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Application of 2^K full factorial on the production of charcoal briquettes made from coconut shell

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Abstract

The production of charcoal briquettes using 2k full factorial Design in Design Expert V12 software was utilized in this research work. The factors considered are: Quantity of $CaCO_3$, Quantity of $NaNO_3$ and Quantity of Starch binder. Analysis of variance (ANOVA) indicates that the linear effect of all the factors: A (Quantity of Catalyst), B (Quantity of $CaCO_3$) and C (Quantity of Starch) are significant with P-values of 0.0050, 0.0062, and 0.0003 respectively. Other significant effects are the interactive effect of BC (Quantity of $NaNO_3$ and Quantity of Starch) and that of the combine effect of all the three (3) factors (ABC) with P-values of 0.0125 and 0.0031 respectively. The Model F-value of 755.59 implies the significant of the model. The coefficient of determinant (R2) for the model of 0.9995 and Adjusted R2 of 0.9981 shows that the model equation has a very good fit to the experimental data. Briquettes produced from Run 7 and 4 have the least volatile matter of 1.54% and 1.67% respectively, the lowest ash content of 2.14% and 2.19 % respectively and the highest percentage fix carbon of 97.67% and 96.56% respectively.

Keywords: ANOVA; Biomass; Briquettes; Heating Value; Solid Fuel

1. Introduction

The world continues to suffer from energy crisis and environmental related challenges, these lead for the exploration of other energy sources [1]. In Nigeria, it's obvious that, fuel wood had since become a major source of fuel for families and small-medium enterprises due to the instability and escalating cost of petroleum products together with irregular electricity supply [2,3]. For the past two decades in Nigeria, over 40 % of the total primary energy consumption is of fuel wood and charcoal which constitutes about 39 million tones [4]. Similarly, [5,3] reported an average daily consumption ranging from 0.5-1.0 kg of dry fuel wood per person is being consumed in the country for cooking and other domestic purposes. Certain disadvantages are attributed to the use of wood as a fuel source: deforestation, climate change, soil erosion, desertification, and health problems, as a result of exposure to carbon emission during indoor domestic cooking. As such, there is the need to put an end to the use of wood as a fuel that is to say if only an alternative source can be provide [6].

Biomass for energy consists of any organic material that can be used as a fuel; including firewood, forest wastes, dung, vegetable matter and agricultural residues. About 15% of global energy consumption is from biomass with larger percent coming from agricultural residues [7]. The use of biomass feedstock(s) for the substitution of fossil fuel(s) has an additional importance from climate change consideration since biomass has the potential to be CO_2 neutral [8]. The disadvantages of using raw agricultural residues have as an energy feedstock. These include: relatively low calorific value, difficulty in controlling the rate of burning, large volume or area required for storage, and problems in its transportation and distribution [9]. Several of these disadvantages may be attributed to the low bulk density of agricultural residues which can be converted into high density fuel briquettes [10]. In this research work, briquettes were produced from carbonized agro-residue coconut shells (CS) through the application of full factorial design (FFD).

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The effect three factors (Quantity of $CaCO_3$, Quantity of $NaNO_3$ and Quantity of Starch) and their interactive effect on the heating value of the briquettes will also be studied.

2. Methodology

2.1. Sample Collection and Preparation

Coconut Shells being mostly considered as a waste were collected from Bakin Dogo Market, Kaduna State.

The collected coconut shells (CS) were air dried to reduce moisture content to between 8-12% which is within the acceptable operating limit for briquetting. The dried (CS) were then crushed to reduce the size. The crushed raw material (CS) was carbonised in a locally fabricated retort kiln. The carbonized CS was manually crushed and passed through a sieve to ascertain for uniform particle size of 5mm.

Cassava starch was used as binder. Two (2) starch ratios notably: 200g and 300g of the weight of sample were used to determine the effect of binder concentration on physical and chemical characteristics of briquettes produced.

2.2. Experimental Procedure

The production process was carried out based on the experimental design table developed using Design Expert V12 software. Three (3) parameters (Quantity of $CaCO_3$, Quantity of $NaNO_3$ and Quantity of Starch) were investigated in this research work and were coded as shown in Table 1. For Run 1, 500 g of the sieved carbonized CS was weighed for the production of each sample. The weighed raw material (CS) were thoroughly mixed with 200g of prepared starch as binder, 50g of $CaCO_3$, and 25g of $NaNO_3$ according to the design of experiment as presented in Table 2. Afterwards, the mixture was fed into a cylindrical mold which was compacted using a hydraulic press. On extruding, the produced briquettes were cut at a length of 5cm with a diameter of 3cm. The compacted briquettes were air dried for two (2) days and further drying was achieved in a tray dryer for 6hrs at 105°C. The remaining seven (7) runs were carried out in a similar procedure.

Table 1 Two Level Regular Factorial Design showing the Coding of Factors

Factor	Name	Units	Type	Low	High
A [Numeric]	Quantity of $CaCO_3$	g	Numeric	50.00	70.00
B[Numeric]	Quantity of $NaNO_3$	g	Numeric	15.00	25.00
C[Numeric]	Quantity of Starch	g	Numeric	200.00	300.00

Table 2 Experimental Design Table showing Factors and Responses

Std	Run	Factor 1 A: Quantity of $CaCO_3$ (g)	Factor 2 B: Quantity of $NaNO_3$ (g)	Factor 3 C: Quantity of Starch (g)	Response Heating Value Kcal/kg
3	1	50	25	200	2784.09
5	2	50	15	300	3693.43
4	3	70	25	200	2533.01
7	4	50	25	300	4149.08
2	5	70	15	200	3174.78
1	6	50	15	200	2132.11
8	7	70	25	300	4476.89
6	8	70	15	300	4012.75

3. Results and discussion

3.1. Effect of Variables and Pareto Chart

Statistical analysis of the model was performed and the effect of investigated variables were evaluated to check the adequacy of the empirical model. The significance of each of the coefficient is checked from P-value (probability of error value). According to Table 3, ANOVA for selected factorial model, P-values less than 0.0500 indicate model terms are significant. In this case, the linear effect of all the factors: A (Quantity of Catalyst), B (Quantity of $CaCO_3$) are significant with P-values of 0.0050, 0.0062, and 0.0003 respectively. In the same vein, the interactive effect of BC (Quantity of $NaNO_3$ and Quantity of Starch) and that of the combine effect of all the three (3) factors (ABC) are also significant with P-values of 0.0125 and 0.0031 respectively. The Model F-value of 755.59 implies the model is significant. There is only a 0.13% chance that an F-value this large could occur due to noise. The effects of the coefficients of the variables are further explained in a Pareto chart as shown in Figure 1.

Table 3 Analysis of Variance (ANOVA)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	4.962E+06	5	9.923E+05	755.59	0.0013	significant
A-Quantity of $CaCO_3$	2.587E+05	1	2.587E+05	197.01	0.0050	
B-Quantity of $NaNO_3$	2.115E+05	1	2.115E+05	161.05	0.0062	
C-Quantity of Starch	4.073E+06	1	4.073E+06	3101.25	0.0003	
BC	1.034E+05	1	1.034E+05	78.75	0.0125	
ABC	4.184E+05	1	4.184E+05	318.62	0.0031	
Residual	2626.61	2	1313.30			
Cor Total	4.964E+06	7				

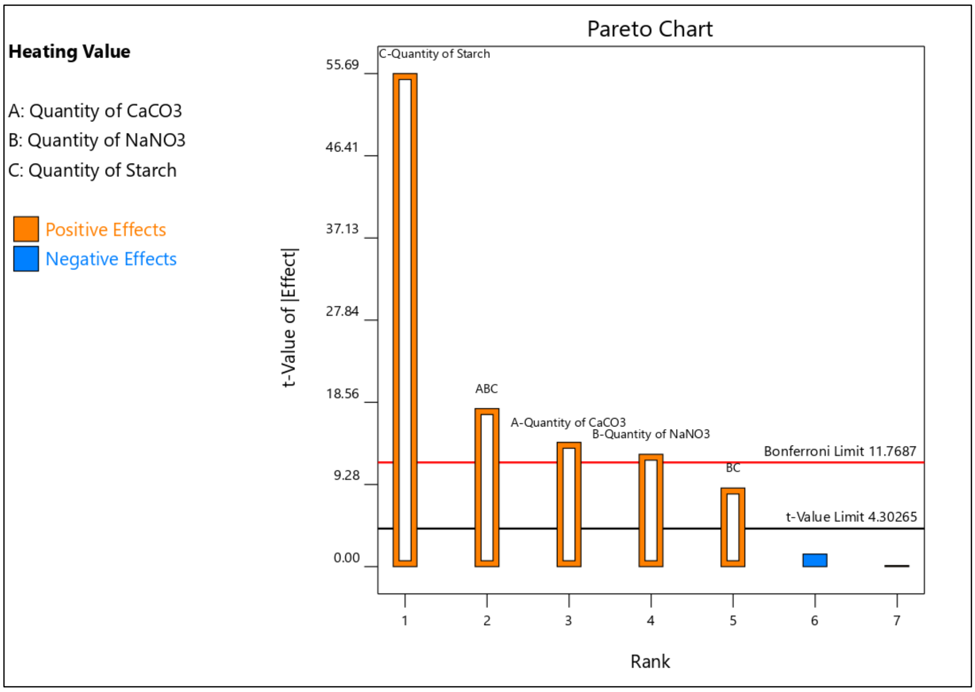

Figure 1 Pareto Chart of the Standardized Effect

From Fig. 1, linear effect of starch is considered the most significant parameter followed by the combine effect of all the three (3) factors. Other factors in hierarchical order of significance are linear effect of $CaCO_3$, the linear effect of Quantity of $NaNO_3$, and the interactive effect of BC (Quantity of $NaNO_3$ and Quantity of Starch). Other factors and their interactions are of less significance on the response.

3.2. Polynomial Model and Model Fitness

Equation (1) in terms of coded factors can be used to make predictions about the response for given levels of each factor. By FFD, the high levels of the factors are coded as +1 and the low levels are coded as -1 as indicated in Table 1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

Heating Value	= +4083.04 + 229.95B + 1427.04 C + 227.40 BC + 323.44 ABC ………… (1)

Equation (2) in terms of actual factors can be used to make predictions about the response for given levels of each factor. Here, the levels should be specified in the original units for each factor. This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the center of the design space.

Heating Value = -1504.56536 +51.92388 Quantity of $CaCO_3$ - 90.44750 Quantity of $NaNO_3$ +5.17460 Quantity of Starch + 0.862069 Quantity of $NaNO_3$ * Quantity of Starch - 0.006788 Quantity of $CaCO_3$ * Quantity of $NaNO_3$ * Quantity of Starch …….. (2)

The accuracy of the predicted model equations can be proved by comparing experimental / actual values and predicted data. The comparison was performed by generating a fitted-line plot for the results obtained, showing how close it was or how far it deviated from the fitted line. As shown in Fig. 2, agreement between predicted values and experimental values proved that the response surface models in this research were adequate for predicting the percentage yield of oil.

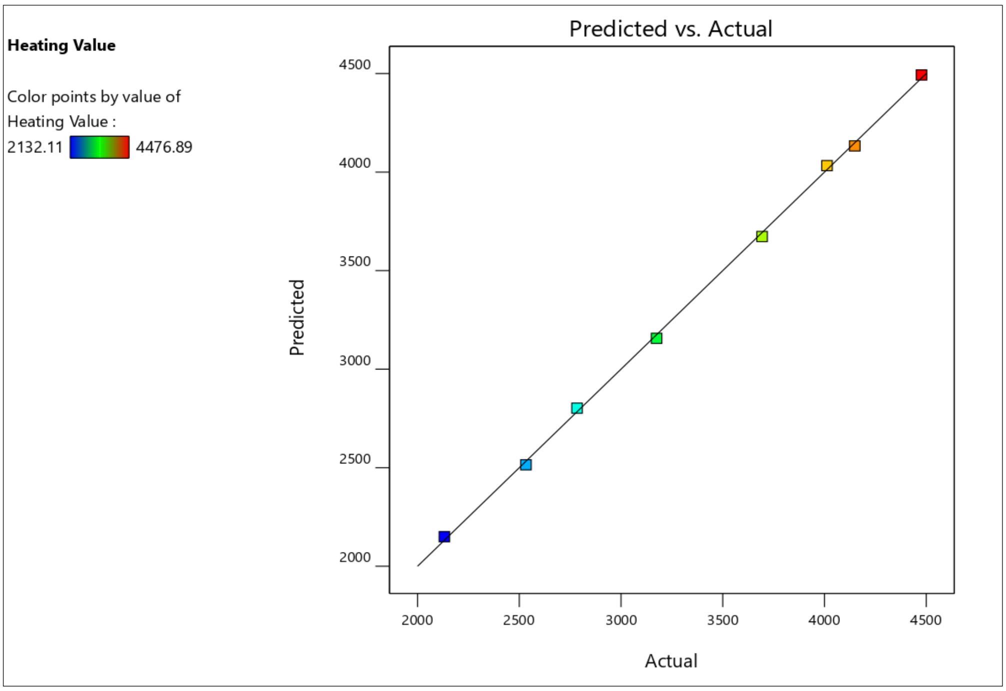

Figure 2 Fitted line plot between predicted values and actual values

The high value of regression coefficient of determination (R^2) for the model of 0.9995 and Adjusted R^2 of 0.9981 are both indications of how good the data fit the proposed model equation. Also, the Predicted R^2 of 0.9813 is in reasonable agreement with the Adjusted R^2 of 0.9981; i.e. the difference is less than 0.2.

3.3. Response Surface Analysis

The effects of process variables on the response can be elaborated by visualization using response surface plots. Figure 3 shows that the heating value keep increasing from 213.11 to 4476.89 kcal/kg with increase in in the quantity of $NaNO_3$

from 15 to 25g. A similar trend is witness with the quantity of starch with an increase from 200 to 300g but with low intensity.

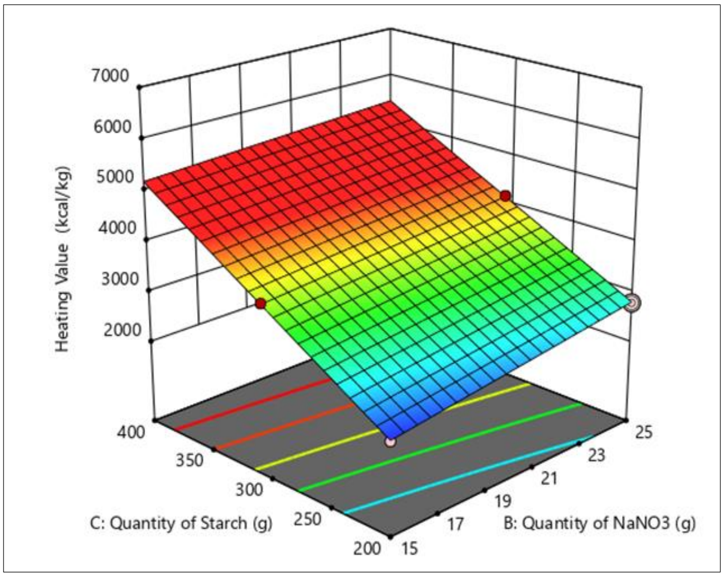

Figure 3 Effect of Quantity of Starch (g) and Quantity of **$NaNO_3$** (g) on Heating Value (kcal/kg)

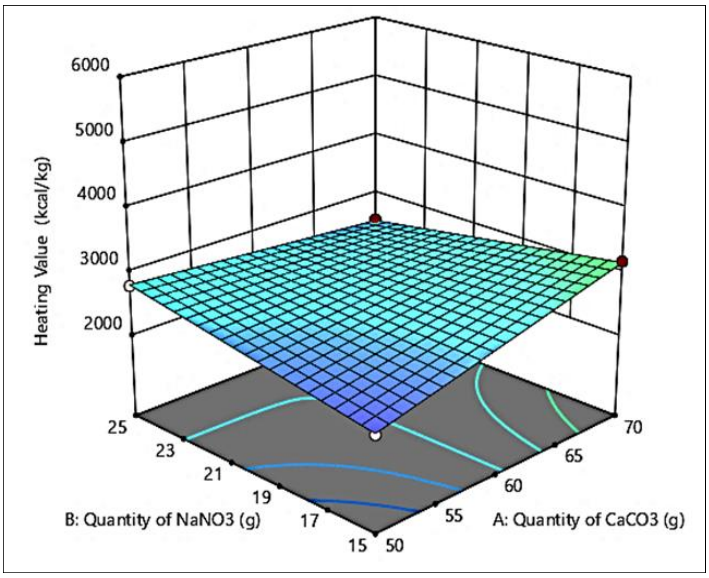

Figure 4 Effect of Quantity of **$CaCO_3$** (g) and Quantity of **$NaNO_3$** (g) on Heating Value (kcal/kg)

The surface plot depicted in Figure 4 is almost a flat plot indicating low intensity of the investigated factors on the response. Thus, there is little difference in the increase in heating value caused by the effects of the quantity of $CaCO_3$ (g) and that of quantity of $NaNO_3$ (g). The plot being a straight line is also an indication of the dominance of the linear terms in the predicted model.

3.4. Physicochemical Properties of Produced Briquettes

The briquettes produced were analysed so as to characterize them. The physicochemical properties of the produced briquettes are given in Table 4. Whereas Fig 5 is an illustration of the charcoal briquettes produced which are cylindrical in shape.

Table 4 Physicochemical Characterization of Produced Briquettes

Runs	VM (wt. %)	AC (wt. %)	FC (wt. %)	HV (kcal/kg)
1	2.11	3.09	92.38	2784.09
2	2.01	2.93	93.43	3693.43
3	2.27	3.11	91.22	2533.01
4	1.67	2.19	96.56	4149.08
5	2.25	2.96	93.24	3174.78
6	2.87	3.25	90.67	2132.11
7	1.54	2.14	97.67	4476.89
8	1.97	2.37	94.09	4012.75

VM = Volatile Matter, AC = Ash Content, FC = Fixed Carbon, HV = Calorific Value.

Figure 5 Produced Briquettes

The briquette with the least volatile matter is expected to have the highest energy value. From Table 4, Run 7 and 4 briquettes were observed to have the least volatile matter of 1.54% and 1.67% respectively. Thus, Run 6 briquette has the highest volatile matter of 2.87% followed by Run 3 briquette with VM of 2.27%. These results in the briquettes having the lowest HV of 2132.11 and 2533.01 kcal/kg respectively. This implies that more energy will be required to burn off the volatile matter before the release of its heat energy.

High ash content decreases the burning rate and reduces the heating value of fuel. As seen from Table 4, briquettes made from Run 7 and Run 4 has the lowest ash content of 2.14% and 2.19 % respectively. The highest ash content was observed in Run 6 (3.25%) and Run 3 (3.11%). This is significant in them having low burning rate.

Run 7 and Run 4 briquettes have the highest percentage fix carbon of 97.67% and 96.56% respectively. The high values can be traced to the carbonisation method employed before the production of the briquettes. High fixed carbon implies high calorific value as indicated in Table 4 for both Run 7 (4476.89 kcal/kg) and Run 4 (4149.08 kcal/kg) . The lowest carbon content was observed in Run 6 (2132.11kcal/kg) and Run 3 (2533.01 kcal/kg). The variation in fixed carbon when compared to the overall constituents is most likely due to the concentration of binder in the briquette preparation.

4. Conclusion

The ANOVA from the 2^K full factorial indicates that the linear effect of starch is considered the most significant parameter followed by the combine effect of all the three (3) factors. Other factors in hierarchical order of significance are linear effect of $CaCO_3$, the linear effect of Quantity of $NaNO_3$, and the interactive effect of BC (Quantity of $NaNO_3$ and Quantity of Starch). Other factors and their interactions are of less significance on the response. The coefficient of determinant (R^2) for the model of 0.9995 and Adjusted R^2 of 0.9981 which shows that the model equation has a very good fit to the experimental data.

Run 7 and 4 briquettes were observed to have the least volatile matter of 1.54% and 1.67% respectively. Thus, Run 6 briquette has the highest volatile matter of 2.87% followed by Run 3 briquette with VM of 2.27%. These results in the briquettes having the lowest HV of 2132.11 and 2533.01 kcal/kg respectively. Briquettes made from Run 7 and Run 4 has the lowest ash content of 2.14% and 2.19 % respectively whereas the highest ash content was observed in Run 6 (3.25%) and Run 3 (3.11%). Run 7 and Run 4 briquettes have the highest percentage fix carbon of 97.67% and 96.56% respectively whereas the lowest carbon content was observed in Run 6 (2132.11kcal/kg) and Run 3 (2533.01 kcal/kg).

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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