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Parametric Improvement of Hammer Mill for Bambara Flour Production Using Desirability Optimization Methodology

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Abstract

Characterization and optimization of hammer mill for bambara flour production which reduces drudgery, time loss and multiple milling associated with existing technologies for bambara nut milling operation was performed. Desirability function analysis and optimization technique was utilized to obtain the optimal result which revealed the process/operational parameters (factors) with significant influence on the machine as the bambara grains' moisture content, number and speed of cross beaters. It also showed throughput and milling efficiency as its functional performance indicators. The number and speed of the cross beater and the bambara nut moisture content affect the particle size of the milled bambara flour directly. The optimal values of the number and speed of cross beaters and bambara nut moisture content were determined as 6, 1610.00rpm and 11.42% respectively which caused increase in capacity and efficiency of the machine.

Keywords: Bambara flour, efficiency, hammer mill, operational parameters, optimization

1.0 INTRODUCTION

Bambara nut is a crop with a high prospective for the realization of food security and poverty alleviation in Nigeria and Africa at large, as it shows considerable drought resistance and potentially high nutritional qualities [1,2]. It constitutes the third most common legume after groundnut and cowpea grown in sub-Saharan Africa and most productive crop under poor soil [3-5]. It has been demonstrated to be a completely balanced food because it is found to be very rich in iron (4.9-48 mg/100 g) when compared to a range of (2.0-10.0mg/100g) for most food legumes, protein (18.0-24.0%) with high lysine and methionine contents, ash (3.0-5.0%) fat (5.0-7.0%,) fibre (5.0-12.0%) potassium (1144-1935mg/100g), sodium (2.9-12.0mg/100g), calcium (95.8-99 mg/100g), carbohydrate (51-70%), oil (6-12%) and energy (367-414 kcal/100 mg) according to [6,7]. The protein content of bambara seed is of superlative best worth and has over plus lysine which complements cereals in the diet [2]. The composition of the seeds, with regards to human nutrition is very well balanced because it has all the essential nutrients that a balanced food needs. As a result, it is seen as adequate in the prevention of malnutrition and other health problems such as kwashiorkor. The freshly harvested pods are eaten when cooked, decorticated and consumed as a vegetable snack, while dry, seeds are either roasted and eaten as snack in a method alike to peanut when boiled [3,7].

Nevertheless, processsing of the grain to flour makes it more resourceful for various diet/beverage productions [8,9]. The flour can be used for preparation of boundless formulas such as fufu, relish, soup/stew, Moi–Moi (Okpa), water yam pudding (Ojojo), milk, biscuit, bread, pastries and food thickener [9-11]. Therefore, the incessant demand for a mechanized bambara flour milling system in this sector in order to reduce drudgery associated with traditional milling method. Milling is seen as the most important stage in Bambara flour production this is because dry bambara nuts must be crushed into fine particle as much as possible to weaken the bond between its coat and cotyledon before further operation. The milling process is partially mechanized with the latest version of hammer mill as developed by [12] for maize and wheat milling as shown in figure 1. There has been ineffective appropriation/matching of other grain flour milling machineries for bambara flour production. Multiple milling operations with existing mills which dominates this sector presently in order to reduce excessive loss of bambara cotyledon flour and drudgery adds in making bambara flour production in this sector strenuous and unhygienic.

The present situation of ineffective mechanized milling system in bambara flour production establish the

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elementary cause of persistence underutilization of this crop and subsistence level of its farming in sub-Saharan region. The ineffective mechanization of the bambara nut milling processes was ascribed to its negative 'hard-to-cook' trait by [13-15].

This is because bambara nut showed high binding strength between the nut's seed coat and cotyledon which is attributed to its phenolic compound content and absence of inherent crack in seed coat. Hence, the need for a milling system that can confront this peculiarity to enable effective milling operation.in bambara flour production, which will also position bambara groundnut adequately for alleviating future food and nutritional challenges in accordance with [16]. Since this will enable significant contribution of crop to the well-being of present and future generations, therefore a parametric improvement of a hammer mill for bambara nut milling was carried out for bambara flour production. According to [17] hammer mill is currently widely accepted and also adopted in food and feed industries as a result of its benefits of high productivity and flexibility of grinding a large variety of product. Thus, the characterization and optimization of functional parameters of this hammer mill design for bambara flour production.

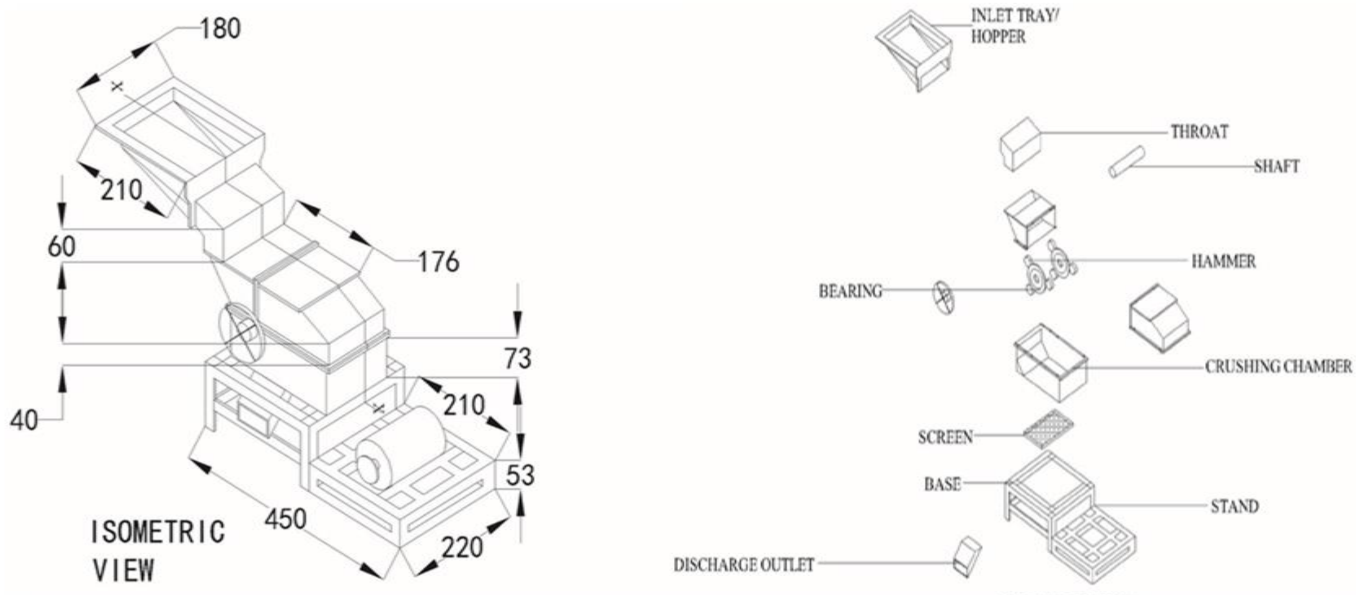

Figure 1: Petrol Hammer mill [12]

2.0 METHODOLOGY

This study involves one-factor-at-a-time screening tests, multifactor-response experimental evaluation/modeling and simulation-optimization of a bambara flour milling machine. The operational/process parameters (factors) of the machine investigated are the moisture content of the bambara grain, number and speed of beaters while particle size of flour constitute the machine's key performance indicator evaluated.

Screening tests were used to determine the significant level/limits within which the operational parameters of the bambara flour milling machine affect its performance. This entails evaluating the machine' performance indicators when it operates at varied settings of one factor and constant design/normal operating settings of others to ascertain the lowest and highest values within which the varied factor significantly affects the responses simultaneously. The factor values at which any of the responses starts and also when all stops changing value while the factor varies constitutes the respective lower and upper limits of the factor studied at that time. Accounting for the maximum fiber content of the bambara groundnut which according to [18] is 4.9%, the performance parameters of this machine were determined from the experimental results using the following mathematical relations;

$$\eta = \frac{100M_f}{0.951\mathrm{M}_f} \tag{1}$$

$$TP = \frac{M_g}{t} \tag{2}$$

Where t, M_g, M_f constitutes processing time, mass of bambara groundnut processed and mass of fine flour extracted respectively.

The main effects/linear relation among the operational and performance parameters of the bambara flour milling machine were experimentally assessed in this study using a randomized single replicate full factorial design with the same test procedure as in factor screening. The sixteen (16) runs, two level coded factorial design layouts shown in Table 1 were developed based on equation (3) using version 18 of Minitab software.

$$n = 2^{k-q} + n_c \quad (3)$$

Where n_c, q, k and n constitutes the number of center points, factors, fractions and runs in the design factor values of -1 and 1 as displayed in the table indicate the low and high factor values. The design matrix as shown in table 1 also represent the factors in their coded values where A represents the number of the cross beaters, B denotes the speed of the cross beaters and C is moisture content.

Table 1: Complete design layout

Std order	Run order	Factor value					
			Coded			Actual	
		A	B	C	n_b	N_b(rpm)	m(%)
12	1	0	1.68	0	4.00	-2528.40	13.05
10	2	1.68	0	0	6.72	1505.00	13.05
8	3	1	1	1	6.00	1610.00.	14.05
13	4	0	0	-1.68	4.00	1505.00	-21.92
11	5	0	-1.68	0	4.00	-2528.40	13.05
9	6	-1.68	0	0	-6.72	1505.00	13.05
6	7	1	-1	1	6.00	1400.00	14.05
2	8	0	0	0	4.00	1505.00	13.05
18	9	0	0	1.68	4.00	1505.00	21.92
14	10	0	0	0	4.00	1505.00	13.05
20	11	0	0	0	4.00	1505.00	13.05
5	12	-1	-1	1	2.00	1400.00	14.05
16	13	0	0	0	4.00	1505.00	13.05
15	14	0	0	0	4.00	1505.00	13.05
17	15	0	0	0	4.00	1505.00	13.05
7	16	-1	1	0	2.00	1610.00	13.05
3	17	-1	1	-1	2.00	1400.00	12.05
19	18	0	0	0	4.00	1505.00	13.05
1	19	-1	-1	-1	2.00	1400.00	12.05
4	20	1	1	-1	6.00	1610.00	12.05

The optimal parameters of the bambara flour milling machine were determined in this investigation using desirability optimization plots. The desirability or derringer function analysis constitutes the third step of DOM. This procedure approximates minima or maxima in response patterns within any design space [19]. It simultaneously solves multi-variant models with the objective of finding the optimal settings of input factors or design variables that maximize, minimize or target some performance measures/quality characteristics or responses [20,21]. This methodology involves specifications of targets which each system response must fulfil in the measuring procedure through its developed individual functions [22]. The desirability optimization plots (contour and surface plots) were applied in visualizing how each response and two factors of this machine relate based on the fitted models. It is a confirmed and widely used industrial research and analytical tool because its predictions are always or nearly close to the optimal operating conditions of the true system. Hence, its application by [23, 24] in determining the optimal mix for acid reclamation of used engine oil and optimal design for rice husk-saw dust reinforced polyester ceiling board production respectively. These plots presented the graphical orientations functional space and iteration history of establishing this machine's optimal operation. The contour plots depicted two-dimensional view of the surface where factor points with the same response are connected to produce contour lines of constant responses while the surface plot provided the three-dimensional view of the surface. The optimal settings of operational and performance parameters of the machine were simulated from geometric mean of each response' functions based on mathematical relation given by [20] as shown in equation (4) and (5).

$$D = \left(d_1(Y_1) \times d_2(Y_2) \times \ldots . \times d_1(Y_1)\right)^{1/k} \quad (4)$$

$$D(Y) = \left(d_1(y_1)^{k_1} \times d_2(y_2)^{k_2} \times \ldots . \times d_n(y_n)^{k_n}\right)^{\frac{1}{\sum_i k_i}} \quad (3)$$

Where y_1 denotes the determined value of response i, d_1 (y_1) is the converted desirability value of ith response and k_i represent the relative importance of response i compared to others.

The mathematical programming model formulated from the developed models was simulated for the machine's optimal parameters prediction using Minitab desirability optimizer with maximization of particle size of flour $\leq$ 35µm.

The model solution or prediction criterion for optimal parameter conditions was based on coded factor settings with maximum overall desirability value close to one. The optimal settings of the operational parameters of the machine were derived from the coded solution using their transformation relations before confirming their accuracy with three experimental trails using the same test procedure as factor screening.

3.0 RESULTS AND DISCUSSION

This experimental factor screening results revealed the functional limits within which the grain moisture content and cross beater of this machine influence its milled grain particle size as shown in table 2 without establishing the combined settings of these factors for optimal particle size production.

Table 2: Functional limits of the grain moisture content and cross beater

S/No	Factor Description	Symbols		Limits	
		Coded	Actual	High (+1)	Low (-1)
1	Number of cross beaters	A	n_b	6.00	2.00
2	Cross beaters' speed (rpm)	B	N_b	1610.00	1400.00
3	Grain moisture content (%)	C	m	14.05	12.05

The inability to visualize/establish the combined optimal settings of these factors from this classical one factor at a time characterization of this machine prompted its multifactor analysis based on twenty runs two levels (-1 and +1) full desirability optimization methodology with 0, -1.68 and 1.68 as the coded center and axial points. The center and axial factor values augmented the factorial settings for effective fiiting of the flour particle size function. The optimal-coded factors transformation equations used for this evaluation were derived from their respective limits as follows.

$$A = \frac{\boldsymbol{n_b} - 4}{2} \quad (6)$$

$$B = \frac{N_b \; - 1505}{105} \quad (7)$$

$$C = \frac{m - 13.05}{1} \quad (8)$$

The actual/coded factor settings and results of experimental evaluation of the combined effects of grains' moisture content, number and speed of cross beaters on the milled grain particle size (P_f) shown in table 3**.**

Table 3: Multifactor evaluation of particle size of flour processed with this machine

Std order	Run order	Factor value						P_f (µm)
		Coded			Actual			
		A	B	C	n_b	N_b(rpm)	m(%)	
12	1	0	1.68	0	4.00	-2528.40	13.05	27.69
10	2	1.68	0	0	6.72	1505.00	13.05	27.21
8	3	1	1	1	6.00	1610.00.	14.05	28.40
13	4	0	0	-1.68	4.00	1505.00	-21.92	30.25
11	5	0	-1.68	0	4.00	-2528.40	13.05	31.75
9	6	-1.68	0	0	-6.72	1505.00	13.05	17.85
6	7	1	-1	1	6.00	1400.00	14.05	27.70

Std order	Run order	Factor value						P_f (µm)
			Coded			Actual		
		A	B	C	n_b	N_b(rpm)	m(%)	
2	8	0	0	0	4.00	1505.00	13.05	30.70
18	9	0	0	1.68	4.00	1505.00	21.92	20.10
14	10	0	0	0	4.00	1505.00	13.05	33.20
20	11	0	0	0	4.00	1505.00	13.05	17.11
5	12	-1	-1	1	2.00	1400.00	14.05	30.60
16	13	0	0	0	4.00	1505.00	13.05	19.10
15	14	0	0	0	4.00	1505.00	13.05	30.13
17	15	0	0	0	4.00	1505.00	13.05	23.10
7	16	-1	1	0	2.00	1610.00	13.05	24.45
3	17	-1	1	-1	2.00	1400.00	12.05	33.45
19	18	0	0	0	4.00	1505.00	13.05	31.11
1	19	-1	-1	-1	2.00	1400.00	12.05	28.85
4	20	1	1	-1	6.00	1610.00	12.05	32.15

Positive slope of the main effect plot of these experimental results indicated positive linear correlations between the individual terms and the response. Its partial steeping profile revealed that quadratic terms of the factor and their interactions are vital for adequate approximation of the milled bambara grain particle size. Hence, the nonlinear simulation of the milled bambara particle size is a function of the number and speed of this machine's beaters and moisture content of the bambara grain processed.

The coded and actual versions of the function of the milled bambara particle size derived from the multifactor test results constitutes equations (9) and (10) respectively.

$$P_f = 80.098 + 15.798\,A + 10.005\,B + 0.437\,C - 12.366\,A^2 - 7.292\,B^2 - 2.900\,C^2 + 7.337\,AB - 1.063\,BC \qquad (9)$$

$$P_f = 26.1n_b + 10.38N_b + 78.02m - 3.09{n_b}^2 - 0.00004{N_b}^2 - 2.9m^2 + 0.003n_bN_b - 0.008mN_b - 539.13 \qquad (10)$$

Statistical residual analysis (figure 2) showed that this function is adequate for further investigation of this response because its histogram, normal and scatter plots depicted dumb-bell, straight line and structure less profiles respectively as desired. This implies normal distribution of errors associated with the function which is expected of a good prediction model. The prediction adequacy of this particle size model was also confirmed exponentially to over 95% as shown in figure 3. The analysis of variance as shown in table 4 and 5 also confirms its adequacy.

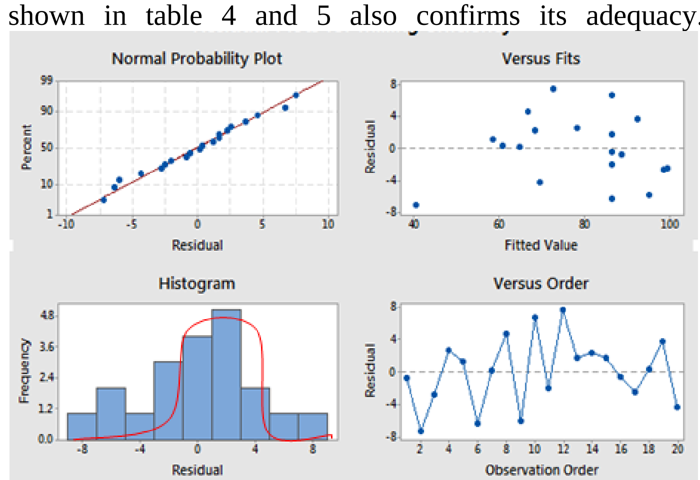

Figure. 2: Residual plots of the bambara flour particle size function

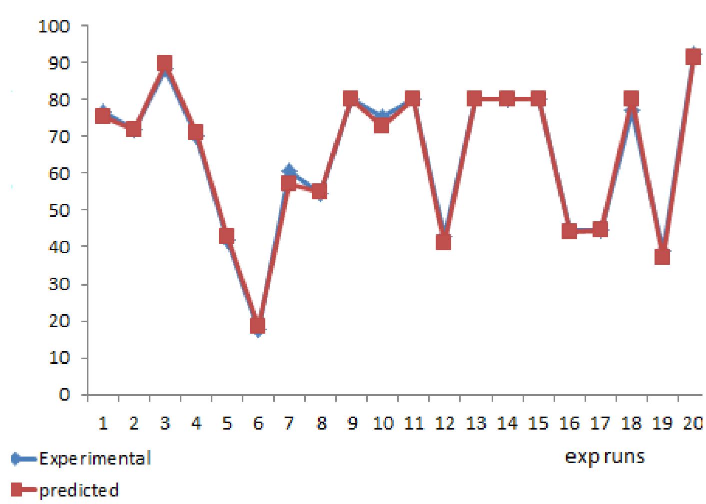

Figure 3: Experimental runs and prediction accuracy of the bambara flour particle size function

Table 4: Analysis of variance for the quadratic model of the bambara flour particle size

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	7976.12	886.24	1100.79	0.000
Linear	3	4778.04	1592.68	1978.25	0.000
A	1	3408.50	3408.50	4233.67	0.000
B	1	1366.93	1366.93	1697.86	0.000
C	1	2.60	2.60	3.23	0.032
Square	3	2757.56	919.19	1141.71	0.000
A*A	1	2203.72	2203.72	2737.22	0.000
B*B	1	766.38	766.38	951.92	0.000
C*C	1	121.16	121.16	150.49	0.000
2-WayInteraction	3	440.52	146.84	182.39	0.000
A*B	1	430.71	430.71	534.98	0.000
A*C	1	0.78	0.78	0.97	0.348
B*C	1	9.03	9.03	11.22	0.007
Error	10	8.05	0.81		
Lack-of-Fit	5	8.05	1.61	11780.86	0.334
Pure Error	5	0.00	0.00		
Total	19	7984.17			

Table 5: Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		80.098	0.366	218.88	0.000	
A	31.596	15.798	0.243	65.07	0.000	1.00
B	20.009	10.005	0.243	41.21	0.000	1.00
C	0.873	0.437	0.243	1.80	0.032	1.00
A*A	-24.732	-12.366	0.236	-52.32	0.000	1.02
B*B	-14.585	-7.292	0.236	-30.85	0.000	1.02
C*C	-5.799	-2.900	0.236	-12.27	0.000	1.02
A*B	14.675	7.337	0.317	23.13	0.000	1.00
A*C	-0.625	-0.313	0.317	-0.99	0.348	1.00
B*C	-2.125	-1.063	0.317	-3.35	0.007	1.00
Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF

The ANOVA for the fitted quadratic polynomial model of bambara flour particle size as shown in Table 4 to 5 showed the value of coefficient of determination (R^2) of 0.9990, R^2 as 99.9% with no significant lack of fit at $p > 0.05$, $p = 0.348$ which means that the model was capable of explaining 99.90 of the results. The ANOVA results indicated that the model used to fit response variable was very significant at $p < 0.05$ ($p=0.000$) and adequate to represent the relationship between the model and the independent variable. The fisher's F-test was also used to judge the significance of the model which suggested that the model had a very high model F-value (F=1100.79). The adjusted coefficient of determination (adjusted R^2) value of this model is 0.9981 which indicated that only 0.19% of the total variations were not explained by the model. Also, the R^2 (predicted) value of 99.17% indicated a very high predictive ability of the model. The contour and desirability optimization plots of the particle size of the flour as per various factor pairs with the factors held their center values are shown in the figures 4 and 5

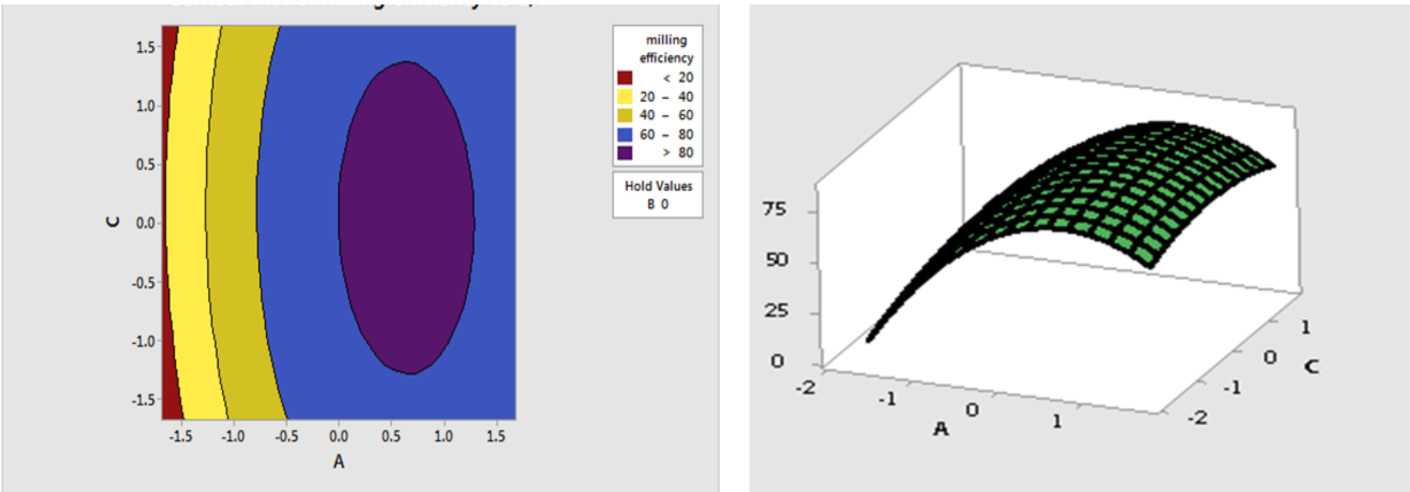

Figure 4: Contour and surface plot of particle size of flour verse moisture content and number of cross beaters

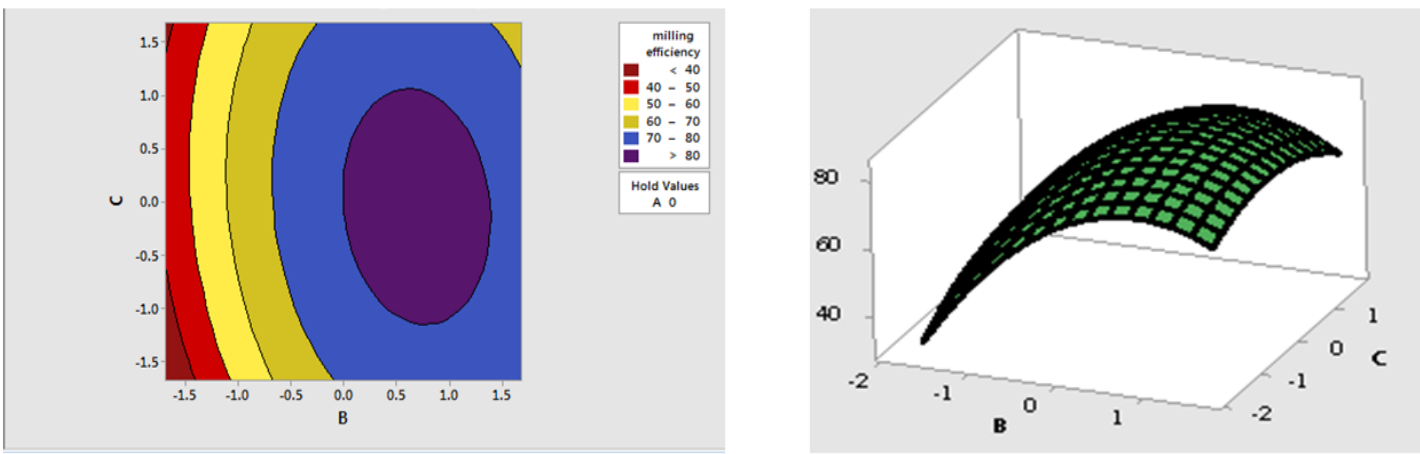

Figure 5: Contour and surface plots of particle size of flour verse moisture content and speed of cross beaters

Desirability simulation of the bambara flour particle size function shown in figure 6 revealed possible effective milling operation within the axial settings of the factors. The particle size of milled bambara flour produced when the machine operates with the upper and lower axial factor settings are 35µm and 17µm respectively.

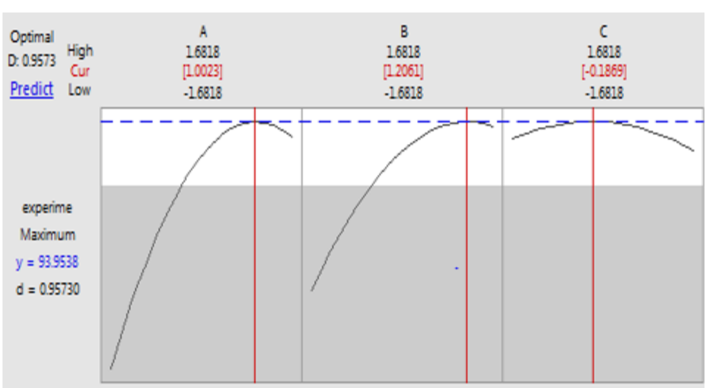

Figure 6: Desirability simulation plot of the bambara flour particle size function

This desirability simulation plot also showed 1.0023, 1.2061 and -0.1869 as the optimal coded settings of the number and speed of cross beaters as well as the bambara nut moisture content respectively.

4.0 CONCLUSION

Characterization and optimization analysis of the hammer milling machine for bambara flour production revealed that the operational parameters (factors) with significant influence on the machine includes the bambara grains' moisture content, number and speed of cross beaters it also showed throughput and milling efficiency as its functional performance indicators. The number and speed of the cross beater and the bambara nut moisture content affect the particle size of the milled bambara flour directly. The optimal values of the number and speed of cross beaters and bambara nut moisture content were determined as 6, 1610.00rpm and 11.42% respectively which causes increase in capacity and efficiency of the machine. The milling capacity and efficiency of the machine was determined as 4.72kg at 1.19min and 98.45% respectively.

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