%, respectively, while their optimum values were 0.70 kg·m$^{-3}$, 10.88, 98.11 and 99.86%, respectively, at a mixing ratio and binder quantity of 75 : 25 and 60 g, respectively. The physical properties, such as the density, moisture content and water resistance were significantly influenced by the variation in the mixing proportion and the quantity of the binder while its effect on the shatter index was insignificant. These properties show the suitability of the admixture of the jatropha shell and *Eucalyptus camaldulensis* waste for the briquette production at the optimum mixing proportions.

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Table 6. Analysis of variance for the relationship between the shatter index and the briquette constituents

| Source | Sum of Square | *df* | Mean Square | *F*-value | *P*-value |
|---|---|---|---|---|---|
| Model | 0.16 | 3 | 0.055 | 1.87 | 0.2050 |
| *A* | 0.05 | 1 | 0.052 | 1.76 | 0.2170 |
| *B* | 0.03 | 1 | 0.028 | 0.97 | 0.3511 |
| *AB* | 0.08 | 1 | 0.084 | 2.88 | 0.1238 |
| Residual | 0.26 | 9 | 0.029 | | |
| Lack of fit | 0.13 | 5 | 0.026 | 0.79 | 0.6060 |
| Pure error | 0.13 | 4 | 0.033 | | |
| Correlation total | 0.43 | 12 | | | |

*A* – jatropa; *B* – binder

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