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Optimization of Calorific Value of Densified Bush Mango Shell and Palm Pressed Fibre Briquettes

Edeh John Chijioke[1, *], Eze Nixson Nwakonam[2], Ibeh Matthew Imagwuike[1], Eboh Francis Chinweuba[1]

[1]Department of Mechanical Engineering, Michael Okpara University of Agriculture, Umudike, Nigeria

[2]Engineering Research and Development Program, Projects Development Institute, Enugu, Nigeria

Email address:

edeh.john@mouau.edu.ng (Edeh John Chijioke)

[*]Corresponding author

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Abstract: Energy value of biomass materials can be enhanced through composition, densification and process parameter manipulation. In this study, biomass briquettes of bush mango shell (BMS) and palm pressed fibre (PPF) compositions were evaluated and its calorific values optimized. The effects of biomass concentration, dwelling/compaction time and compression pressure on calorific value were investigated for briquette samples in the compositions of BMS: PPF ratios of 100:0, 75:25, 50:50, 25:75, and 0:100) as sample A, B, C, D and E respectively. An empirical prediction model of the combustion property of the briquettes was developed and optimized using response surface methodology. It was observed across the samples that as bush mango shell composition increased, the calorific value improved significantly from 12.4kJ/kg to 18.65kJ/kg. Increase in dwelling time and pressure also showed slight increase in calorific value of the briquette samples. An optimum calorific value of 19.03 kJ/kg for briquette sample B (75:25 biomass ratio) was realized at dwelling time of 40 minutes and pressure of 25MPa as adequately predicted by a reduced second order model. The model prediction accuracy was over 98% (Pred. R^2 of 0.9858) with Coefficient of Variance of 0.64% and Adeq. Precision value of 63.936. Thus, Sample B briquettes possess improved combustion properties with burning rate of 0.472g/min at optimum conditions hence suitable for adoption by investors in renewable energy sector.

Keywords: BMS and PPF Briquettes, Biomass Concentration, Dwelling Time, Compression Pressure, Calorific Value, Optimization

1. Introduction

The important role of energy in human wellness and country's economic development has continued to spark interest in the unrelenting quest for clean and renewable energy sources. Nigeria is endowed with energy potential of over 47.97MTOE from an annual generation of 168.49 million tonnes of agricultural residues and wastes [1]. Under utilization of such enormous energy potentials of biomass wastes (which are basically of plant origin and product of processing such as rice husks, cassava peels, groundnut shells, sugar cane bagasse, corn cobs, coconut shells and husks sawdust, bush mango shell, kernel shells, palm fibres) in their crude state has resulted in huge energy and economic waste. Even disposal management system of these wastes has been inefficient constituting daunting environmental challenges with devastating manifestation in land, air, water pollutions and degradations [2].

Energy from biomass constituting over 84% of Nigerian Energy potentials [3] can prospectively be an alternative approach to solving the country's electricity problems of incessant shortfalls and low availability especially in rural areas; frequent power outages and unreliability even in the urban centers. Sawadogo and Tankoano opined that generation of energy from biomass materials can guarantee energy security, tackle environmental problems; Duca *et al* observed that it contributes to efficient management and economic development of rural areas while Trubetskaya *et al* argued that it offers the potential to reduce the greenhouse gas emissions from fossil fuels [4-6]. Traditionally, their remote exploitation, especially in rural communities, is basically as direct fuel. Nevertheless, the prospects of biomass wastes application in production of pressurized solid fuel briquettes with high energy value have been under investigations by researchers [7-9].

Usually, the biomass exhibits poor energy characteristics when explored in their crude state [10]. They also display low bulk densities owing to their porous structure thus, making processing, storage, shipping and combustion hard [11]. Mendoza-Martinez *et al* opined that biomass conversion to a more usable, condensed energy state is a panacea for its consideration as viable fuel [12]. Consequently, densification and briquetting of several combinations of different biomasses had shown evidence of high heating values. The calorific or heating value (which is the thermal energy released per unit quantity of fuel when the fuel is burnt completely) is an important indicator of the quality of the pressed fuel briquettes. Thus; biomass densification offers a unique opportunity of converting crude biomass wastes of low calorific value into densified solid fuel of ready-to-use, high-energy content and eco-friendly state (briquettes). It also ensures necessary homogeneity and improves their bulk densities for haulage and transport optimization. This briquetting technology remains the most viable option for producing renewable energy as solid fuel usually for rural household cooking where energy shortfalls thrive [13, 14].

Mendoza-Martinez *et al* produced and characterized banana leaves waste and coffee-pine wood residue briquettes as an alternative fuel [12]. It was further observed that calorific values of briquettes can be improved when more than one biomass composite is tried. To this end, Padilla *et al* investigated properties and characterized briquettes of coconut fiber and sugarcane straw [15]. De Oliveira *et al* studied characterization and production of banana crop and rice processing waste briquettes [16]. Also, Chungcharoen and Srisang worked on the preparation and characterization of fuel briquettes made from dual agricultural waste of cashew nut shells and areca nuts [17]. Kumar and Chandrashekar investigated briquettes from invasive forest weeds: *lantana camara* and *prosopisjuliflora* [18] while Kpalo *et al* worked on hybrid briquettes from corncobs and oil palm trunk bark under a low pressure densification technique [19]. They all conclude that briquettes of combined biomasses exhibit higher calorific values than when produced from the individual constituents.

However, in spite these great works, little or no attention was paid on optimization of the calorific values of the briquettes composites with respect to their process parameters. Bush mango shell and palm pressed fibre are among the biomasses whose utilization of the energy potentials in their crude state has resulted in colossal energy and economic losses. Thus, there is need to harness the energy potentials of these biomass wastes combination through a technologically articulated process of conversion to briquettes of high energy values. This briquette combustion characteristic is largely dependent on the types of biomass, mix ratio, additives (binders) and processing methods and conditions. Optimization of these controlling factors and process parameters will guarantee the best briquette products of high calorific values.

2. Materials and Method

2.1. Materials

The materials used in the biomass briquettes production includes bush mango shells and palm pressed fibre (accessed from refuse sites in Nsude, Udi local government area of Enugu, Nigeria), cassava starch (binding agent accessed from a local cassava processing plant at Emene, Enugu, Nigeria). Laboratory and other equipment used include: a set of sieve (0.5mm – 1.5mm mesh size), steel spatula, stirrer, bowls, hand gloves, metal files, mobile hardness tester, furnace, milling machine, Bunsen burner, bomb calorimeter (PARR 6200), tripod stand, water, stop watch, die, heater, Scanning Electron Microscope (SEM) and Digital Weighing Machine (DWM of 0.1g accuracy). A hydraulic press briquetting machine (KENNEDY Model HBP020, UK) for briquette sample productions. Minitab and Design Expert software (version 21.1) were employed in the analysis.

2.2. Method

The briquettes were produced at TOAN Engineering and services limited workshop, Emene and analyzed at Project Development Institute (PRODA), all in Enugu State, Nigeria according to the standard methods. The combustion properties of the biomasses were improved upon by densification of the biomasses through briquettes formation. Briquettes production was done using various proportions of the two biomasses. Optimization of the process parameters that affects the production of the best performing briquettes were conducted using RSM.

The biomass samples of bush mango shells and palm pressed fibers were sun dried for one week to a moisture content of about 12%, then milled separately using an electric milling machine and then sieved with a sieve shaker of 0.5mm mesh size to obtain the required particle size.

The biomass powder samples were mixed in the ratio of bush mango shell to palm pressed fibre as 100:0, 75:25, 50:50, 25:75, 0:100 and labeled Sample A, B, C, D and E respectively. 10% by weight of starch was added to each composition as a binder. Thereafter, the mixtures were introduced to the briquetting machine for briquette samples production.

The briquettes were produced in a cylindrical mould of 56.6 mm inner diameter and height of 74 mm. The mould was filled with the mixtures and densification done under constant operating conditions (temperature and pressure) with manually operated air hydraulic piston press briquetting machine of 20-tonne capacity.

Ten briquettes of each sample were produced while their initial densities were noted at the point of ejection from the mold. The resultant briquettes (Figure 1) were exposed on a flat surface for air drying at room temperature (28°C) and condition for a period of seven days prior to testing. The dried briquettes (Figure 2) were taken to the laboratory for further analysis.

Figure 1. *Briquettes (wet) immediately after extrusion from machine.*

Figure 2. *Briquettes (dried at temperature 28°C) after ten days.*

Briquette density was determined. Also, the relaxed density and maximum density were noted and density ratio determined using Equation 1. The relaxed density, (ρ_R) of the briquettes was determined in dry conditions after nineteen days [20] when the briquette has remained stable. It is also known as spring back density and calculated as the ratio of the new weight to the new volume. The maximum density, (ρ_M) is the compressed density of a briquette immediately after ejection from the briquetting machines.

Density ratio (D.R) is calculated as thus

$$\text{D.R} = \frac{\rho_R}{\rho_M} \quad (1)$$

2.3. Briquettes Performance Evaluation and Optimization Procedure

2.3.1. Determination of Calorific Value

To determine the calorific value, a bomb calorimeter was employed using ASTM standard procedure [21]. The weight of the biomass sample was measured in grams. The sample was put into a crucible. Two ends of the ignition thread (nichrome wire) of noted length were fixed on two electrode poles and they were made to keep a good touch on the sample to be evaluated. 10ml of distilled water was poured into the oxygen bomb and the cover was screwed down. Oxygen at a pressure of 2.8-3.0MPa was made to flow into, and fill the bomb. The oxygen bomb was put onto the clamp in the inner canister. The temperature sensor was put into the canister. The power was turned on and the stir button was pressed. The water was allowed to stir until the temperature reading stabilized and the initial temperature was noted T_0. The fire button was pressed and the instrument automatic lly measured and saved the data. When testing counts got to about 31 counts, the experiment was finished. The final temperature was noted as T_f. The stirring was stopped and the temperature sensor was pulled out. The length of the unburnt firing wire was measured. The inner lining of the oxygen bomb and crucible were washed with distilled water. 2 drops of methyl red indicator were added into a burette and titrated with 0.0709N sodium carbonate. The titre volume V was recorded. Then the calorific value was calculated using the Equation (2).

Burning rate was also determined as the ratio of total weight of burnt briquette to the total time taken, measured in g/mins.

$$\text{Calorific value} = \frac{\text{E}\Delta\text{T} - \emptyset - \text{V}}{\text{w}} \quad (2)$$

Where,

$\text{w} = \text{Weight of sample}$

$\text{E} = \text{Energy equivalent of the calorimeter per degree Celsius}$

$\Delta\text{T} = \text{Change in temperature}$

$\emptyset = \text{Correction for heat of combustion of firing wire, 2.3l}$

$\text{V} = \text{Volume of titre used during titration}$

2.3.2. Experimental Design and Optimization

The central composite design (CCD) of response surface methodology (RSM) of Design Expert software (version 21.1) was used in this study to design the experiment and to optimize the briquette production process parameters for the biomasses. The experimental design is a two-level three factor full factorial design, including 20 experiments. Biomass concentration, Time, and compaction pressure were selected as independent factors for the optimization study. The response chosen was the calorific values obtained from briquettes produced. Six replications of centre points were used in order to predict a good estimation of errors and experiments were performed in a randomized order. The actual and coded levels of each factor are shown in Table 1 while the design matrix is shown in Table 2. The coded values were designated by −1 (minimum), 0 (centre), +1 (maximum), −α and +α (axial points: the distance from the centre point, either inside or outside the range).

The empirical equation is represented as shown in Equation (3):

$$Y = \beta_0 + \sum_{i=1}^{3} \beta_i X_i + \sum_{i=1}^{3} \beta_{ii} X^2{}_i + \sum_{i=1}^{3} \sum_{j=i+1}^{3} \beta_{ij} X_i X_j \quad (3)$$

Selection of levels for each factor was based on the experiments performed to study the effects of process variables on the briquettes production from bush mango shell and palm pressed fibre.

Table 1. *Range of each factor in actual and coded form for biomass briquettes.*

Factor	Units	Low level	High level	-α	+α	0 level
+Biomass concentration (C_B)	(%)	25 (-1)	75 (+1)	0 (-2)	100 (+2)	50
Compaction Time (T_C)	Minutes	20 (-1)	40 (+1)	10 (-2)	50 (+2)	30
Compaction Pressure (P_C)	KPa	15 (-1)	25 (+1)	5 (-2)	30 (+2)	20

Table 2. *Experimental design Matrix for Briquettes Production.*

Run order	Biomass concentration (%) C_B		Compaction Time (Minutes) T_C		Compaction Pressure (KPa) P_C		Response Briquettes Calorific Value (kJ/kg)
	Coded	Real	Coded	Real	Coded	Real	
1	-1	25	-1	20	-1	15	
2	+1	75	-1	20	-1	15	
3	-1	25	+1	40	-1	15	
4	+1	75	+1	40	-1	15	
5	-1	25	-1	20	+1	25	
6	+1	75	-1	20	+1	25	
7	-1	25	+1	40	+1	25	
8	+1	75	+1	40	+1	25	
9	-2	0	0	30	0	20	
10	+2	100	0	30	0	20	
11	0	50	-2	10	0	20	
12	0	50	+2	50	0	20	
13	0	50	0	30	-2	5	
14	0	50	0	30	+2	30	
15	0	50	0	30	0	20	
16	0	50	0	30	0	20	
17	0	50	0	30	0	20	
18	0	50	0	30	0	20	
19	0	50	0	30	0	20	
20	0	50	0	30	0	20	

3. Results and Discussion

3.1. Effect of Process Parameters on Calorific Value of Briquettes

The effects of bush mango shell and palm pressed fibre proportions on calorific value of composite briquettes produced from them are shown in Figure 3. The calorific value of the composite briquettes ranges from 16.81 kJ/kgto 18.65kJ/kg for briquettes produced from sample (A) and (B), 14.85kJ/kg for sample (C) and 12.9 to 12.31kJ/kg for samples (D) & (E). It was observed that the calorific value decreases as the concentration of PPF increases for all the biomass ratios considered. The composition with 75:25 BMS and PPF mixing ratio has the highest calorific value while 25:75 BMS and PPF biomass mixing ratio, has the least calorific value of 12.4kJ/kg.

The energy value obtained for the briquettes compositions of bush mango shell (BMS) and palm pressed fibre (PPF) at the mixing ratio of (75:25) was found to meet the minimum requirement of calorific value (>17,500 J/kg) for producing commercial briquettes [22]. They can therefore produce enough heat required for household cooking and small-scale industrial cottage applications. The results of the calorific value of the briquettes produced in sample (C-D) compare well with the results of the heating value of cowpea 14,372.93 J/kg; and soya-beans-12,953 J/kg [23] while sample (E) compares with rice husk briquette of 12,600 J/kg [24].

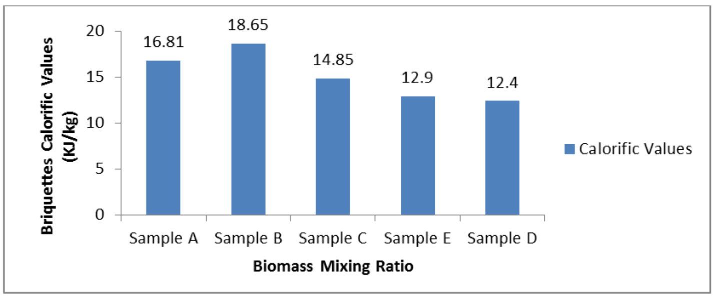

Figure 3. *The effect of BMS and PPF proportions on calorific value briquettes.*

Figure 4 shows the effect of compression time on calorific value of briquettes produced with various biomass concentrations. It can be observed that the calorific value of the briquettes slightly increased with increase in dwelling time.

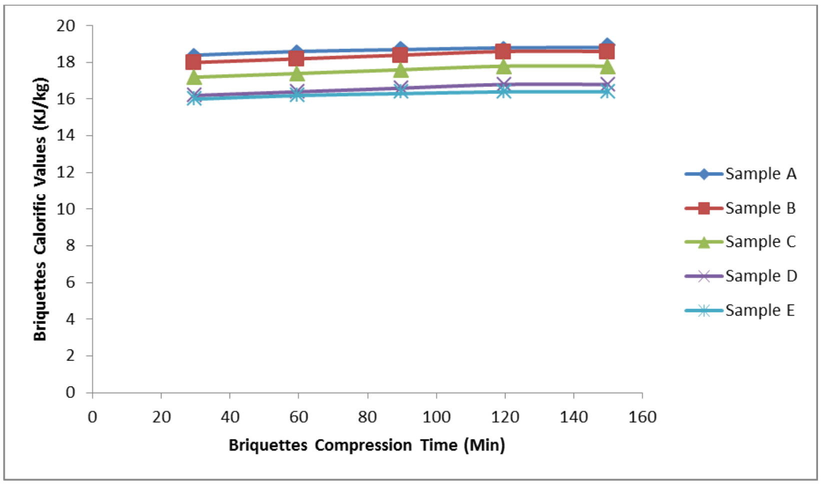

Figure 4. *Shows the effect of compression time on calorific value of briquettes.*

The effect of pressure on calorific value of briquettes produced from various biomass concentrations is seen in Figure 5. From the Figure 5, it could be inferred that increase in pressure slightly increased the calorific value due to uniform dispersion of the starch binder.

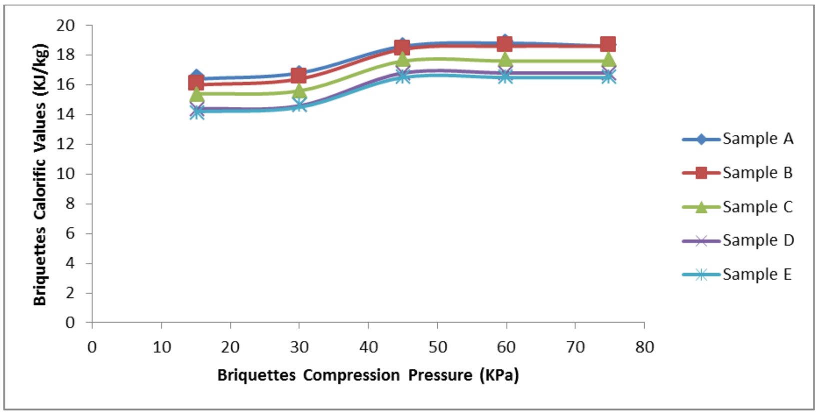

Figure 5. *Effect of pressure on calorific value of briquettes.*

3.2. Statistical and Optimization of Calorific Value of Biomass Briquettes

The empirical relationship between calorific value (Y_{CV}) and the three variables in coded values was obtained by using the statistical package Design-Expert 13 version for determining the levels of factors which gives optimum calorific value. A quadratic regression equation that fitted the data was gotten as

$$Ycv = 17.079 + 0.009256C_B + 0.017642T_C + 0.01811P_C - 0.0001583C_BT_C + 0.000183C_BP_C + 0.0000833T_CP_C - 0.000105{C_B}^2 + 0.00047{T_C}^2 - 0.000403{P_C}^2 \quad (4)$$

The above equation represents the quantitative effect of the factors; biomass concentration, dwelling/compaction time and pressure which were coded as factors; (C_B, T_C, and P_C) upon the response (calorific value, Y_{CV}). Coefficients with one factor represent the effect of that particular factor while the coefficients with more than one factor represent the interaction between those factors. Positive sign in front of the terms indicates synergistic effect while negative sign indicates antagonistic effect of the factor. The adequacy of the above proposed model was tested using the Design Expert sequential model sum of squares and the model test statistics. From the sequential test, it was seen that the model F-value (422.38) of the quadratic model is large compared to the values for the other models for the equation. And from the statistics test, the regression coefficient (R^2 = 0.9942) is high, and the adjusted R^2 (0.9918) is in close agreement with the predicted R^2 (0.9858) value. The coefficient of variance (CV) which is the ratio of the standard error of the estimate to the mean value of the observed response, and considered reproducible once not greater than 10% was gotten as 0.64%.

An "Adeq Precision value"that measures the signal-to-noise ratio (with desirable ratio greater than 4) was observed from this experiment as 63.936, which indicates an adequate signal. This model can therefore be used to navigate the design space. This test is shown in Table 3.

Analysis of variance (ANOVA) was applied for estimating the significance of the model at 5% significance level since a model is considered significant if the p-value (significance probability value) is less than 0.05. From the p-values presented in Table 3, it could be stated that the linear terms C_B, T_C andP_C with the quadratic term ${T_C}^2$ were significant model terms. Based on this, the insignificant terms of the model excluding the term that support hierarchy were removed and the model reduced to Equations (5):

Table 3. *Regression coefficients of calorific value for BMS and PPF briquettes.*

Source	Degree of freedom	Sum of square	Mean Square	F-value	P-value (Prob >F)
Model	17	70	4.12	422.38	< 0.0001
C_B	1	3.33	3.33	341.42	< 0.0001
T_C	1	0.26	0.26	27.08	< 0.0001
P_C	1	0.18	0.18	18.47	0.0001
C_BT_C	1	0.006017	0.006017	0.62	0.4365
C_BP_C	1	0.02017	0.002017	0.21	0.6516
T_CP_C	1	0.000416	0.0004167	0.043	0.8372
${C_B}^2$	1	0.0083	0.0083	0.85	0.3613
${T_C}^2$	1	0.17	0.17	17.10	0.0002
${P_C}^2$	1	0.00765	0.007658	0.79	0.3805
Residual	42	0.41	0.00975		
Lack of fit	27	0.31	0.012	1.81	0.1142
Cor. Total	59	70.41			

Std. Dev. = 0.099; Mean = 15.52; C.V.% = 0.64; PRESS = 1.00; R^2 = 0.9942; Adj. R^2 = 0.9918; Pred. R^2 = 0.9858; Adeq. Precision = 63.936.

$$Ycv = 17.079 + 0.009256C_B + 0.017642T_C + 0.01811P_C + 0.00047{T_C}^2 \quad (5)$$

In order to validate the model, thecalorific value of was optimized and 19.03kJ/kg obtained at optimum conditions and then compared with the experimental value of 18.65kJ/kg determined from Equation 2; it was observed that the error between the experimental and predicted value was less than 2%, therefore it can be concluded that the generated model has sufficient accurancy to predict the calorific value of densified bush mango shell and palm pressed fibre briquette composite.

3.3. The 3-D Surface and Contour Plot for Calorific Value of the Mixed BMS and PPF Briquettes

The 3D response surface plot and contour plot were generated to estimate the effect of the combinations of the independent variables on the calorific value.

Figures 6 & 7 show the interaction effect of biomass concentration and dwelling time on calorific value of mixed BMS and PPF briquettes. It was observed that the calorific value increased as dwelling time increased and decreased as biomass concentration increased.

Figures 8 & 9 show the interaction effect of biomass concentration and pressure on calorific value ofmixed BMS and PPF briquettes. It was observed that thecalorific value increased as pressure increased and decreased as biomass concentration increased.

Figures 10 & 11 show the interaction effect of pressure and dwelling time on calorific value of mixed BMS and PPF briquettes. It was observed that thecalorific value increased as both the dwelling time and pressure increased.

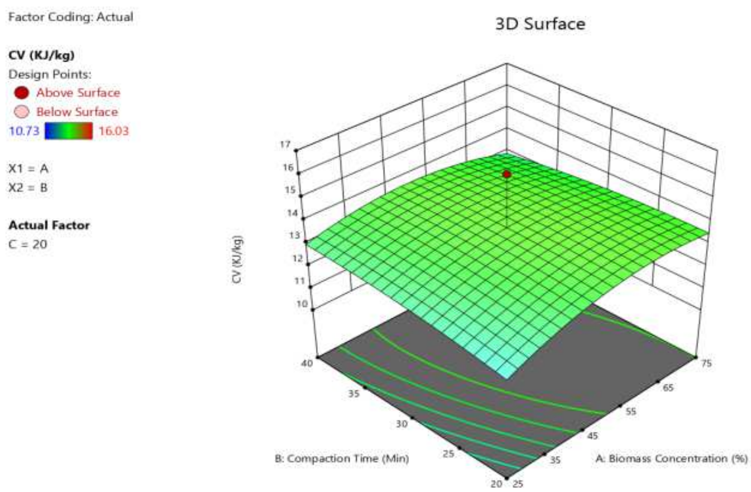

Figure 6. *Response surface 3D plot of effects of CB and TC on YCV.*

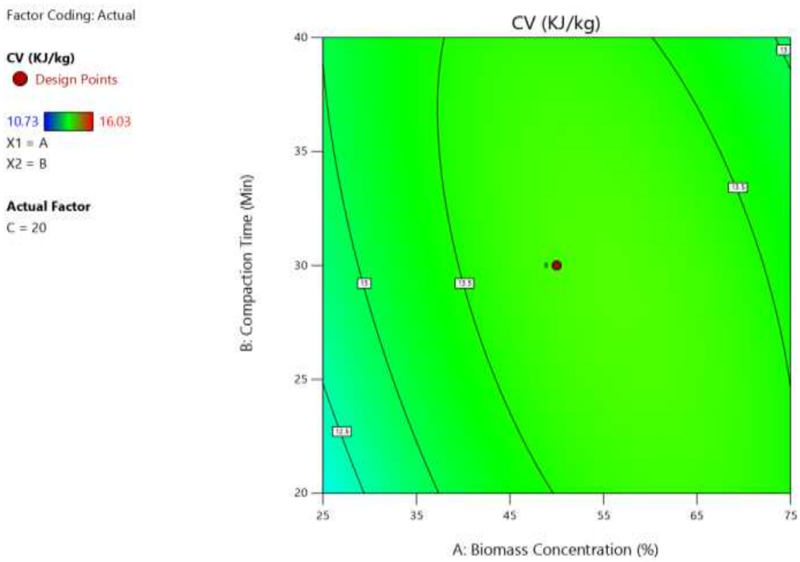

Figure 7. *Contour plot of effects of CB and TC on YCV.*

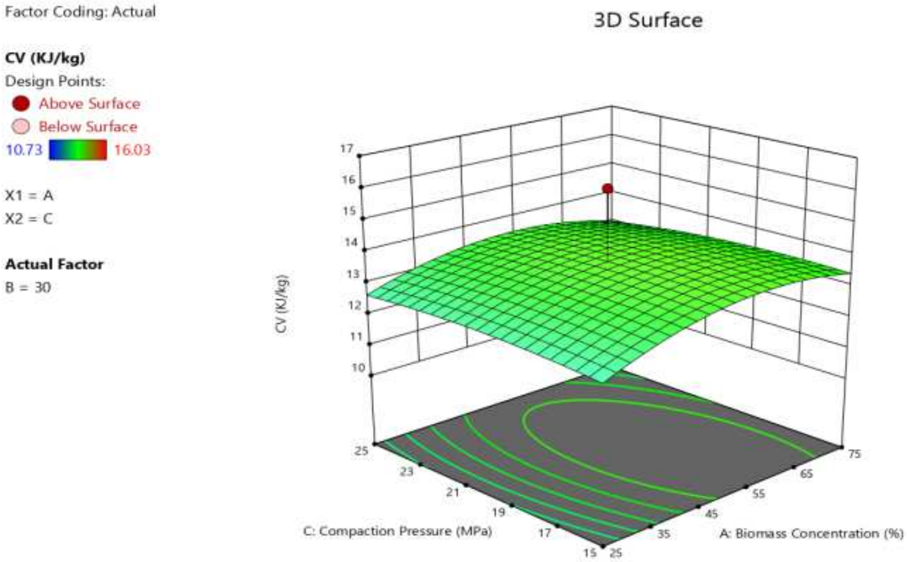

Figure 8. *Response surface 3D plot of the effects of C_B and P_C on Y_{CV}.*

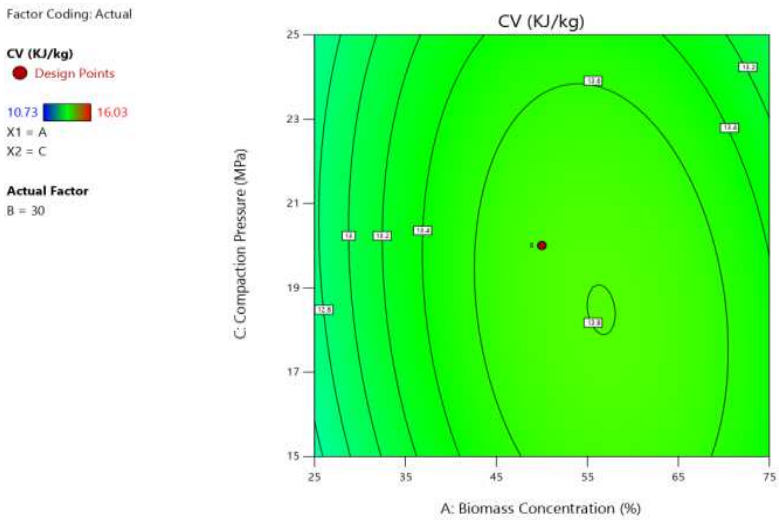

Figure 9. *Contour plot of the effects of C_B and P_C on Y_{CV}.*

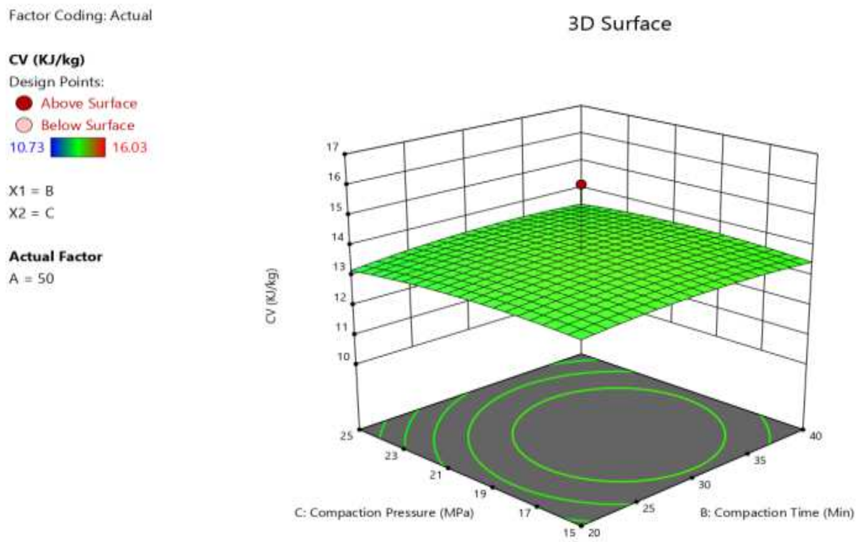

Figure 10. *Response surface 3D plot of the effects of T_B and P_C on Y_{CV}.*

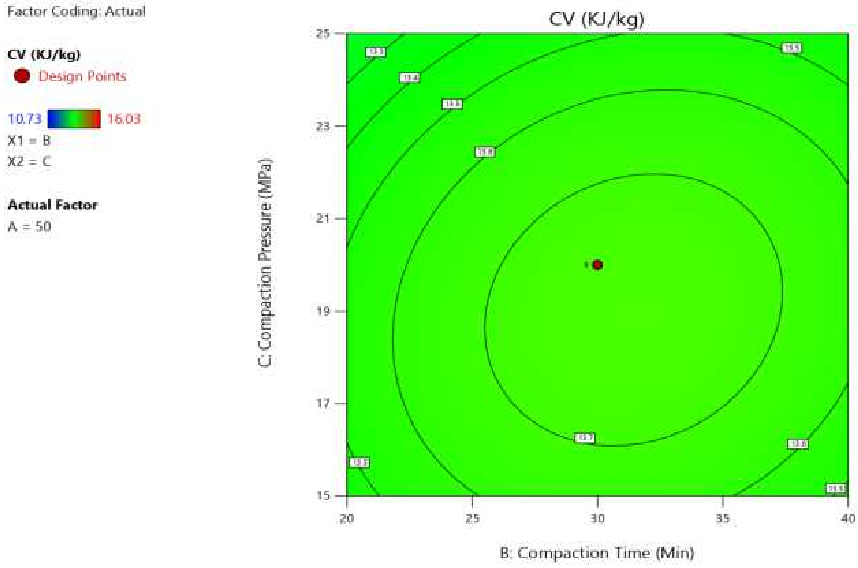

Figure 11. *Contour plot of the effects of T_B and P_C on Y_{CV}.*

4. Conclusion

Briquettes produced from the mixed biomasses of bush mango shell and palm pressed fibre showed good bio-fuel characteristics with higher calorific value than when it was produced from either of the separate biomass. The effects of pressure, biomass concentration and compaction time on the calorific value were very significant. Increase in BMS concentration and compaction pressure caused decrease in the burning rate though elongated the ignition time but increased the calorific value of the briquettes. The implication of this observation is that less fuel might be required for cooking with briquettes produced from high concentration of BMS biomass.

A developed second order empirical model adequately predicted the calorific value of the briquettes with biomass concentration, compaction pressure and dwelling time as controlling variables at an accuracy of 98%. Calorific value of 19.03kJ/kg was optimum at factor settings of BMS:PPF ratio of 75:25, pressure of 25MPa and time of 40 minutes. This compared well with experimental calorific value of 18.65kJ/kg with less than 2% prediction error. Therefore, the production of briquettes from bush mango shells and palm pressed fibre and their utilization is recommended since their usage as solid bio-fuel will promote environmental friendliness, reduce desertification and its environmental implications and consequently, reduce health hazards associated with the use of fuel wood, coal and fossil fuels.

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