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STATISTICAL OPTIMIZATION OF THE PHYSICAL AND MECHANICAL PROPERTIES OF BRIQUETTES OF *CEIBA PENTANDRA* SAWDUST AND AGRICULTURAL RESIDUE

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Abstract:
Utilization of biomass residue from agricultural and sawmilling activities for energy would reduce the pressure on forest stands. This study characterized briquettes made of Ceiba pentandra sawdust, oil palm empty fruit bunch, and sugarcane peels at varying compacting pressures as alternative sources of energy. Using two level factorial design analyses, statistical models describing the relationships between material compositions of the briquettes and their physical and mechanical properties such as shatter index, impact resistance index, compressive strength in cleft and relaxed density were derived. Combinations of pressure and materials for manufacturing briquettes with standard physical and mechanical properties were also determined using numerical optimization. Generally, increasing the compacting pressure improved the physical and mechanical properties of the briquettes. Oil palm empty fruit bunch content impacted negatively on all the properties. Contrastingly, Sugarcane peels and Ceiba pentandra sawdust had a strong positive effect on most of the physical and mechanical properties. All the briquettes were durable recording an average of 98% shatter resistivity. The optimization results generated briquettes with standard shatter index (98 %), impact resistance index (117.08 – 239.25 %), compressive strength in cleft (20 N/mm), and relaxed density (363.23 – 504.75 kg/m^3) suitable for packaging, transportation, storage, and domestic utilization. Generally, this study indicates that briquettes with good physical and mechanical properties can be produced from Ceiba pentandra sawdust, oil palm empty fruit bunch, and sugarcane peels at low compacting pressure. Additionally, briquettes with specific desired attributes could be produced by varying the compositions of the materials and compacting pressure.

Key words*: biomass; briquettes; mechanical property; optimization; residue.*

INTRODUCTION

Energy is important in the activities of human beings. Man taps various forms of energy for utilization from naturally occurring resources. Biomass, fossil fuels (coal/peat, crude oil and natural gas) and nuclear resources are the popular sources of energy. Fossil fuels and nuclear energy have been rated environmentally unfriendly and unsustainable because of their non-renewability and extraction and utilization hazards. Emission of pollutants such as SO_2, NO_x and volatile organic compounds (VOC's), CO, particulates and CO_2 associated with the combustion of fossil fuels contribute significantly to acid precipitation and other health issues (Radovic 1997). Additionally, instability as a result of conflicts and wars in especially crude oil producing regions has resulted in fluctuating and price hikes. These drawbacks have culminated in the demand for safer and less costly alternatives such as biomass energy to reduce the overdependence on fossil fuels (IEA 2014). Advantages of the use of biomass for energy production includes it being nearly inexhaustible, locally generated, not impacting the environment negatively and not resulting in major accidents as in nuclear and oil energy (Shekhar 2011). The various forms of biomass are dominated by wood and forest residues, agricultural crops, agricultural residue, sewage, municipal solid waste and algae (Potgieter 2011).

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From 1973 to 2012 there was 47.97% increase in the total energy consumed worldwide, thus from 4672 to 8970 Mtoe (million tonnes of oil equivalence) in terms of fuel (IEA 2014). Implications were that, there was the need to explore sustainable sources of energy to satisfy the increasing population and market size. Consequently, many sources of energy were placed under thorough scrutiny and researched to evaluate the sustainable ones to improve upon their extraction and utilization.

Ghana has also experienced significant increase in energy demand in recent times due to population growth, urbanization and increased industrial activities. The increased demand is, however, more prominent in the consumption of wood fuel, particularly wood charcoal (Duku *et al*. 2011). According to the Food and Agriculture Organization of the United Nations, consumption of wood fuel increased from 20.6 million m^3 in 2004 to 35.4 million m^3 in 2008, while that of wood charcoal alone increased from 752,000 m^3 to 1.48 million m^3 during the same period (Duku *et al*. 2011). Firewood, a traditional wood energy system was the most dominant source of biomass energy in the year 2011, constituting 25.28% of the total energy consumption in Ghana, with charcoal and petroleum products taking14.60% and 48.46%, respectively (Energy Commission Ghana 2013). The continuous use of forest trees as wood fuel at this alarming rate will lead to depletion of the resource base. Hence converting residues from agricultural processes, sawmills and felled timber into usable energy products to augment the available energy will be handy to relieve pressure on the forest and ensure fuel sufficiency, sustainability and environmental protection.

In 2010 the total crop production for some selected and prominent crops (rice, maize, millet, sugarcane, coffee, cocoa, oil palm fruit, and coconut) was estimated as 5,600,200 tonnes with a potential residue of 4,536,320 tonnes meaning 81% went to waste in the form of agricultural residue (Mitchual *et al.* 2014). This implies, products such as briquettes that could use these residues as raw material can be produced readily and at low cost. It is therefore necessary to utilize the residue from agriculture, sawmills, felling activities and various biomass waste to reduce the pressure on the forest and limit emissions from the use of non-renewable energy sources.

The objective of this study therefore was to produce briquettes using low compacting pressure without binding agents from agricultural residues of oil palm empty fruit bunch and sugarcane peels and sawmill residue of *Ceiba pentandra* sawdust. The study also investigated the effects of material compositions and compacting pressures on the physical and mechanical properties of the briquettes.

MATERIALS AND METHODS

Experimental design

The four variables studied included compacting pressure levels (20 and 50 MPa), oil palm empty fruit bunch content (0 to 50g), sugarcane peels content (0 to 50 g) and *Ceiba pentandra* sawdust content (0 to 50g). A two-level factorial design was selected and different compositions of briquettes formulated using Design Expert Software version V.7.0 (Stat-Ease Corp. Minnesota). The formulated briquettes were assessed for their physical and mechanical properties. Five replicates were run for each formulation. The material contents for each formulation were represented as percentages in the design matrix. Thus 0 g of a material was 0% and 50g was represented as 100%. Table 1 present the experimental design matrix in the two different approaches used by Design Expert Software to indicate the levels of factors. The levels are; (i) the actual levels of factors or the actual values in the experiment and (ii) the coded factor levels where -1 represents low levels and +1 represents high levels and 0 a center point. The coded factor levels are represented as:

$$Coded\ Factor\ Levels\ = \frac{AV-FM}{(RFV/2)} \quad (1)$$

where: AV is Actual Value;
FM is Factor Mean;
RFV is Range of the Factorial Values.

Table 1

Experimental design matrix in terms of actual and coded factor levels generated by Design Expert software

Experiment number	**Type**	**Factors**				**Responses**				
		Pressure (MPa)	**Oil Palm Empty Fruit Bunch (%)**	***Ceiba pentandra* Sawdust (%)**	**Sugarcane Peels (%)**	**Shatter Index (%)**	**Impact Resistance Index (%)**	**Moisture Content (%)**	**Compressive Strength in Cleft (N/mm)**	**Relaxed Density (kg/m^3)**
1	Fact	20 (-1)	0 (-1)	0 (-1)	0 (-1)	0	0	0	0	0
2	Fact	50 (+1)	0 (-1)	0 (-1)	0 (-1)	0	0	0	0	0
3	Fact	20 (-1)	100 (+1)	0 (-1)	0 (-1)	97.80	205.30	10.48	5.70	312.37
4	Fact	50 (+1)	100 (+1)	0 (-1)	0 (-1)	98.92	305.00	10.48	13.18	534.20
5	Fact	20 (-1)	0 (-1)	100 (+1)	0 (-1)	99.26	133.00	7.52	11.34	383.02
6	Fact	50 (+1)	0 (-1)	100 (+1)	0 (-1)	99.72	380.00	7.52	28.23	602.74
7	Fact	20 (-1)	100 (+1)	100 (+1)	0 (-1)	97.74	225.00	9.00	14.65	405.06
8	Fact	50 (+1)	100 (+1)	100 (+1)	0 (-1)	99.76	311.11	9.00	31.20	597.45
9	Fact	20 (-1)	0 (-1)	0 (-1)	100 (+1)	99.48	203.00	7.52	4.27	400.46
10	Fact	50 (+1)	0 (-1)	0 (-1)	100 (+1)	99.76	343.00	7.52	11.16	640.76
11	Fact	20 (-1)	100 (+1)	0 (-1)	100 (+1)	99.26	188.88	9.00	19.12	363.56
12	Fact	50 (+1)	100 (+1)	0 (-1)	100 (+1)	99.80	200.00	9.00	34.46	523.69
13	Fact	20 (-1)	0 (-1)	100 (+1)	100 (+1)	99.16	100.00	7.52	15.41	405.51
14	Fact	50 (+1)	0 (-1)	100 (+1)	100 (+1)	99.68	133.00	7.52	41.52	642.53
15	Fact	20 (-1)	100 (+1)	100 (+1)	100 (+1)	98.36	55.55	8.51	15.56	225.20
16	Fact	50 (+1)	100 (+1)	100 (+1)	100 (+1)	99.51	188.88	8.51	38.53	511.43
17	Center	35 (0)	50 (0)	50 (0)	50 (0)	99.45	100.00	8.51	22.45	455.68

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Determination of moisture content

The moisture content of the samples was determined in accordance with the European Standard EN 13183-1 (2002). A sample of 2 g of each biomass and their combinations were weighed and placed in a laboratory oven at a temperature of 103 ± 2^{0}C for drying. The samples were dried until weights of successive weighing's at 2 hours intervals differed by 0.01 g or less. An electric balance with accuracy of 0.01 grams was used to measure the change in mass. The moisture content of the specimen was then computed using Equation 2.

$$\text{Moisture content } (\%_{db}) = \frac{\mathrm{M_1 - M_0}}{\mathrm{M_0}} \times 100 \qquad (2)$$

where: M_0 and M_1 are the oven dry mass and initial mass, in g, respectively.

Material preparation and briquette manufacturing

The oil palm empty fruit bunch, sugarcane peels and sawdust of *C. pentandra* were sun dried for 21 days to eliminate moisture and prevent insect, fungal and bacterial attacks. The dried materials were milled in a local attrition mill and subsequently sieved with sieve mesh aperture of >1.5 mm. The sieved biomass was conditioned at 25^{0}C and 55% humidity for 24 hours in the laboratory before the briquette formulation and manufacture. The average moisture content of the biomass materials used for the study was 8.51% which is acceptable for the production of quality briquettes (Table 1).

The briquettes were manufactured with a cylindrical mold of dimensions 55.3 mm ID (internal diameter) and 52.5 cm height. The formulated biomass raw material loaded into the mold was compressed with a manual hydraulic press with a gauge and piston. To allow for free movement of the piston and air escape during compression of the biomass, a clearance of about 0.1 mm was provided between the piston and the inner wall of the mold.

Relaxed density

Relaxed density of the briquettes were assessed with ISO 3131 (1975) 30 days after production. An electronic balance with an accuracy of 0.01 g was used to determine the mass of the briquettes. A digital Vernier Calliper was used to determine the diameter and length of the briquettes at three different points for each briquette. The relaxed density was then computed as shown in Equation 3:

$$RD = \frac{108{,}000 \times M}{\pi[d_1 + d_2 + d_3]^2 \times [l_1 + l_2 + l_3]} \quad [\text{g/cm}^3] \qquad (3)$$

where: M is the mass of briquettes, in g;
d_1, d_2 and d_3 are diameters of the briquettes measured at different points on length, in mm;
l_1, l_2 and l_3 are lengths of the briquettes measured at different points on each diameter, in mm.

Shatter index (durability)

Shatter index was used to assess the briquettes durability. The assessment was based on the method described by Suparin *et al*. (2008). Samples of the briquette were repeatedly dropped 3 times from 1.5 m high onto a concrete floor. The fraction of the shattered briquette retained was used as an index of briquette breakability. The percentage weight loss of briquettes was expressed as a percentage of the initial mass and the shatter index was obtained by subtracting the percentage weight loss from 100 as shown in Equations 4 and 5 (Sengar *et al.* 2012):

$$\text{Percent weight loss} = \frac{\text{IWBS} - \text{WAS}}{\text{IWBS}} X\ 100 \quad [\%] \qquad (4)$$

where: IWBS is initial weight of briquette before shattering, in g;
WAS is weight of briquette after shattering, in g.

$$\text{Shatter Index} = 100 - \text{Percent weight loss} \quad [\%] \qquad (5)$$

Compressive strength in cleft

Compressive strength in cleft of briquettes was determined using an Instron Universal Strength testing machine with load cell capacity of 100 KN in accordance with ASTM D 2166-85. The samples of briquette were placed horizontally in the compression test fixture and the load was applied at a constant rate of 0.305

mm/min until the briquette failed by cracking. The Compressive strength was then computed as in Equation 6:

$$\text{Compressive strength in cleft} = \frac{3 \times \text{LFP}}{[l_1 + l_2 + l_3]} \qquad [\text{N/mm}] \qquad (6)$$

where: l_1, l_2 and l_3 are lengths of the briquettes measured at three different points, in mm;
LFP is the load at fracture point, in N.

Impact resistance index

The impact resistance index (IRI) of the briquettes was determined in accordance with ASTM D440:2007 of the drop shatter for coal. Each briquette was repeatedly dropped from a stationary starting point of 2 m height onto a concrete floor until it fractured. The number of drops and the number of pieces each briquette broke into were recorded. From these data, impact resistance index (IRI) was calculated using Equation 7.

$$\text{IRI} = \frac{\text{Average number of drops(N)}}{\text{Average number of pieces(n)}} \times 100 \qquad (7)$$

RESULTS AND DISCUSSIONS

Relaxed density

Regression analysis on the relaxed density obtained the best fit model equation for the experimental data with prob F< 0.05 and high R^2, adjusted R^2 as well as adequate precision values (Table 2). Equation (8) describes the derived linear regression model predicting the relaxed density in terms of coded factors:

$$\text{Relaxed Density} = 409.25 + 97.35A + 24.87B + 62.37C + 54.89D - 61.70BC - 83.04BD - 80.34CD + 42.02BCD \qquad (8)$$

where: A is the pressure,in MPa;
B is the oil palm empty fruit bunch content, in %;
C is the *Ceiba pentandra* sawdust content, in %;
D is the sugarcane peels content, in %.
These description for the variables apply to all analyses in this paper.

Table 2

Analysis of variance (ANOVA) for two-level factorial model

Property	F-Value	Prob>F [a]	R^2	Adj. R^2	Adequate [b] Precision
Relaxed Density	199.65	0.0001	0.9557	0.9509	49.107
Shatter Index	40,440.36	0.0001	0.9997	0.9997	552.022
Impact Resistance Index	8,019.25	0.0001	0.9993	0.9992	292.069
Compressive Strength in Cleft	500.83	0.0001	0.9819	0.9799	72.707

[a]Values of "Prob>F" less than 0.05 indicates significant model terms.
[b]Adequate precision measures the signal-to-noise ratio. A ratio greater than 4 is desirable for the model.

Pressure (factor A), oil palm empty fruit bunch content (factor B), *Ceiba pentandra* sawdust content (factor C) and sugarcane peels content (factor D) positively affected the relaxed density of the briquettes due to their positive algebraic signs (Equation 8). The results suggests that relaxed density increased with pressure, *Ceiba pentandra sawdust* content, oil palm empty fruit bunch content and sugarcane peels content whereas opposite trends were observed for interaction factors BC, BD, and CD.

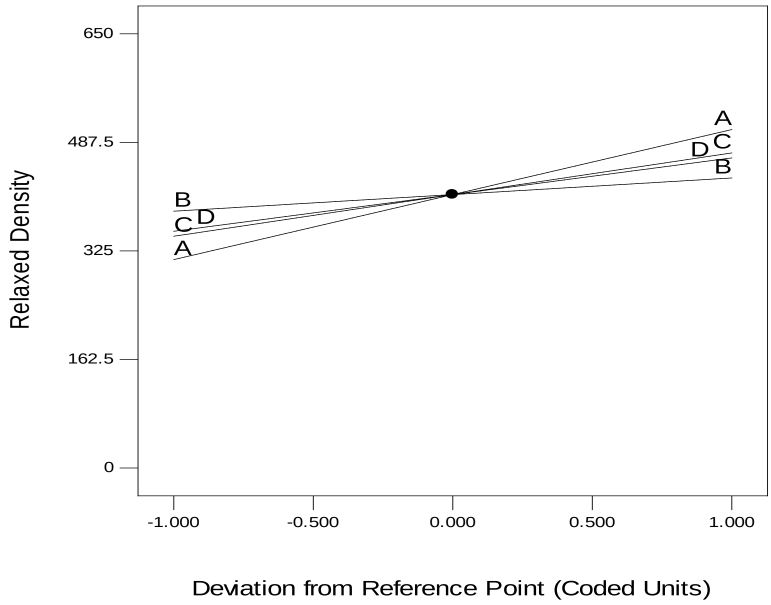

Fig. 1.
Perturbation plots of relaxed density of the briquettes against compacting pressure level (factor A), oil palm empty fruit bunch content (factor B), Ceiba pentandra sawdust content (factor C), and sugarcane peels content (factor D).

The perturbation plot (Fig. 1) showed steep plots for pressure (A), oil palm empty fruit bunch content (B), *Ceiba pentandra* sawdust content (C) and sugarcane peels content (D). The relative importance of these variables are indicated by the values of their regression coefficients with A being the highest followed by C, D, and B, respectively. Density of briquettes is an important quality attribute that influences its transportation, speed of combustion, energy production and stability (McKendry 2002, Demirbas and Sahin-Demirbas 2004). The relaxed density of the briquettes increased with increasing compacting pressure (Table 1) irrespective of material type, quantity and combinations. The increased relaxed density with pressure may be due to reduced void ratio and plastic deformation of the particles (Mitchual *et al.* 2014). Factors B, C and D were involved in significant interactions (interactions BC, BD, CD, and BCD) implying that the effect of one factor depended on the level of the other. These factors therefore have to be investigated together (Afrifah and Matuana 2012).

Cube plots illustrating the variation of the relaxed density of the briquettes with respect to the interaction between oil palm empty fruit bunch, *Ceiba pentandra* sawdust and sugarcane peels contents are presented in Fig. 2a and Fig. 2b. Generally, at constant pressure the relaxed density of the briquettes increased with increase in all materials and combinations (Fig. 2a, Fig. 2b). Material type influenced the relaxed density. This is in line with observation made by several researchers that density, moisture content and particle size of the original biomass influence the briquettes density (Kers *et al.* 2010). Sugarcane peels produced briquettes with the highest relaxed density, followed by *Ceiba pentandra* sawdust with the least being oil palm empty fruit bunch. Consequently, inclusion of oil palm in a combination resulted in briquettes with lower density (Fig. 2a, Fig. 2b). Similar results were observed by Mitchual *et al.* (2019) in their work involving briquettes of oil palm mesocarp fibre and *Ceiba pentandra* sawdust. The low relaxed density of briquettes of the oil palm mesocarp fibre and their combinations was attributed to weak bond formation between the fibres which resulted in higher expansion of the briquettes after removal from the press as well as low bulk density of the oil palm mesocarp fibre (Mitchual *et al.* 2019). Several organisations have defined the density of standard biomass briquettes to be in the range of 1000 – 1400 kg/m^3 (FAO 1990, Hahn 2004).

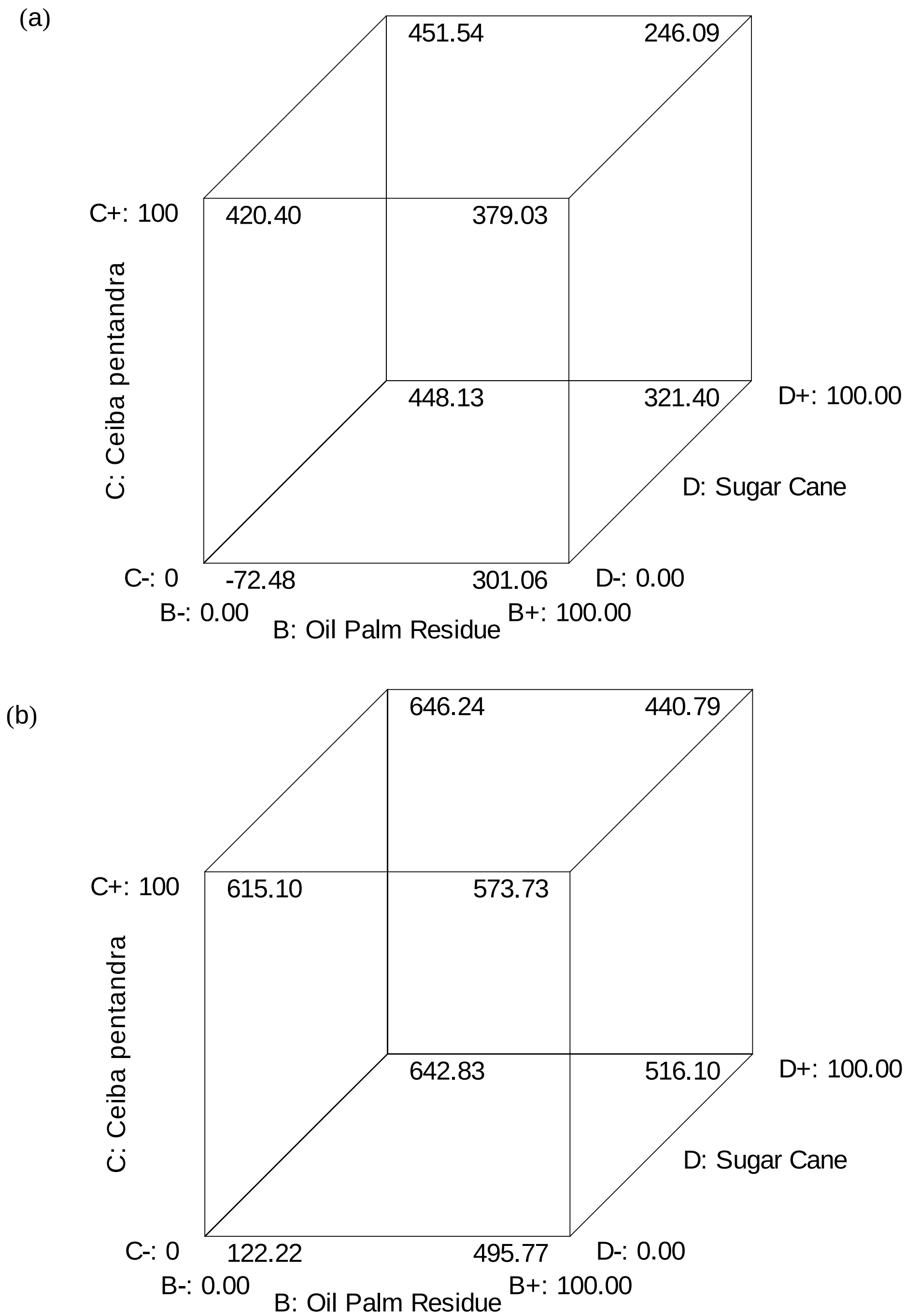

Fig. 2.
Cube graphs of the relationships between relaxed density and oil palm empty fruit bunch (factor B), Ceiba pentandra sawdust (factor C) and sugarcane peels (factor D) contents at compacting pressures of (a) 20 MPa and (b) 50 MPa.

The observed relaxed densities for all composition of briquettes in this study fell below the standard mark of 1000 – 1400 kg/m^3 (Fig. 2a, Fig. 2b). However, the relaxed density of the briquettes conformed to those produced with similar hydraulic presses which are usually less than 1000 kg/m^3 and mostly between 300 – 600 kg/m^3 (Saedy 2004, Tumuluru *et al.* 2010). Additionally, the low densities may be due to the low compacting pressure and room temperature used in this study (Kers *et al.* 2010).

Compressive strength in cleft

Regression analysis for compressive strength in cleft of the briquettes suggested that the data was best-fit by a linear model, after dropping insignificant terms. A square root transformation was applied to the

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data to normalise the variance of the residuals in the system. Table 2 shows the analysis of variance (ANOVA) results for the linear model. The reduced model, containing only significant terms and described by coded factors is as shown in Equation 9:

$$Sqrt(CS + 0.47) = +3.90 + 0.77A + 0.63B + 0.97C + 0.67D + 0.28AC + 0.16AD - 0.57BC - 0.37CD \quad (9)$$

All the main factors (A, B, C, and D) along with some of their interactions (AC, AD, BC and CD) were significant for the compressive strength in cleft. Because of the positive algebraic signs of A, B, C, D, AC, and AD, increases in them would improve the compressive strength in cleft of briquettes produced. By contrast two-factor interactions of BC and CD had negative algebraic signs, which indicated a negative effect on compressive strength in cleft.

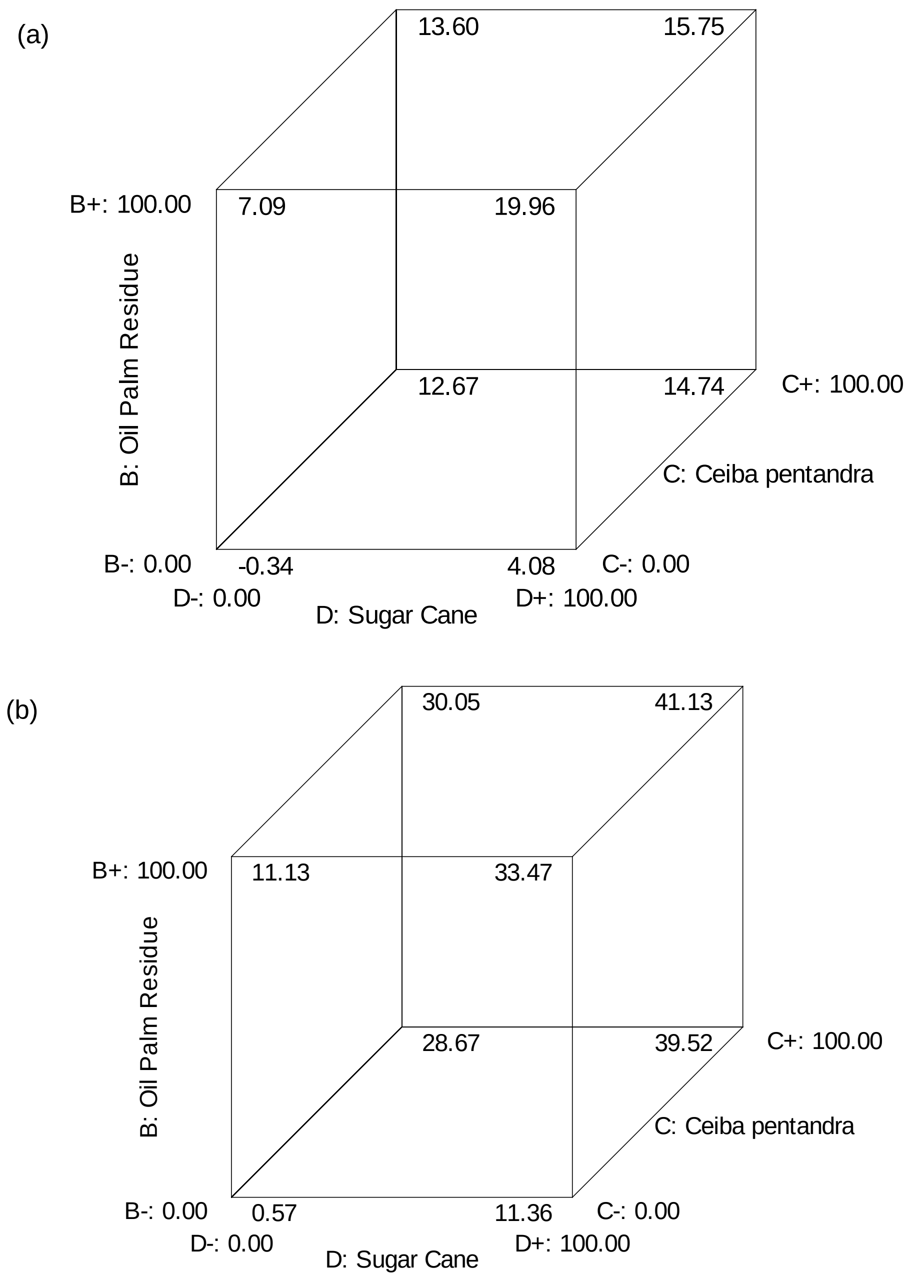


Fig. 3.
Cube graphs of the relationships between compressive strength in cleft and oil palm empty fruit bunch (factor B), Ceiba pentandra sawdust (factor C) and sugarcane peels (factor D) contents at compacting pressures of (a) 20 MPa and (b) 50 MPa.

Fig. 3a and Fig. 3b show the cube graphs of the variation of compressive strength in cleft of the briquettes as a function of oil palm empty fruit bunch, *Ceiba pentandra* sawdust and sugarcane peels contents at pressure levels of 20 and 50 MPa. The compressive strength of the briquettes increased with increase in compacting pressure (Fig. 3a, Fig. 3b). This result is in line with observations made by Mitchual *et al.* (2014) on briquettes made from maize cobs and sawdust. This increase in compressive strength in cleft may be attributed to enhanced formation of mechanical interlocking bond and improved adhesive force between particles when pressure is applied to loose biomass material (Grover and Mishra 1996). Additionally, the compressive strength increased with a rise in biomass content irrespective of composition or mixing ratio and compacting pressure (Fig. 3a, Fig. 3b). Fig. 3a and Fig. 3b also indicate that composition of the briquettes affects their compressive strength in cleft. Mixed biomass briquettes tended to have higher compressive strength compared to their pure counterparts (Fig. 3a, Fig. 3b). Observation have been made by some researchers that the introduction of certain species such as *Ceiba pentandra* improves the binding force through mechanical interlocking and adhesion between the particles and consequently the compressive strength (Mitchual *et al.* 2014). Briquettes of pure *Ceiba pentandra* sawdust had higher compressive strength compared to those of pure sugarcane peels and oil palm empty fruit bunch confirming observation made by Mitchual *et al.*(2014) that briquette of *Ceiba pentandra* had higher compressive strength. This trend was explained by the fact that the thinner cell wall of the low density *Ceiba pentandra* made it easy for the particles to undergo plastic deformation when pressed leading to the formation of stronger bonds (Mitchual *et al.* 2014). Studies have shown that briquettes with compressive strength of 19.6 N/mm is adequate for storage, handling and use as domestic fuel (Rahman *et al.* 1989). At the minimum pressure of 20 MPa only briquettes made of a blend of oil palm empty fruit bunch and sugarcane peels achieved this standard (Fig. 3a). By contrast at the high compacting pressure of 50 MPa all the briquettes except those of pure oil palm empty fruit bunch and pure sugarcane peels achieved compressive strength higher than the minimum specified (Fig. 3b). This implies that if the briquettes are produced at relatively high compacting pressure adequate compressive strength for handling and storage would be attained.

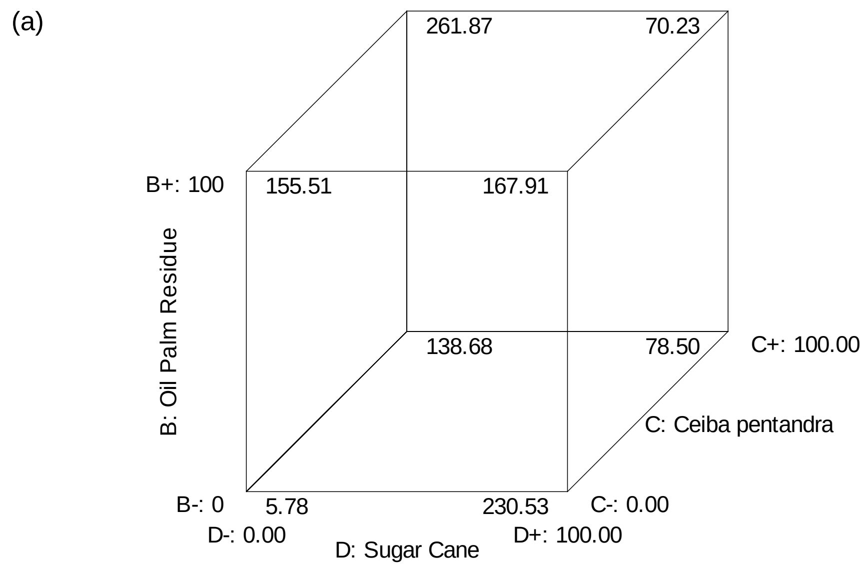
Impact resistance index

Results of the regression analysis for impact resistance index (IRI) suggest that the data was best-fit by a linear model. A power transformation was applied to the data for IRI in order to normalize the variance of the residuals in the system. Shown in Table 2 are the summarised results of the analysis of variance (ANOVA). Presented below is the reduced model, containing only significant coded factors:

$$(\text{Impact Resistance} + 3.80)^{0.85} = +83.80 + 17.80A + 10.91B - 17.82BD - 25.36CD + 16.70BCD + 11.61ABCD \qquad (10)$$

The positive lambda value of the power model (Equation 10) indicates that the positive algebraic signs of the significant factors result in increase in IRI when those factors are increased. Based on the regression coefficients of the significant main factors (Equation 10), factor A (compacting pressure) had higher influence on the IRI than factor B (oil palm empty fruit bunch content). The other factors were involved in interactions and investigated together (Equation 10).

Fig.4a and Fig. 4b show the cube graphs of the variation of IRI of the briquettes as a function of oil palm empty fruit bunch content, *Ceiba pentandra* sawdust content, and sugarcane peels content pressed at 20 and 50 MPa. The IRI increased as pressure was increased irrespective of the composition of the briquette samples produced (Fig. 4a, Fig. 4b). Similar observation has been made by Mitchual *et al.* (2014) for briquettes produced at low compacting pressure without binder, where impact resistance index was found to be directly proportional to.compacting pressure. Increasing the pressure bring the particles close enough together to adhere to eachother through short range forces such as valence forces, hydrogen bridges, Van der waals forces and electrostatic forces or by the particles forming interlocking bonds (Kaliyan and Morey 2009). There was a general decrease in IRI when either oil palm empty fruit bunch, *C. pentandra* sawdust and a combination of the two residues was added to pure sample of sugarcane peels (Fig. 4a, Fig. 4b). Sugarcane peels briquettes recorded the highest IRI at both pressures (ie. 230.53% and 394.32% at 20 MPa and 50 MPa, respectively), whereas that of *Ceiba pentandra* sawdust was the least (ie. 138.68% and 293.32% at 20 MPa and 50 MPa, respectively) (Fig. 4a, Fig. 4b). The comparatively high IRI of briquettes of sugarcane peels may be due to its long fiber length. Several researchers have reported improved mechanical interlocking or folding with long fibers or particles that leads to the formation of strong bonds (Tabil *et al.* 2011, Mitchual *et al.* 2014). Quality briquettes have been described as those having impact resistance index of 100 or more (Wilaipon 2009). Other researchers have classified IRI greater than 80% as high, 70 to 80% as medium and less than 70% as low (Adapa *et al.* 2003). Fig. 4a and Fig. 4b indicate that IRI for pure *Ceiba pentandra* sawdust briquette was medium at 20 MPa whereas the rest were high irrespective of material composition and compacting pressure (Fig. 4a, Fig. 4b). Therefore, briquettes produced in this study would have adequate resistance against shock load.



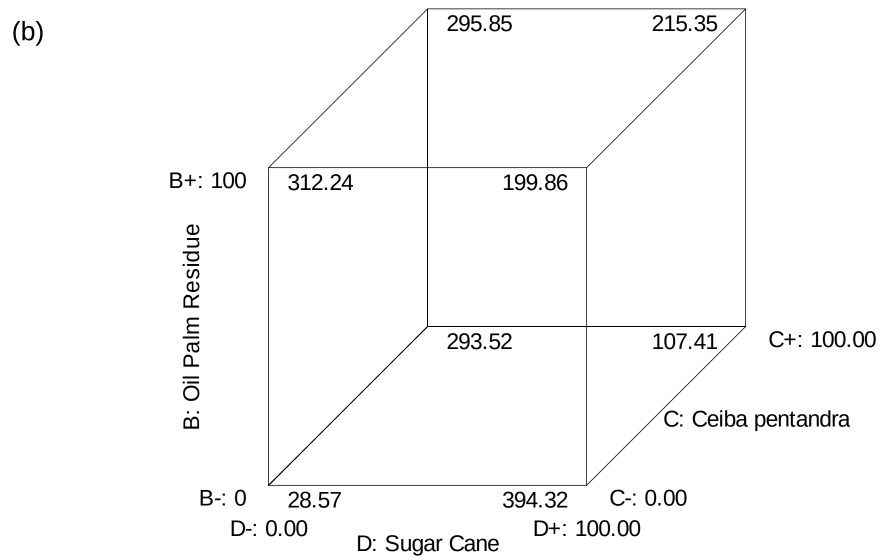


Fig. 4.
Cube graphs of the relationships between impact resistance index and oil palm empty fruit bunch (factor B), Ceiba pentandra sawdust (factor C) and sugarcane peels (factor D) contents at compacting pressures of (a) 20 MPa and (b) 50 MPa.

Shatter index

Regression analysis on shatter index obtained best-fit linear model equation for the experimental data with “Prob>F” values of less than 0.05, high R^2, and desirable adequate precision values (Table 2). The model with significant terms describing the shatter index is as follows:

$$\text{Shatter index} = +86.76 + 0.38A + 12.13B + 12.39C + 12.61D - 12.44BC - 12.27BD - 12.58CD + 12.34BCD \quad (11)$$

All the main factors (A, B, C, and D) positively affected the shatter index due to their positive algebraic signs. Contrastingly, with the exception of interaction factor BCD, all the significant interaction factors in the model negatively affected the shatter index as shown by their negative algebraic signs (Equation 11). The effect of pressure (factor A) on the shatter index was marginal as depicted by its low coefficient (0.38)

(Equation 11). Approximately, coefficients for the other significant factors were similar (between 12.13 and 12.61) implying equivalent influence on the shatter index (Equation 11).

Cube plots illustrating the variation of the shatter index of the briquettes with respect to the interaction between oil palm empty fruit bunch content, *Ceiba pentandra* sawdust content, and sugarcane peels content (interactions BC, BD, CD, and BCD) are shown in Fig.5a and Fig. 5b. Generally, the shatter index was high for the briquettes irrespective of compacting pressure and material composition (Fig.5a, Fig.5b). The high shatter index or the low ratio of material loss from the samples after testing implies good quality for transportability, handling and stoarage of the briquettes (Tembe *et al.* 2014). Fig.5a and Fig. 5b indicates a slight decrease in the loss of material when pressure is increased from 20 MPa to 50 MPa. According to the Pellet Fuel Institute's (PFI) fuel grade requirement, briquettes with durability or shatter index range of 95.0 - 97.59% are of acceptable quality (Wilson 2010). Shatter index of all the briquettes in this study were within the range of the PFI fuel grade requirement, hence, of high durability. This high shatter index for the briquettes may be attributed to strong interlocking bonds between the biomass materials or fibres (Demirbas and Sahin-Demirbas 2004).

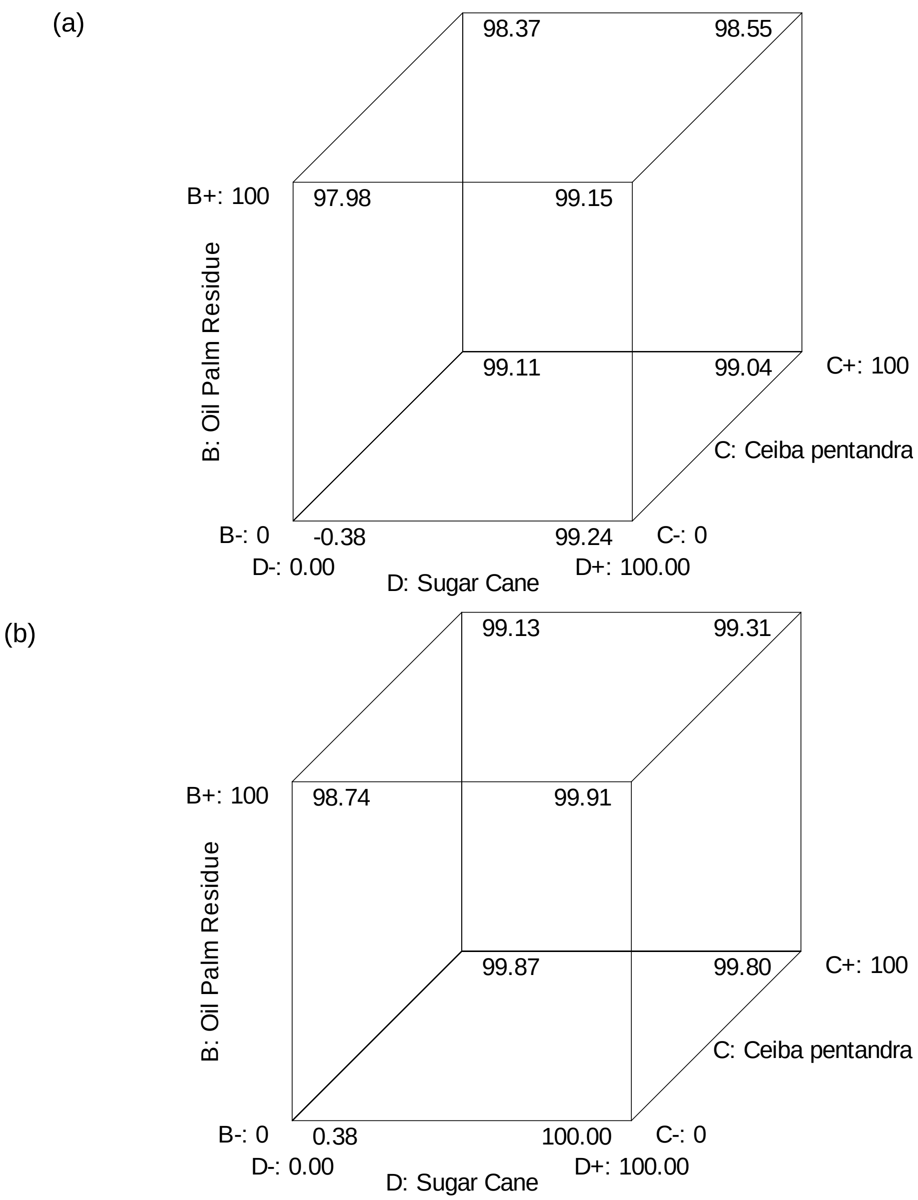


Fig. 5.
Cube graphs of the relationships between shatter index and oil palm empty fruit bunch (factor B), Ceiba pentandra sawdust (factor C) and sugarcane peels (factor D) contents at compacting pressures of (a) 20 MPa and (b) 50 MPa.

Numerical optimization of the physical and mechanical properties of briquettes of oil palm empty fruit bunch, *Ceiba pentandra* sawdust and sugarcane peels

Design Expert software function for numerical optimization was used to determine the combinations of oil palm empty fruit bunch, *Ceiba pentandra* sawdust, and sugarcane peels contents and compacting pressure levels that would result in targeted and favorable relaxed density, compressive strength in cleft, shatter index and impact resistance index. This numerical optimization function is based on a desirability function, which transforms each response value to a desirability index (d_i). Each desirability index is defined by three parameters (good, lower, and upper). The program presents five desirability index options (minimum, maximum, target, in range, and equal to). After defining these settings, the desirability index varies between zero (worst case) and one (ideal case). Optimization results presented by Design Expert are based on the criteria settings and are a series of solutions that best maximize the desirability index (Afrifah and Matuana 2012).

The optimization criteria values used were based on reported data by other researchers and institutions. The goals of the relaxed density and impact resistance index were set "in range" as the results of these properties for the briquettes produced fell within the accepted standard reported by other researchers (Saedy 2004, Wilaipon 2009, Tumuluru *et al.* 2010). Targeted values were set for shatter index (98%) and compressive strength in cleft (20 N/mm) to ensure that the optimization solutions attained are at least the minimum qualities required for handling and utilization of the briquettes (Rahman *et al.* 1989, Wilson, 2010). Goals for the material compositions of the briquettes were also set in range.

Table 3

Numerical optimization settings

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Compacting Pressure	is in range	20	50	1	1	3
Oil Palm Empty Fruit Bunch	is in range	0	100	1	1	3
Ceiba pentandra Sawdust	is in range	0	100	1	1	3
Sugarcane Peels	is in range	0	100	1	1	3
Shatter Index	is target = 98	0	99.9	1	1	3
Impact Resistance Index	is in range	0	380	1	1	3
Compressive Strength in Cleft	is target = 20	0	46.98	1	1	3
Relaxed Density	is in range	0	642.528	1	1	3

Table 3 summarizes the optimization criteria settings used to optimize the physical and mechanical properties of the briquettes. The desirability functions of the relaxed density (RD), compressive strength in cleft (CSC), shatter index (SI) and impact resistance index (IRI) were set as follows:

(i) if SI < 0 or SI > 99.9, IRI < 0 or IRI > 380, CSC < 0 or CSC > 46.98, and RD < 0 or RD > 642.53 then $d_i = 0$ (worst case)

(ii) if 0 ≤ SI ≤ 99.9, 0 ≤ IRI ≤ 380, 0 ≤ CSC ≤ 46.98, and 0 ≤ RD ≤ 642.53 then $d_i = 1$ (ideal case).

The other optimization parameters were set to the default settings of one for the weights of upper and lower limits for the input factors, and three for the importance which is a relative scale that weights each of the resulting d_is in the overall desirability product. Ten cycles were run per optimization. The epsilon value for the minimum difference in eliminating duplicate results was set at its default value (Afrifah and Matuana 2012).

Ten optimum solutions were produced by numerical optimization with a desirability of 1.00 for all results. The solutions as shown in Table 4 indicates a range of combinations of compacting pressure (29.07 – 43.26 MPa), oil palm empty fruit bunch content (5.70 – 97.42%), *Ceiba pentandra* sawdust content (13.32 – 98.25%), and sugarcane peels content (0.40 – 93.69%) that would result in briquettes with standard physical and mechanical properties for handling and utilization. In addition, the solutions present opportunity for producing briquettes with required properties while minimizing certain parameters such as compacting pressure to reduce manufacturing cost.

Table 4
Numerical optimization solutions for relaxed density, compressive strength in cleft, shatter index and impact resistance index of the briquettes

Solutions	Compacting Pressure	Oil Palm Empty Fruit Bunch	*Ceiba pentandra* Sawdust	Sugarcane Peels	Shatter Index	Impact Resistance Index	Compressive Strength	Relaxed Density	Desirability
1	41.76	97.42	39.91	36.08	98.0001	239.247	20	456.712	1.000
2	34.94	95.73	63.95	43.24	97.9998	211.785	20	414.914	1.000
3	29.53	43.10	89.87	80.98	97.9998	129.399	20	428.804	1.000
4	33.95	31.71	68.94	93.69	98	154.228	20	477.454	1.000
5	29.07	87.09	65.39	78.91	98.0002	155.1	20	363.233	1.000
6	30.70	5.70	91.29	83.99	97.9998	117.087	20	499.35	1.000
7	30.43	92.44	30.15	79.38	98.0001	174.813	20	376.89	1.000
8	30.81	87.03	86.03	53.47	98	182.945	20.0001	391.171	1.000
9	35.56	23.39	98.25	0.40	98.0001	227.563	20.0001	504.749	1.000
10	43.26	97.15	13.32	52.04	98	230.416	20	460.083	1.000

CONCLUSIONS

This study investigated the effects of compacting pressure and material composition (oil palm empty fruit bunch content, *Ceiba pentandra* sawdust content, and sugarcane peels content) on the shatter index, impact resistance index, compressive strength in cleft and relaxed density of briquettes. Using two level factorial design analyses, statistical models describing the relationships between material compositions of the briquettes and their physical and mechanical properties were derived. Best combinations of compacting pressure and material composition for manufacturing briquettes with standard physical and mechanical properties for handling and utilization were also determined using numerical optimization.

Generally, increasing the compacting pressure and proportions of materials enhanced all the physical and mechanical properties studied irrespective of the material composition for the briquettes. Material composition and content was also observed to significantly influence the properties of the briquettes. Mostly, increasing oil palm residue content impacted negatively on the physical and mechanical properties. Alternatively, Sugarcane peels had a strong positive effect on relaxed density, whiles *Ceiba pentandra* sawdust had a strong positive effect on compressive strength in cleft. All the briquettes were durable recording an average of 98% shatter resistivity. The optimization results generated briquettes with standard properties suitable for transportation, packaging, storage, and domestic utilization.

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