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MODELING THE PERFORMANCE OF A BAOBAB SEED DECORTICATOR USING RESPONSE SURFACE METHODOLOGY

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ABSTRACT

Decortication of baobab seed manually after soaking or roasting is time consuming, labour-intensive and uneconomical. The demand for baobab kernel as a source of protein is increasing for use as supplement for animal protein ration, for edible oil consumption and for other industrial uses. To ameliorate this problem, a baobab seed decorticator has been developed. This study therefore focused on the effects of process parameters; moisture content of seed, speed of decorticator and concave-shaft clearance on percentage clean kernel (P_{ck}), percentage broken kernel (P_{bk}), percentage whole seed (P_{ws}) and decorticating efficiency (DE), using Response Surface Methodology (RSM). In designing the experiments, Box-Behnken Design (BBD) was selected. Analysis of Variance (ANOVA) was carried out to evaluate and select the appropriate dependent (P_{ck} P_{bk}, P_{ws} and DE) and independent variables using both the F and P-values calculated at 95% confidence level (α=0.05). Mathematical models relating the process parameters to the responses were developed. The developed models were validated by comparing the predicted and actual experimental values. The selected quadratic models were adequate for predicting the performance of the developed decorticator. It was observed that a decrease in percentage clean kernel recovery would result if concave-shaft clearance and moisture content were increased. Likewise, the concave-shaft clearance had the highest positive effect while moisture content had the highest negative effect on percentage of broken kernel. All the three factors (process parameters) had positive effects on decorticating efficiency.

Keywords: *Baobab seed-Decorticator, Modelling, Crop and machine parameters, Decortication efficiency, Percent clean kernel.*

INTRODUCTION

The continuous increase in population and inadequate supply of protein to human being have inadvertently increased the occurrence of malnutrition in developing countries (De-Caluwé *et al.,* 2009). Hemmingsen (2015) stated that developing countries, Nigeria inclusive, do not produce enough food and of the right nutritional qualities to meet their daily needs. The dearth in food supply especially those rich in protein, is of such magnitude that the developing nations have to depend, mostly on cereal grains, starchy roots and tubers for their energy and protein needs. In view of above, the quests for alternative sources of protein from lesser-known tree crops become imperative.

The baobab tree (*Adansonia digitata* L.) is versatile, widely used for household, medicinal and nutritional purposes; it also provides additional income to farmers (Wickens and Lowe, 2008). Every part of the baobab is reported to be useful. Baobab is widespread in Africa but its seed is one of the lesser-known, ignored and under-exploited vegetable. Though, it has high protein and calorific content than other crops presently in use in animal feed, the potential of its seeds remain untapped (Buchmann *et al*., 2010). In the Northern part of Nigeria, the leaves are used in the preparation of soup commonly called "miyan kuka" in Hausa and "luru" in Yoruba. The seeds are used as thickening agent in soup and cow milk hawked by Fulani women. They may also be fermented and used as flavours or they can be roasted and eaten as snacks or made into a drink. The seed contains edible oil and has more protein than groundnuts and also rich in amino acid lysine, vitamin B1 (thiamine), calcium and iron (Adejuyitan *et al*., 2012).

The animal protein consumption rate in Nigeria and other developing countries was estimated to be about 8 g per caput per day which is 27 g less than the recommended requirement by the National Research Council of the United State of America (Buchmann *et al.,* 2010). The alternative source of protein if malnutrition is to be averted is plant protein. Baobab seed is one of the various seeds that are underutilised which can supply the required protein for human and animals' need. The problem of wrong selection of seed and machine parameters for optimal operation of decorticators is important. Mathematical modelling of a process gives the relationship between the process parameters and variables with their interactions and the dependent variable, in this case the decortication efficiency, percentage clean kernel, percentage broken kernel and percentage whole seed (un-decorticated). Hence, the objective of the research was to develop mathematical models which represent the performance of baobab seed decorticator with a view to enhancing its functionality.

MATERIALS AND METHODS

Baobab fruits were obtained at Igbo-Ologun community, Saki, Oyo State, Nigeria where the plants were in abundance. The fruits were cracked and the seeds manually extracted, washed with water and sun-dried for six hours. Initial moisture content of the seed was determined by oven drying method at 102±2 ºC. A baobab seed decorticator was developed based on data obtained from determination of some physical and mechanical properties of baobab seed and kernel (Ola *et al.,* 2017). The pictorial view of the developed decorticator is presented in Plate 1 (Akande *et al.,* 2019). The performance of the decorticator was optimized and mathematical model equations developed to predict the influence of the independent variables on responses: percentage clean kernel recovery (P_{ck}), percentage broken kernel (P_{bk}), percentage whole seed (P_{ws}) and decorticating efficiency (DE).

The choice of independent and dependent variables was guided by preliminary investigations and literature review (Aminu *et al*., 2018; Saleh *et al.,* 2022). The independent variables considered were speed of operation (300, 375, and 450 rpm), concave-shaft clearance (8, 9 and 10 mm) and moisture content (10, 15 and 20%). The RSM tool (Design-Expert version 12.0.1.0) was utilized for the experimental design, analyses and generation of model equations that depicts the various performance of the developed baobab decorticating machine. The predicted results were compared with the experimental results obtained as suggested by Fakayode *et al*. (2019). The response variables of the baobab decorticating machine at different levels of the independent variables were evaluated using linear, two-factor interaction (2FI), quadratic and cubic models to determine which model performed best as suggested by Fakayode *et al.* (2019) and Falade and Aremu (2018). Analysis of variance was conducted using various performance criteria (matrix) to determine the adequacy of the developed models, significance, fitness and as well as their interactions with the performance responses as pointed out by Falade and Aremu (2018).

Plate 1: Pictorial view of the developed baobab seed decorticator (Akande *et al*., 2019)

The P-value was also analysed. Optimization of the variables used was carried out, maximizing the desired responses [Percentage clean kernel (P_{ck}) and Decorticating Efficiency (DE)] and minimizing the undesired responses [Percentage broken kernel (P_{bk}) and Percentage whole seed (P_{ws})] (Hussain and Singh, 2015).

To study all standard effects of the independent variables on the responses, an appropriate predictive model obtained from regression analysis was obtained from the global predictive equation from which specific solution may be derived as presented in Equation 1 (Fetel and Gaumon, 2008)

$$Y = \beta_o + \sum_{i=1}^{k} \beta_i X_i + \sum_{\text{i<}} \sum_{j=3}^{k} \beta_{ij} X_i X_j X_k + \sum_{\text{i=1}} \sum_{j=1}^{k} \delta_{ij} X_i X_j X_k + \boldsymbol{\varepsilon} \qquad (1)$$

Where: Y is the percentage clean kernels

β_o is the model intercept,

$\sum_{i=1}^{k} \beta_i X_i$ characterises the main linear effects of individual process variables (moisture content, speed and clearance),

$\sum_{\text{i<}} \sum_{j=2}^{k} \beta_{ij} X_i X_j$ Incorporates the interaction effects between variables $\sum_{\text{i=1}} \sum_{j=1}^{k} \delta_{ij} X_i X_j$ represents the main quadratic effects of the variables

$\boldsymbol{\varepsilon}$ is the random error of experimentation,

X_{ijk} represents the matrix of the uncoded process variables

The determination of the unknown coefficients of $\boldsymbol{\beta}_o$, $\boldsymbol{\beta}_i$, $\boldsymbol{\beta}_{ij}$ and $\boldsymbol{\delta}_{ij}$ were accomplished via regression analysis implemented on the statistical analysis software (Design Expert, Version 12) using the empirical data recorded from experimentations.

EXPERIMENTAL DESIGN

Table 1 shows the experimental design matrix for the proposed Box-Behnken Design (BBD). BBD was selected because it offers fewer number of experimental runs and suitable for the development of reliable response surface models for optimization study. A total of seventeen experiments were conducted at different levels of factors.

Evaluation of model parameters was carried out using analysis of variance (ANOVA). The selection of appropriate model and significant model terms for the percentage clean kernel recovered was achieved by using response surface methodology at 95% confidence level ($\alpha = 0.05$). The evaluation was guided by using Fisher's 'F' and P'-tests statistical tools. While the F-test determines the relative degree of significance of the regression terms, the p-statistics checks the probability that indicate the risk associated with the acceptance of factor significance.

The reliability of the developed model was assessed using the correlation coefficients (R-square, adjusted, and predicted R-square values). The closer these correlation coefficients were to unity, the better the selected model and its terms.

Table 1: Design matrix for the BBD

Std	Run	A:Clearance Mm	B:Speed Rpm	C:MC %	P_{ck} %	P_{bk} %	P_{ws} %	DE %
7	1	8	375	20	63.82	5.95	1.89	98.11
8	2	10	375	20	75.24	1.82	0	100
1	3	8	300	15	72.46	13.59	0	91.79
16	4	9	375	15	64.83	5.67	1.65	98.35
13	5	9	375	15	65.1	5.4	1.87	98.13
17	6	9	375	15	64.67	6.01	1.72	98.28
3	7	8	450	15	65.9	7.97	0	100
6	8	10	375	10	71.15	2.81	0.42	99.58
15	9	9	375	15	66.98	5.92	1.58	98.42
12	10	9	450	20	67.64	7.21	0	100
4	11	10	450	15	68.34	6.86	0	100
5	12	8	375	10	64.23	9.92	4.17	95.83
11	13	9	300	20	58.84	11.05	1.83	92.56
10	14	9	450	10	63.95	10.02	0	100
2	15	10	300	15	65.05	8.52	1.89	98.11
9	16	9	300	10	56.83	12.28	2.78	93.42
14	17	9	375	15	62.95	7.67	1.65	98.35

RESULTS AND DISCUSSION

Analysis of variance (ANOVA) of responses (P_{ck} P_{bk}, P_{ws} and DE)

Tables 2 and 3 present the analysis of variance (ANOVA) for the percentage clean kernel (P_{ck}) and percentage broken kernel (P_{bk}) Model evaluation showed that quadratic model was adequate for the percentage clean kernel (P_{ck}) with the F-value of 15.01 and P-value of 0.0041 (Table 2). The p-values less than 0.05 give indication that the model terms are significant. In this case A, B, AB, B^2 are significant model terms. Values of p-statistics greater than 0.05 indicate the model terms are not significant. For this analysis, it means a 0.41% probability exists that the estimated F-value could occur due to noise. The Lack of Fit of 0.76 implies it is not significant relative to the pure error which is expected according to Arinkoola *et al.* (2015). Non-significant lack of fit is good and for the model to fit.

Table 2: The ANOVA for P_{ck} using the response surface quadratic model

Source	Sum of Squares	DF	Mean Square	F-value	p-value	Remarks
Model	264.64	9	29.4	15.01	0.0041	Significant
A-Clearance	25.39	1	25.39	12.96	0.0155	Significant
B-Speed	21.32	1	21.32	10.88	0.0215	Significant
C-MC	9.68	1	9.68	4.94	0.0768	Not significant
AB	13.89	1	13.89	7.09	0.0447	Significant
AC	2.2	1	2.2	1.12	0.3383	Not significant
BC	0.7056	1	0.7056	0.3601	0.5746	Not significant
A^2	10.5	1	10.5	5.36	0.0685	Not significant
B^2	64.23	1	64.23	32.78	0.0023	Significant
C^2	6.54	1	6.54	3.34	0.1272	Not significant
Residual	9.8	5	1.96			
Lack of Fit	1.57	1	1.57	0.7638	0.4315	Not significant
Pure Error	8.23	4	2.06			
Cor Total	274.44	14				

The results of analysis of variance (ANOVA) for percentage broken kernel (P_{bk}) is presented in Table 3. The quadratic model selected indicates an F-value of 26.15 and p-value of 0.0001 at 95% confidence level. This result implies the quadratic model is adequate for modelling the percentage broken kernel (P_{bk}) of decorticated baobab seed. The p-value of 0.0001 obtained from this analysis implies that only a 0.01% probability exists for F-value estimated could occur due to noise which gives more confidence to the degree of accuracy of the model and interpretation inferences drawn from this study. The P-values were less than 0.05 which indicate that the model terms are significant. In this case, B (speed), C (moisture content) and B^2 (quadratic terms of speed) are significant model terms. P-values greater than 0.0500 indicate the model terms are not significant at 95% confidence level. Also, the lack of fit F-value of 1.04 is small and implies the Lack of Fit is not significant relative to the pure error (Mu'azu *et al*., 2012).

The results of ANOVA for percentage whole seed P_{ws} is presented in Table 4. The quadratic model selected indicates an F-value of 26.15 and p-value of 0.0001 at 95% confidence level. This result implies the quadratic model is adequate for modelling the percentage broken kernel, P_{bk} of decorticated baobab seed. The p-value of 0.0001 obtained from this analysis implies that only a 0.01% probability exists for F-value estimated could occur due to noise which gives more confidence to the degree of accuracy of the model and interpretation inferences drawn from this study. The p-values were less than 0.05 which indicates that the model terms are significant. In this case, speed (B), moisture content (C) and the quadratic term of the speed (B^2) are significant model terms. The lack of fit F-value of 1.56 implies the lack of fit is not significant relative to the pure error. For the decorticating efficiency (DE), the ANOVA result is presented in Table 5. The quadratic model selected indicates an F-value of 24.57 and p-value of 0.00128. These statistics imply the cubic model is adequate for modelling the percentage whole seed (P_{ws}) of decorticated baobab seed.

Table 3: The ANOVA for P_{bk} using the response surface quadratic model

Source	Sum of Squares	DF	Mean Square	F-value	p-value	Remarks
Model	148.3	7	21.19	26.15	< 0.0001	Significant
A-Clearance	0.4201	1	0.4201	0.5187	0.4897	Not significant
B-Speed	22.38	1	22.38	27.63	0.0005	Significant
C-MC	10.13	1	10.13	12.5	0.0064	Significant
AB	3.92	1	3.92	4.84	0.0553	Not significant
AC	2.22	1	2.22	2.74	0.1322	Not significant
A^2	3.89	1	3.89	4.8	0.0561	Not significant
B^2	69.44	1	69.44	85.72	< 0.0001	Significant
Residual	7.29	9	0.81			
Lack of Fit	4.12	5	0.8232	1.04	0.4998	Not significant
Pure Error	3.17	4	0.7936			
Cor Total	155.59	16				

Table 4: The ANOVA for percent whole seed (P_{ws}) using the response surface quadratic model

Source	Sum of Squares	DF	Mean Square	F-value	p-value	Remarks
Model	19.07867	9	2.119852	24.57329	0.00128	Significant
A-Clearance	0.18432	1	0.18432	2.136635	0.203665	Not significant
B-Speed	0.367205	1	0.367205	4.256635	0.094054	Not significant
C-MC	1.528369	1	1.528369	17.71683	0.008415	Significant
AB	0.057408	1	0.057408	0.665477	0.451729	Not significant
AC	0.8649	1	0.8649	10.02591	0.024916	Significant
BC	0.225625	1	0.225625	2.615442	0.166751	Not significant
A^2	0.878284	1	0.878284	10.18106	0.024244	Significant
B^2	0.025822	1	0.025822	0.299331	0.607825	Not significant
C^2	1.12376	1	1.12376	13.02661	0.015393	Significant
Residual	0.431333	5	0.086267			
Lack of Fit	0.382813	1	0.382813	1.55915	0.4935	Not significant
Pure Error	0.04852	4	0.01213			
Cor Total	19.51	14				

The p-value of 0.00128 obtained from this analysis performed at 95% confidence level implies that only a 0.128% probability can exist for the F-value obtained occur due to noise. In this case moisture content (C), interaction between clearance and moisture content (AC), the quadratic term of clearance (A^2) and the quadratic term of moisture content (C^2) were significant model terms. The p-values greater than 0.0500 indicate the model terms are not significant at 95% confidence level.

Table 5: The ANOVA for DE using the response surface quadratic model

Source	Sum of Squares	DF	Mean Square	F-value	p-value	
Model	64.57048	9	7.174498	337.4011	2.03E-06	Significant
A-Clearance	0.283756	1	0.283756	13.34441	0.014702	Significant
B-Speed	0.424808	1	0.424808	19.97779	0.006581	Significant
C-MC	0.111955	1	0.111955	5.265012	0.070248	Not significant
AB	9.9856	1	9.9856	469.6012	3.88E-06	Significant
AC	0.8649	1	0.8649	40.67438	0.001403	Significant
BC	0.6075	1	0.6075	28.56941	0.003077	Significant
$\hat{A}^2$	0.003777	1	0.003777	0.177603	0.690945	Not significant
B^2	2.078411	1	2.078411	97.74318	0.000181	Significant
C^2	0.003777	1	0.003777	0.177603	0.690945	Not significant
Residual	0.10632	5	0.021264			
Lack of Fit	0.0578	1	0.0578	4.765045	0.094438	Not significant
Pure Error	0.04852	4	0.01213			
Cor Total	64.6768	14				

The Lack of Fit F-value of 4.765045 implies the lack of fit is not significant relative to the pure error. There is a 9.4438% chance that a Lack of Fit F-value this large could occur due to noise. The study found that lack of fit was insignificant in the model and so the study concludes that the reduced model is adequate. In general, the overall model is adequate for prediction purpose in this study.

Mathematical Model Equations for the Responses

The quadratic model for the percentage clean kernel recovery (P_{ck}) as a function of concave-shaft clearance (A), speed (B) and moisture content (C) is presented in Equation 2.

$$P_{ck} = -7.15983 - 25.55517A + 0.986567B - 3.96157C - 0.037956AB + 0.226333AC + 0.001120BC + 2.26200A^2 - 0.000807B^2 + 0.057947C^2 \qquad (2)$$

Equation 2 depicts that the coefficients of the model terms, a measure of the degrees to which various independent variables influence the machine's performance are unequal. Also, the equation reflects the synergistic effects of variables on the P_{ck}. The positive main (B) and interaction (AC and BC) terms in the equation represented a direct relationship between it and the P_{ck}. Thus, the increase in (B), (AC) and (BC) would lead to an increase in the P_{ck}. Conversely, the coefficients (main and interaction) with negative signs indicating an inverse relationship with the P_{ck}. Thus, a decrease in P_{ck} would result if (A) and (C) were increased.

The model equation relating the process variables with the percentage broken kernel, P_{bk} is presented in Equation 3.

$$P_{bk} = +125.75500 + 7.91276A - 0.681802B - 1.56600C + 0.013 + 0.149000AC - 0.959737A^2 + 0.000721B^2 \qquad (3)$$

According to Equation (3), as the A, AB, AC and B^2 increase, the percentage broken kernel recovered also increases. It was observed however that (A) has the highest positive effect as a singular factor while moisture content (C) has the highest negative effect on percentage of broken kernel (P_{bk}).

Equation 4 also shows the relationship between the factors and the percentage whole seed recovery.

$$P_{ws} = +89.34900 - 13.99900A - 0.062667B - 0.399850C + 0.002767AB + 0.093000AC + 0.000633BC + 0.564250A^2 + 0.000017B^2 - 0.025530C^2 \quad (4)$$

From Equation 4, the interactions between clearance (A) and speed (B), interactions between clearance and moisture content (C), interactions between speed and moisture content (BC), the quadratic terms of clearance (A^2) and speed (B^2) have positive signs indicating an increase in whole seed recovery with increase in any of the two variables. The quadratic term of clearance (A^2) has the highest positive effect on the whole seed recovery followed by interaction between clearance and moisture content (AC) while clearance (A) has the highest negative effect on the percentage whole seed recovery as increase in (A) will decrease the percent whole seed recovery.

Equation 5 also shows the relationship between the factors and the decortication efficiency, DE.

$$DE = -41.94900 + 10.12400A + 0.366000B + 1.60260C - 0.021067AB - 0.093000AC - 0.0018000BC + 0.037000A^2 - 0.000154B^2 + 0.001480C^2 \quad (5)$$

All the three factors; clearance (A), speed (B) and moisture content (C) have positive effects on decorticating efficiency of the developed machine with clearance having the highest effect as a single factor. The quadratic terms of clearance (A^2) and moisture content (C^2) also have positive effects on decorticating efficiency with (A^2) contributing more. However, interactions between clearance and speed (AB), interactions between clearance and moisture content (AC), interactions between speed and moisture content (BC) and the quadratic term of speed (B^2) have negative effects on decorticating efficiency, interactions between clearance and moisture content (AC) being the highest contributing factor.

Validation of the developed models

The coefficient of determination, the adjusted coefficient of determination and precision obtained when the plot of actual experimental data for P_{ck}, P_{bk}, P_{ws} and DE were plotted against the predictions using the developed equations (2) to (5) were (0.9643, 0.9000, and 16.11), (0.9531, 0.9381 and 18.55), (0.9779, 0.9167and 17.39), and (0.9984, 0.9954 and 68.96), respectively. The correlation coefficient close to one is adequate. This indicates that the quadratic model selected is adequate and the model could be regarded predictive and amenable for sampling within the experimental domain for the optimization study, this is similar to the findings of Okonkwo *et al.* (2019) on evaluation of a locust bean dehuller. Figures 1a-d are the cross plot of the predicted values by the quadratic model equations against the actual experimental measurements for (a) P_{ck}. (b) P_{bk} (c) Pws and (d) DE. These Figures show the degree to which the experimental and predicted values agreed with each other. It can be observed from Figures 1 (a-d) that majority of the points were positioned along the 45° line drawn from the origin. This shows that the models developed in this study were representative and suitable for use as objective function during the optimization process. The model developed for the response is considered accurate, as all the measured values were closer with the line of the best fit. Similarly, the comparison of both predicted and actual values were fairly good, indicating that empirical model derived from RSM could be used to describe the

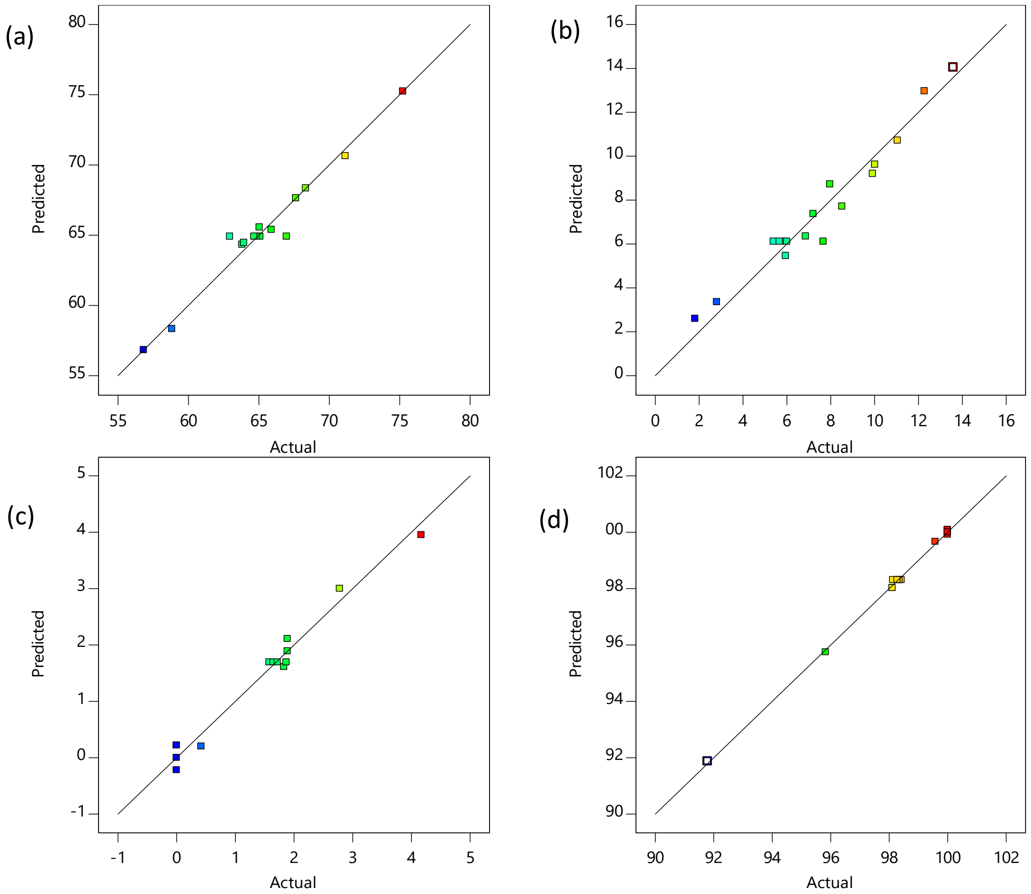

Figure 1: Cross plot of the predicted values by the quadratic model equation against the actual experimental measurements for (a) P_{ck}. (b) P_{bk} (c) Pws and (d) DE

relationship between the factors and responses in the decortication of baobab seeds using the developed machine.

CONCLUSION

Model equations were developed for the responses {(percentage clean kernel (P_{ck}), Percentage broken kernel (P_{bk}), percentage whole seed (P_{ws}) and decorticating efficiency (DE)} as a function of concave clearance, shaft speed and seed moisture content. The developed models were validated by comparing the predicted and actual experimental values. The selected quadratic models were adequate for predicting the performance of the developed baobab seed decorticator. A decrease in Percentage clean kernel recovery would result if concave-shaft clearance and moisture content were increased. Likewise, the concave-shaft clearance had the highest positive effect while moisture content had the highest negative effect on percentage of broken kernel. All the three factors, process parameters had positive effects on decorticating efficiency.

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