

Investigating the Impact of Process Variables on Dehulling Energy Demand of African Breadfruit Seeds: A Response Surface Optimization



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ABSTRACT: Processing African breadfruit (*Treculia Africana*) seeds efficiently and sustainably presents substantial possibilities for addressing food security issues in sub-Saharan Africa; yet, the high energy requirement of dehulling constitutes a major impediment to unleashing its full capabilities. This work examines the influence of process variables on the dehulling energy (Q_d) requirement of African breadfruit seeds. The experiment was designed using the Box–Behnken Design tool of the Design Expert Statistical software to explore the influences of varying process conditions of feed rates (2, 6, and 10 kg/h), moisture contents (7.25, 14.8, and 22.35% w.b), and operating speeds (8, 15, and 22 rpm) on the dehulling energy requirement, dehulling efficiency, seed damage rate, and throughput capacity via response surface methodology. To establish the optimal dehulling energy and conditions, numerical optimization was performed using a desirability index approach. The energy predictive model was developed with a high prediction accuracy ($R^2 = 0.9996$) and validated by the statistical analysis of the experimental data and plots of normal % probability residuals and predicted vs. actual Q_d . Experimental findings show that greater feed rates and machine speeds raise energy demand, and increasing moisture content substantially reduces it. The dehulling energy demand varied between $0.35 \leq Q_d \leq 1.5$ kW/h ranges. At varying process conditions, the dehulling efficiency, seed damage rate, and throughput capacity were found to be in the range of 78 to 93%, 4 to 18%, and 1.9 to 9.82 kg/h, respectively. Synergistic and antagonistic relationships between variables highlight the necessity of diligent optimization to strike an equilibrium between energy economy and seed quality amongst other response variables. At optimum dehulling settings of 4.68 kg/h, 15.38% w.b, and 14.51 rpm, the energy demand, dehulling efficiency, seed damage rate, and throughput capacity were found to be 0.73 kW/h, 72.7%, 0.67%, and 0.41 kg/h, respectively. These findings provide a basis for designing energy-efficient dehulling equipment, promoting eco-friendly and economically viable processing solutions for African breadfruit seeds.

KEYWORDS: Decortication performance, seed processing, energy consumption, kernel damage, peeling parameters.

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I. INTRODUCTION

The nutrient-dense African breadfruit (*Treculia Africana*) is a native food crop of sub-Saharan Africa valued for its seeds, which are an essential source of protein, minerals, and dietary fibre (Nwabueze *et al.*, 2008). It has enormous promise as an economic crop, but processing bottlenecks, particularly when it comes to dehulling, hinder its optimal utilization. Dehulling, or peeling of pericarp and testa (seed coats) to reveal the nutrient-packed kernels of leguminous grains, oilseeds, and cereal grain, is usually a labour, energy, and time-intensive unit operation/process that calls for technical advancements to increase efficiency and productivity. According to Omobuwajo *et al.* (1999), dehulling improves the food product's nutritional profile and appearance while lowering its bulk density, which helps regulate temperatures and moisture transport in subsequent unit operations.

Notwithstanding improvements in agricultural equipment, removal of hard pericarp and endosperm (dehulling) of food

grains generally still requires a lot of energy, resulting in uneven kernel viability, and is expensive to process. These problems lead to large postharvest losses and impede the processing of this indispensable food crop at a commercial scale (Umezuruike and Nwabueze, 2021). To overcome these constraints, a thorough grasp of the variables affecting dehulling performance is of great importance. Transforming African breadfruit seeds into marketable goods for both domestic and foreign markets require effective dehulling. The ability to reduce energy input, seed injury, and increase output ratio through optimizing important process parameters such as feed rate, moisture content, and machine speed facilitates the development of food processing processes that are designed for sustainability.

The energy demand for dehulling is the amount of power supplied to the dehulling system over a specified period to remove the testa or outer coat of food grain. This parameter is essential for assessing the performance efficiency of the system and economic viability, especially for crops with hard

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seed coats like breadfruit seeds. The amount of energy required for dehulling a given batch size of food grains can be influenced by the following factors: moisture content, feed rate, machine speed, and mechanical design (Ozigbo and Bamgboye, 2020; Umezuruike and Nwabueze, 2021). Increased moisture content can reduce the toughness of the seed coat and reduce energy requirement (Abodenyi *et al.*, 2018; Umezuruike and Nwabueze, 2021). Low or moderate moisture levels that cause the seed coat to loosen, lower energy demand and improve dehulling efficiency (Bamgboye, 2020). According to Umezuruike and Nwabueze (2021), processing breadfruit seeds requires more energy due to the increased strain on the machine caused by high feed rates. The machines' rotational speed affects energy consumption because increased rotational speeds usually require more power but can increase efficiency to a certain extent. The interaction of the operational variables of a dehulling process controls its performance characteristics. For example, machine speed controls how the seed and mechanical components interact, feed rate influences throughput capacity, and moisture content influences seed toughness. It is essential, therefore, to comprehend the interactions between these process factors to enhance the general performance and efficiency of energy use. Consequently, estimating the energy demand of a dehulling operation is indispensable to adjust or optimize machine settings or parameters to equilibrate energy requirements and dehulling efficiency (Bangphan *et al.*, 2013). The dehulling process, thus, is more sustainable when there is less energy usage since it results in lower operating expenses. Similarly, sustainable agrifood processing systems benefit from energy-efficient dehulling, especially in areas with potentially scarce energy supplies.

Although a few studies have looked at the impacts of machine speed, feed rate, or moisture content separately (Nwaigbo *et al.*, 2008; Etoamaihe and Ndubueze, 2010; Obi *et al.*, 2018; Umezuruike and Nwabueze, 2021), very few have attempted to combine these factors in a comprehensive optimization strategy. There is currently no precise model to estimate and maximize the energy demand, efficiency of dehulling and seed damage rate of African breadfruit seeds. The objective of this study is to determine the influence of feed rate, moisture content, and machine speed on the energy requirement for dehulling of African breadfruit seeds and associated performance indicators. The study aims to optimize these process factors using response surface methodology (RSM) to reduce energy usage and seed damage rate while increasing throughput capacity and dehulling efficiency. It also intends to establish numerical models to predict the studied response parameters. The outcome of this study is hoped to have wide-ranging effects on the agri-food processing sector and offer a framework for creating effective and environmentally friendly dehulling approaches. This will contribute to sustainable agricultural productivity and economic growth in sub-Saharan Africa by improving breadfruit seed processing and commercialization.

II. METHODOLOGY

The methodology established to execute the aim of this study is described in this section. This includes sample preparation, experimental design, data analysis, and dehulling test. The Box-Behnken Design (BBD) technique of the Design-Expert Statistical tool was adopted in the design of the experimental layout, analyses of data, and generation of 3D response surface plots, as well as the numerical optimization of the energy demand for sample dehulling which was conducted using the principle of desirability function.

A. Preparation of Sample

Samples of African breadfruit (*Treculia Africana*) seeds were procured from a market in Owerri, Imo State, Nigeria. The samples were cleaned to remove debris and defective seeds. A 3 kg batch of viable seed samples was parboiled at a temperature of 70°C for 10 minutes (Omobuwajo *et al.*, 1999). The parboiled samples were drained of water, steamed in an autoclave for 5 minutes and air-dried at a room temperature of 31±0.5°C. Standard procedures outlined in ASAE S352.2 (2003) for ungrounded grains and seeds were used to determine the varying moisture contents. The moisture content was determined as reported by Abodenyi *et al.* (2018) using Eq. (1):

$$m_{(\%wb)} = \frac{x_a - x_b}{x_a - x_c} * 100 \quad (1)$$

Where $m_{(\%wb)}$ is the moisture content (% wet basis), x_a is the mass of moisture can and mass of the sample before oven-drying (kg), x_b is the mass of moisture can and the mass of the sample after oven-drying (kg), x_c is the mass of the empty moisture can (kg).

Eq. (2) was used to calculate the needed quantity of water, M, which was subsequently applied to get the desired moisture content (Davies and Zibokere, 2011; Abodenyi *et al.*, 2018). The samples' moisture contents were altered by three levels of moisture contents: 7.25, 14.8, and 22.35% w.b.

$$x_w = x_s \left(\frac{m_2 - m_1}{100 - m_2} \right) \quad (2)$$

Where x_w , x_s , m_2 , and m_1 represent the mass of added distilled water (kg), the mass of breadfruit seed samples (kg), final (desired) moisture content (% w.b), and initial moisture content (kg), respectively.

B. Design of Experiment and Data Analysis

The Box-Behnken Design (BBD) method of Design-Expert Statistical software (version 11.1) was used to design and analyse the dehulling tests. Three input variables (feed rate, δ ; moisture content, m ; and machine speed, n) each with three levels and four corresponding output variables (energy demand, dehulling efficiency, seed damage rate, and throughput capacity) were taken into account and a total of 17 experimental runs were subjected to factorial statistical randomization (Table 1) to minimize errors in experiments and adverse impacts on the response parameters (Kumar *et al.*, 2011; Uzoma *et al.*, 2020). The 3-factor, 3-level (3³) BBD of the response surface methodology was adopted to estimate the main (linear), interaction, and curvature (quadratic) impacts of the input variables to optimize the energy demand for breadfruit dehulling. In the data analysis, the multiple regression technique was used with the least squares method.

A 2nd-order type polynomial equation (Eq. 3) was used to express the response of the experimental values.

$$\mathcal{R} = C_0 + C_1\delta + C_2m + C_3n + C_{11}\delta^2 + C_{22}m^2 + C_{33}n^2 + C_{12}\delta m + C_{13}\delta n + C_{23}mn \quad (3)$$

Where \mathcal{R} is the response variable; δ , m and n represent the feed rate (kg/h), moisture content (% w.b), and machine speed (rpm), respectively; represents the constant regression coefficient; C_1 , C_2 , C_3 represent the coefficient of linear regression; C_{11} , C_{22} , C_{33} , represent the coefficient of quadratic regression; C_{12} , C_{13} , C_{23} represent the interaction regression coefficients.

Table 1: Experimental layout of input variables and levels.

Input variable	Coded symbol	Variable level	
		Actual	Coded
Feed rate (kg/h)	δ	2	-1
		6	0
		10	1
Moisture content	m	7.25	-1
		14.80	0
		22.35	1
Machine speed	n	8	-1
		15	0
		22	1

The total error criteria were used for the statistical significance test at 95% confidence level. Analysis of variance (ANOVA) was applied to identify statistically significant factors for the energy demand and other response variables. The adequacy of the model was evaluated by determining R^2 , adjusted R^2 , adequate precision, and coefficient of variation. Whereas the validity of the model was assessed using the normal plots of residuals and the plots of predicted and experimental data.

The relative influence of each of the input variables on the output variables was established by the numerical optimization method which centred on the desirability function (\mathcal{F}_d) by lowering the energy demand and seed damage rate and increasing the dehulling efficiency and throughput capacity within the experimental range of the input variables (Giri and Prasad, 2007; Chukwuezie et al., 2020). The total desirability index, \mathcal{F}_d expressed in Eq. (4) (Kumar et al., 2011; Nwakuba, 2019) is a statistical indicator utilized in the optimization studies to measure the overall system performance when multiple responses need to be optimized concurrently. In this context, the desirability index shows how efficiently the output variables (energy demand, dehulling efficiency, seed damage efficiency, and throughput capacity) match their optimal values within the limits of the machine input parameters.

$$\mathcal{F}_d = (R_1 * R_2 * \dots, R_n)^{\frac{1}{n}} \quad (4)$$

Where R_1 and R_2 denote experimental responses; n denotes the total number of response variables. The \mathcal{F}_d -coded values which range from $0 \leq \mathcal{F}_d \leq 1$ suggests the optimal dehulling parameters, which depend on the output variables that boost \mathcal{F}_d . Where 0 represents the undesirable response that is

off the acceptable limit, and 1 indicates the most desirable results or response in the target range.

C. Dehulling Test

The dehulling machine was cleaned of any form of residue or dirt to avoid contamination and congestion of the peeling unit. Basic calibrations or settings were made such as the selection of the preset rotational speed via the use of a tachometer. The no-load energy consumption was measured by running the machine when empty until the machine stabilizes. The one-variable-at-a-time approach was utilized to evaluate the impact of the input variables on the laboratory-scale dehuller's performance (Ozigbo and Murphy, 2016). The examined variables and levels were feed rates (2, 6, and 10 kg/h), moisture content (7.25, 14.8, and 22.35% w.b), and machine speed (8, 15, and 22 rpm). The evaluated performance metrics were energy demand, dehulling efficiency, seed damage rate, and throughput capacity. A selected batch quantity of 3 kg at varying input conditions was fed into the machine (Fig. 1). The kernel and its seed coat were separated in the decorticating chamber with the help of a centrifugal blower. The dehulled seeds (kernels) were exited through the discharge chute. With the use of a power meter connected to the electric motor, the amount of energy utilized was determined by measuring the power drawn by the machine over time for each combination of the input conditions. The efficiency of the dehulling (η_d) process was obtained from Eq. (5). The mass of the dehulled seeds was measured and a ratio of the total mass fed into the hopper was calculated. The weight of the damaged seed (cracked or broken kernels) was measured and recorded. The seed damage rate (ζ_d) was estimated by calculating the ratio of the broken or cracked seeds to the total weight of seeds fed as expressed in Eq. (6). The throughput capacity (Q_c) which reflects the number of processed seeds discharged per time was measured using Eq. (7) (Anosike et al., 2016; Ozigbo and Murphy, 2016; Obi and Akubuo, 2018).

$$\eta_d = \frac{x_h}{x_t} * 100 \quad (5)$$

$$\zeta_d = \frac{x_d}{x_t} * 100 \quad (6)$$

$$Q_c = \frac{x_p}{t} * 3600 \text{ kg h}^{-1} \quad (7)$$

Where x_h , x_t , x_d , x_p , and t represent the weight of hulled seeds (kg), the total weight of input seeds (kg), the weight of damaged seeds (kg), the total weight of seeds dehulled and discharged by the machine (kg), and total dehulling time (sec), respectively.

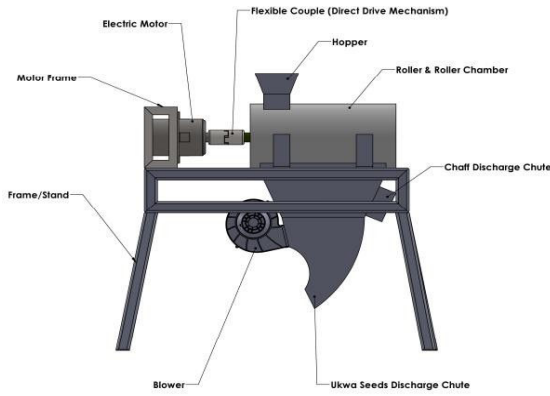


Fig. 1: Isometric view of the laboratory-scale African breadfruit dehulling machine.

II. RESULTS AND DISCUSSION

A. Analysis of Variance (ANOVA) of the Response Variables

Dehulling energy demand, Q_d

Table 2 shows the seventeen (17) experimental runs of the responses for the energy demand and dehulling variables at varying levels of process parameters (feed rate, moisture content, and machine speed). The experimental outcomes yielded a second-degree quadratic function and a linear function was applied to the respective response variables in coded terms.

The quadratic model expresses the energy demand for the dehulling process of African breadfruit seeds at varying δ , m and n levels in Eq. (8).

$$Q_d = 0.8 + 0.3812\delta - 0.0813m + 0.1875n - 0.0250\delta m + 0.0625\delta n - 0.0125mn + 0.0375\delta^2 - 0.0125m^2 + 0.025n^2 \quad [R^2 = 0.9996] \quad (8)$$

Where Q_d represent the dehulling energy demand (kW/h).

The analysis of variance (ANOVA) presented in Table 3 suggests that the quadratic model is statistically significant at $P < 0.05$. The F-value statistically, refers to the variance ratio as described by the model. It is the ratio of the model's mean square (MS) to the error mean square (EMS). This implies that the F-value is a crucial statistical measure employed in the Analysis of Variance (ANOVA) to ascertain if the process parameters significantly influence the response variables in a model.

Table 2: Layout of the Box–Behnken Design (BBD) of the experimental and response variables.

Run	Process Variables			Response Variables			
	Feed Rate (kg/h)	Moisture Content (% w.b)	Speed (rpm)	Energy demand (kW/h)	Dehulling Efficiency (%)	Damage Rate (%)	Throughput Capacity (kg/h)
1	6	14.8	15	0.8	88	10	6.5
2	1	14.8	8	1	78	12	9.6
3	1	22.35	15	1.1	78	13	9.6
4	6	22.35	22	0.9	85	10	5.8
5	6	22.35	8	0.5	78	7	5.3
6	6	14.8	15	0.8	88	10	6.5
7	2	22.35	15	0.4	85	5	1.9
8	2	14.8	22	0.6	93	8	2.2
9	6	7.25	22	1.1	88	15	6
1	2	7.25	15	0.5	90	7	2
1	6	7.25	8	0.7	80	10	5.5
1	1	7.25	15	1.3	80	18	9.8
2	0						
1	6	14.8	15	0.8	88	10	6.5
3							
1	2	14.8	8	0.3	87	4	1.9
4				5			
1	6	14.8	15	0.8	88	10	6.5
5							
1	6	14.8	15	0.8	88	10	6.5
6							
1	1	14.8	22	1.5	85	17	9.82
7	0						

This high F-value and a correspondingly low P-value suggest that the predictors of the model (δ , m , and n) jointly have a substantial impact on the energy demand of the dehulling process. This means that the F-value (1897.73) of the energy model is statistically significant at a 5% level of probability as the model explains a substantial fraction of the variation in the dependent variable in comparison to the unaccounted variation. Conversely, a low F-value is an indication of the inability of the model predictors to account for the variation in the energy use at varying process conditions of the machine. P-values < 0.05 signify that the model terms are statistically significant with a very high coefficient of correlation, R^2 of 0.9996 (Giri and Prasad, 2007; Kumar *et al.*, 2011; Nwakuba, 2019). In this case, δ , m , n , δm , δn , mn , δ^2 , m^2 , and n^2 are significant model terms. Values greater than 0.1 indicate the model terms are not statistically significant. The model, expressed in coded terms, can predict the energy demand of the dehulling process of breadfruit seeds

for given levels of each experimental factor. Typically, the high values of the factors are represented as 1, whereas the low values are denoted as -1. The encoded equation is useful for estimating the relative influence of the variables through the analysis of their coefficients. However, if $P > 0.1$, it indicates that the variable does not significantly influence energy consumption, implying that alterations in that variable may not substantially improve dehulling efficiency, whereas if $p < 0.05$, the variable is statistically significant and exerts a substantial influence on consumption of energy. Since the P-value of the three input parameters is less than 0.0001, it demonstrates the exceptionally high statistical significance of these variables in the response surface model. It further means that these factors have a substantial effect on the energy required for the dehulling process, and this impact is not a result of random coincidence. Therefore, optimizing these parameters is important for reducing the energy demand and enhancing peeling efficiency.

Table 3: ANOVA for the quadratic model of the dehulling energy demand of breadfruit.

Source	Sum of Squares	Df	Mean Square	F-value	P-value	
Model	1.52	9	0.1694	1897.73	< 0.0001	**
δ -Feed Rate	1.16	1	1.16	13023.50	< 0.0001	**
m -Moisture Content	0.0528	1	0.0528	591.50	< 0.0001	**
n -Speed	0.2813	1	0.2813	3150.00	< 0.0001	**
δm	0.0025	1	0.0025	28.00	0.0011	*
δn	0.0156	1	0.0156	175.00	< 0.0001	**
$m n$	0.0006	1	0.0006	7.00	0.0331	
δ^2	0.0059	1	0.0059	66.32	< 0.0001	**
m^2	0.0007	1	0.0007	7.37	0.0300	
n^2	0.0026	1	0.0026	29.47	0.0010	**
Residual	0.0006	7	0.0001			
Lack of Fit	0.0006	3	0.0002			
Pure Error	0.0000	4	0.0000			
Cor. Total	1.53	16				

** signifies highly significant

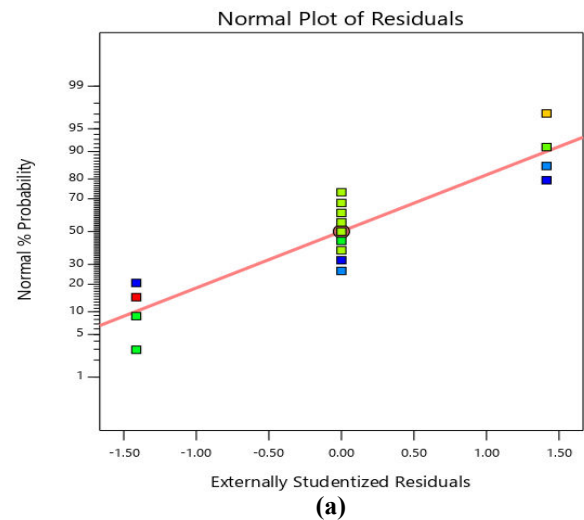
The coefficient of correlation ($R^2 = 0.9996$) symbolizes the percentage of the overall variation in the dependent variable (dehulling energy, Q_d) that can be accounted for by feed rate (δ), moisture content (m), and rotational speed (n). This figure shows that the Q_d -model predicts 99.96% of the variability in dehulling energy usage, with residuals accounting for just 0.04%. The high value of R^2 indicated that the model has an excellent predictive potential within the limit of the experimental/input factors. It also means that the model effectively described the association between energy usage and the process variables (δ, m , and n). This is further corroborated by the low values of the coefficient of variation, C.V (Table 4). Similarly, the robustness, reliability, and high

prediction potential of the energy model are seen in the reasonable agreement between the values of predicted R^2 (0.9535) and the adjusted R^2 (0.9934) with a difference of less than 0.2. Thus, the appropriateness of the model for real-world applications. Adeq. Precision calculates the ratio of signal to noise. A ratio higher than 4 is preferred. The signal strength of 53.469 is sufficient, and the design area can be navigated with the help of this energy model (Kumar et al., 2011).

The desirable high model's R^2 value which is close to unity (1) may potentially give rise to worries about over-fitting, which happens when a model fits a particular dataset too closely, focusing on noise or a small characteristic that doesn't apply to another dataset or a practical situation. This, therefore, resulted in the confirmation of the robustness of the model by cross-validation of the model dataset with plots of normal % probability vs. externally studentized residuals and predicted vs. experimental data (Fig. 2). The closeness of the data points to the straight line shows a strong agreement between the predicted and experimental energy values and also shows that the degree of the outliers in the experimental data has no negative impact on the model (Bangphan et al., 2013; Nwakuba, 2019).

Table 4: Fit statistics of the dehulling energy demand model.

Mean	C.V (%)	Adequate Precision	R^2	Adjusted R^2	Predicted R^2
85.12	0.0440	53.4694	0.9971	0.9934	0.9535



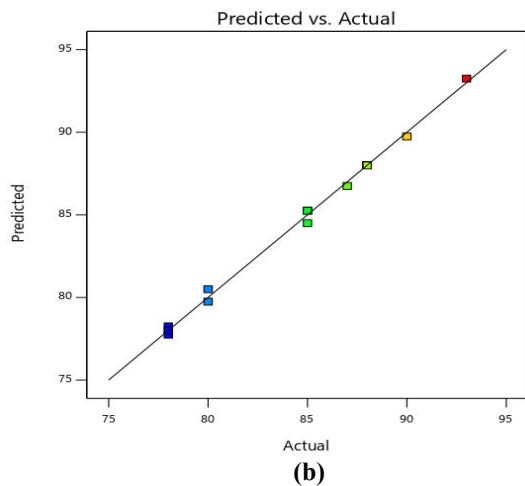


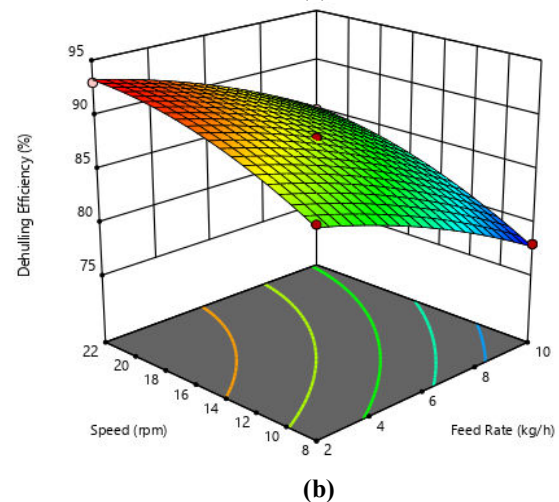
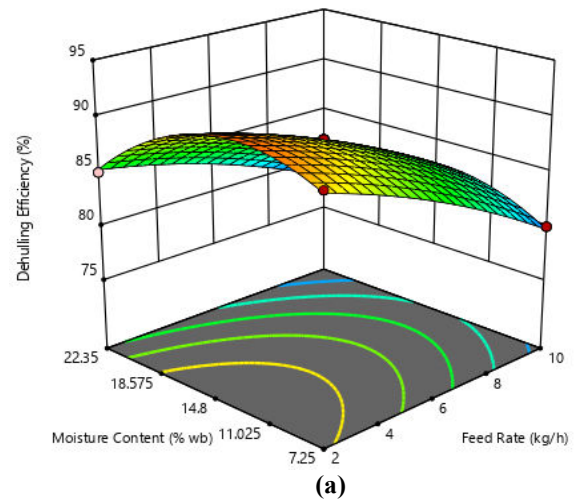
Fig. 2: a) Normal % probability plot of the energy demand; b) plot of predicted vs. actual Q_d .

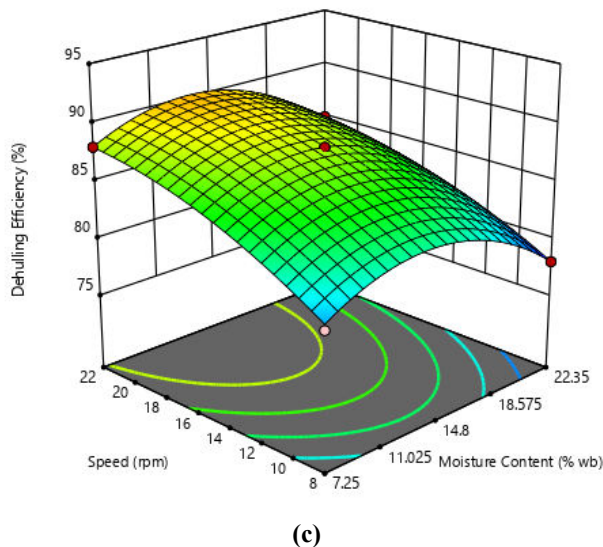
The experimental data was utilized to determine the coefficients of the process factors and their interactions. The relative contribution or significance of the variable coefficients is considered based on their synergistic or antagonistic impact on the energy parameter, *i.e.*, if the variable improves or reduces the prediction of dehulling energy (Nwakuba, 2019). Therefore, the implications of the energy model can be analyzed based on the relative contribution of the linear, interaction, and quadratic coefficients. The constant term (0.8) is the basic energy used when every input factor is at zero or very close to it. For the linear coefficients: (0.3812δ) , $(0.0813m)$, and $(0.1875n)$, the feed rate substantially enhanced the energy usage. As the machine dehulls more sample seeds, a greater feed rate results in a larger energy demand. Feed rate has the greatest positive linear impact, signifying that dehulling more volumes of seed samples consume more energy. Moisture content has the highest negative (detrimental) impact on the dehulling energy demand as higher moisture lessens the friction coefficient which aids the dehulling process. Rotational speed has a positive effect on energy use, as greater rpm increases energy utilization due to high power demand.

The interaction of feed rate and moisture content $(-0.0250\delta m)$ has an antagonistic or reduction impact on the energy demand model when both input parameters are increased, perhaps as a result of moisture's lubricating properties offsetting the rising sample load. Similarly, moisture content and rotational speed $(-0.0125mn)$ have a weak antagonistic impact, marginally lowering energy use when both are increased. Feed rate and speed interaction $(0.0625\delta n)$ have a synergistic impact on energy use. The energy demand for the dehulling machine increases when both the two parameters are increased, probably as a result of increased mechanical effort and sample weight. For the model's quadratic coefficients, feed rate and rotational speed have a curvature negative impact, with dehulling energy demand rising considerably at greater feed rates and machined speeds. Conversely, moisture content has a negative curvature (non-linear) quadratic impact, decreasing energy use at increased amounts of moisture owing to lubrication action.

Dehulling energy demand, Q_d

Dehulling efficiency is a key performance metric for the dehulling process, indicating how successfully the decorticator peeled the seed coats while preserving the kernel. Under varying conditions of feed rate, moisture content, and speed, the efficiency of seed coat removal varied, as shown in Fig. 4. The appropriate amount of moisture makes the seed coat soft and easy to remove. In Fig. 4a to c, highly dried seeds (at decreased moisture content) have brittle coats that can break into tiny pieces, deterring complete removal, and thus lowering the dehulling efficiency. In contrast, excessively soaked seeds (*i.e.*, at increasing moisture content) may possess a sticky seed coat that might stick to the kernel, cause clogging in the decorticating unit, or fail to pop out properly, thus diminishing efficiency. In other words, increasing moisture content level dilutes coat-kernel bonding which enhances adequate peeling. However, excessive hydration might render the seed coat delicate, hence diminishing the peeling efficiency of the machine.





(c)
Fig. 4: 3D plots of dehulling efficiency of a batch of African breadfruit seed at varying: (a) moisture contents and feed rates, (b) machine speeds and feed rates, (c) moisture contents and machine speeds.

A rise in the feed rate reduces the dehulling efficiency as the seeds clog in the dehulling unit increasing internal friction within seeds and friction between dehulling components; reducing dehulling effectiveness, thus lowering η_d . At a reduced feed rate, there is a consistent dehulling operation as well as complete peeling of the seed coat (Fig 4a to b). Therefore, a modest feed rate provides the seed samples with adequate resident time and room in the dehulling chamber to engage with the dehulling mechanisms guaranteeing a complete and effective dehulling operation. These observations were similar to the reports of Omobuwajo *et al.* (1999); Etoamaihe and Ndubueze (2010); and Umezuruike and Nwabueze (2021).

Dehulling efficiency increased proportionally with machine speed (Fig. 4b to c). Elevated rotational speed increases the kinetic energy of the seeds, improves friction effects, and generates greater impact pressures and shear stresses on the seeds, as well as guaranteeing a more seamless seed movement through the dehulling system. These forces facilitate the efficient rupture and removal of the seed coat from the kernel, hence boosting the detachment process and promoting η_d . Nonetheless, there exists an optimal machine rpm beyond which efficiency can remain steady or drop due to kernel rupture or swift ejection of unpeeled seeds. With decreasing machine speed, the mechanical forces, seed-machine interactions and kinetic energy required for efficient seed dehulling reduce. There is insufficient force to disrupt the seed coat-kernel bonding which could lead to ineffective or partial seed dehulling operation. The dehulling efficiency was obtained in the $78 \leq \eta_d \leq 93\%$ range. The prediction equation describing the dehulling efficiency of breadfruit (in coded terms) is expressed in Eq. (9) with a high prediction coefficient of 0.9971. This is useful for identifying the relative impact of the factors by comparing their coefficients. It can be applied to determine the optimal ratio of the process parameters (δ , m , and n).

$$\eta_d = 88 - 4.25\delta - 1.5m + 3.5n + 0.75\delta m + 0.25\delta n - 0.25mn - 0.875\delta^2 - 3.88m^2 - 1.37n^2 \quad [R^2 = 0.9971] \quad (9)$$

Insights from Eq. (9) reveal that the constant value/term, 88 shows the highest possible theoretical efficiency achievable under ideal settings (when the remaining variables either have negligible contributions or negate each other). The negative coefficient in the 2nd term (-4.25) implies that increasing the feed rate would result in a reduction in dehulling efficiency, possibly as a result of overloading and less seed-machine interaction. Similarly, moisture content had an antagonistic effect on dehulling efficiency, given its negative coefficient. Increasing the machine speed (3.5) would have an increasing impact on dehulling, perhaps as a result of improved kinetic energy transmission for efficient/effective seed coat removal. There are slight interaction effects of feed rate and moisture content (0.75) and moisture content and speed (0.25), whereas a slight antagonistic effect is suggested by the interaction effect of moisture content and speed (-0.25). Similarly, the quadratic terms suggested an antagonistic effect on the dehulling efficiency at extreme levels of δ , m , and n as issues such as clogging, sticking, and kernel damage may ensue (Nwakuba, 2019). Knowledge of these parameter associations aids in minimizing wasteful utilization of energy and enhancing resource efficiency in dehulling processes.

Seed damage rate, ζ_d

The percentage of seed samples whose kernels break, shatter or become severely fractured during dehulling operation at varying process conditions is shown in Fig. 5. Moisture content and feed rate had a substantial impact on the percentage of seed damage through their seed-dehulling components interaction effect. Reduction in moisture content causes the product kernel to progressively grow brittle and tough increasing the possibility to shatter or crack when impacted mechanically during seed coat removal (Fig. 5a to c). Additionally, the seed coat may become fragile, which results in pieces of the coat sticking to the kernel and causing greater damage. Increasing the moisture content softens the seed coat and becomes malleable providing some dampening effect during impact. Within the range of the studied moisture levels, the seed coat and kernel uphold an equilibrium between firmness and suppleness. This minimizes ζ_d while enabling efficient removal of the seed coat.

There is a proportional increase in feed rate with seed damage rate. At a reduced feed rate and moderate speed range, fewer seed samples are present in the dehulling chamber and each seed is subjected to an optimum impact force, thus reducing the damage rate (Fig 5a to b). An elevated feed rate causes the dehulling unit to fill up too quickly, increasing the likelihood of seeds colliding with one another or the dehulling units. This enhances the possibility of fracturing or seed damage. The rotational speed of the machine has a considerable effect on ζ_d by varying the forces applied to the dehulled seeds. Speed varies proportionally with seed damage rate. Reducing the rotational speed lessens the contact pressures and shear strains on the seeds. This reduces the

possibility of kernel structural damage. Reduced speeds, on the other hand, can lead to partial dehulling or extended friction on the seeds, which could result in slight seed damage to the seed surface but typically maintain a low seed damage rate. At increased speed, the seeds encounter a high force of impact and collide with each other and adjacent machine parts, thus boosting the chances of seed damage. Similarly, excessive removal of the seed coat could expose the kernel to more mechanical stress and raise the chances of seed injury. The seed damage rate was obtained in the range of $4 \leq \zeta_d \leq 18\%$. Research on mechanical decortication of African breadfruit, peanuts, and soybean seeds demonstrates that greater machine speeds result in more damage to seeds because of increased impact forces (Umezuruike and Nwabueze, 2021; Gustavo *et al.*, 2021; Lioa *et al.*, 2024). Impact hulling research reveals that seeds encounter numerous impacts with machine parts at high rotational speeds, increasing the chances of seed breakage. The current study's findings support this association since higher speeds increase collisions among seeds and between seeds and machine components, which causes greater breakage. The damage rate range of 4–18% indicates that extreme speeds cause unacceptably high kernel breakage, even though moderate rates would be optimal.

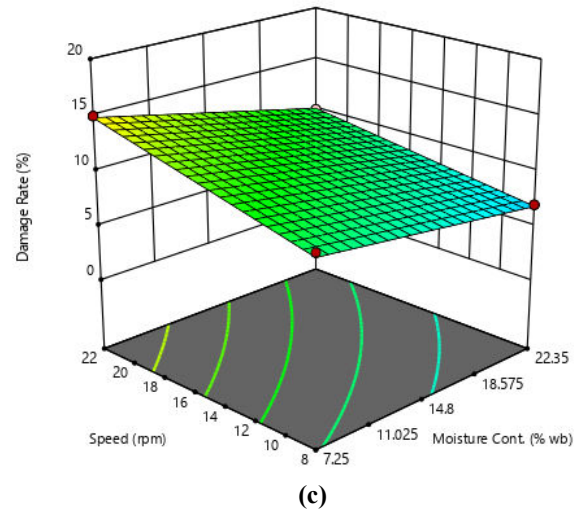
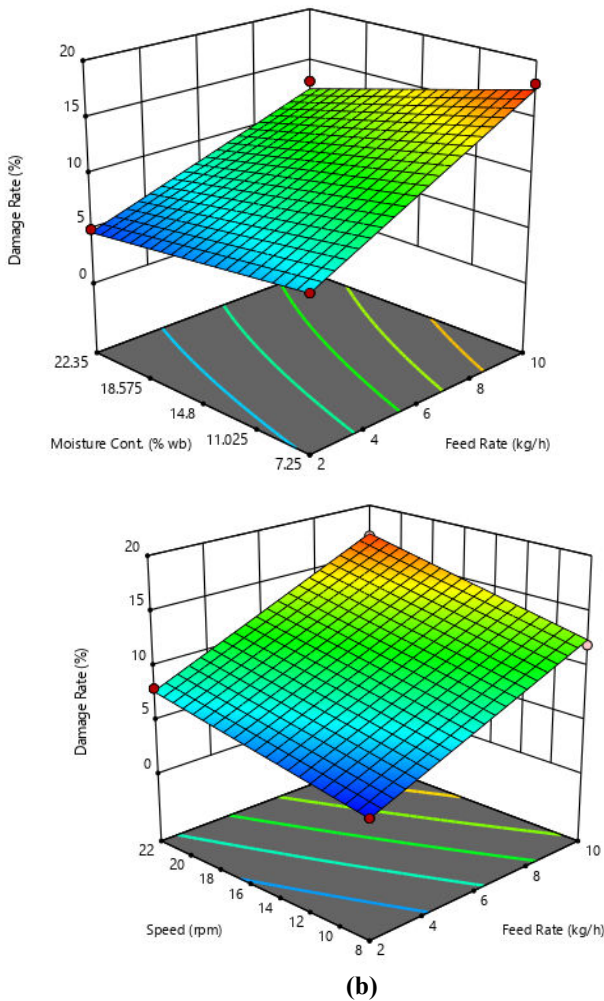


Fig. 5: 3D plots of seed damage rate of a batch of African breadfruit seed at varying: (a) moisture contents and feed rates, (b) machine speeds and feed rates, (c) moisture contents and machine speeds.

Eq. (10) shows the seed damage rate prediction model with $R^2 = 0.9908$ which explains its high level of reliability and how process parameters affect the possibility of seed damage during dehulling operation.

$$\zeta_d = 10.35 + 4.5\delta - 1.87 + 2.13n - 0.75\delta m + m0.25\delta n - 0.5mn \quad [R^2 = 0.9908] \quad (10)$$

The constant term, 10.35 signifies the starting point of seed damage rate when the input factors are at their lowest values or zero point. It suggests that even in controlled settings, some underlying damage happens. The synergistic and antagonistic impacts on seed damage rate can be seen in the linear and interaction variable coefficients. Eq. (10) indicates that seed damage rate can be reduced by increasing the moisture content ($-1.87m$) as higher moisture levels soften the seed coat and reduce the chances of breaking. Similarly, the interaction effects of high feed rate and high moisture content ($-0.75\delta m$) and high moisture content and high machine speed ($-0.5mn$) had a minor reduction in seed damage. In the former, moisture content softens the seed coat and neutralizes the impact of high feed rates. Whereas the latter implies that the seeds have the potential to be softened but might be more resilient to impact actions.

Throughput capacity, Q_c

The quantity of seed samples (kg/h) the dehulling machine can effectively process as affected by varying moisture contents and feed rates are shown in Fig. 6a to c. The amount of moisture in the seed samples affects their physical characteristics, including flowability, firmness of the kernel, and suppleness of the seed coat, all of which have an impact on the seed movement within the dehuller. The seeds and seed coats exhibit diminished stickiness at reduced moisture levels, facilitating their unobstructed passage through the dehulling chamber. This mitigates clogging or obstructions in the system, providing a seamless and uninterrupted seed flow,

thereby enhancing the throughput capacity, Q_c . It is pertinent to state that extremely low moisture levels can degrade product quality and result in inefficient operations. Conversely, increasing the moisture levels diminishes Q_c by rendering seeds sticky and lumpy, impairing their flowability, and hindering the dehulling efficiency. This leads to a reduction in seed processing speed, high friction, and recurrent blockage, which generally reduces the system's efficiency (Davies and Zibokere, 2011; Gustavo et al., 2021).

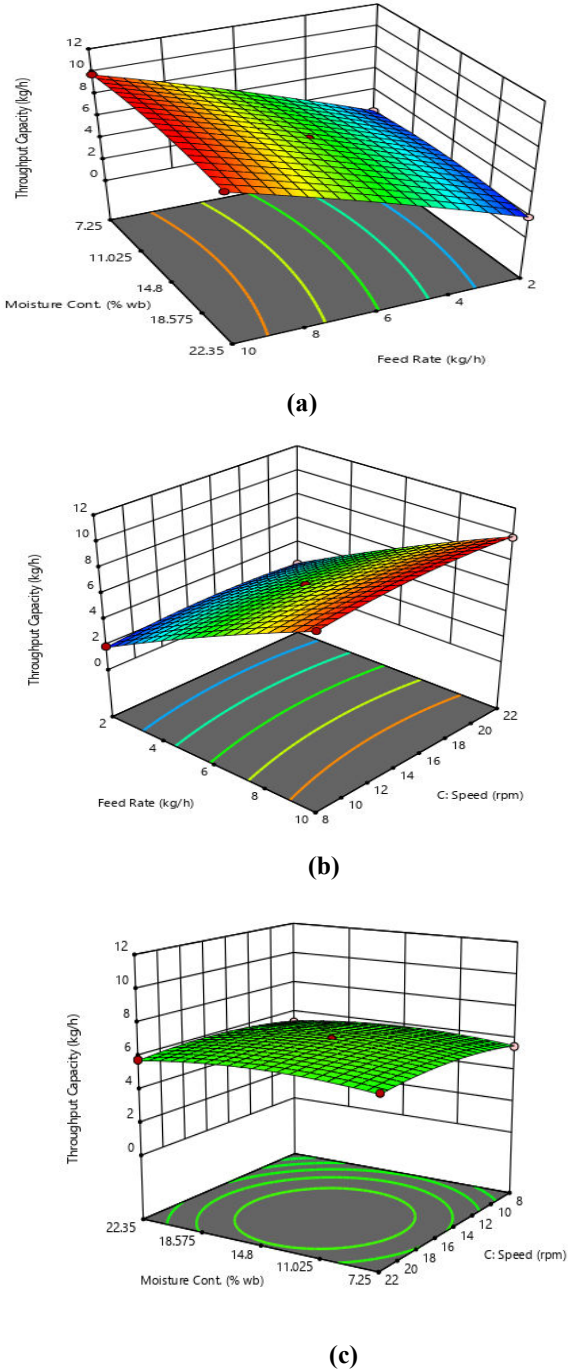


Fig. 6: Response surface plots of throughput capacity of a batch of African breadfruit seed at varying: (a) moisture contents and

feed rates, (b) machine speeds and feed rates, (c) moisture contents and machine speeds.

Increasing the feed rate enhances the systems Q_c by introducing a greater quantity of seeds into the hopper and dehulling chamber during a specified duration, hence immediately boosting the quantity of seeds dehulled or the machine's output (Fig. 6a to b). When the machine is operated at rated/designed speed and elevated feed rates, its capabilities are fully utilized as its efficiency and throughput capacity are enhanced. Since machine speed regulates the dehulling rate, it has an impact on throughput capacity. By speeding up product movement and processing, higher speeds typically boost throughput (Fig. 6b to c); nevertheless, very high speeds might result in inefficient processes, seed damage, or wear and tear on the machine. However, at decreasing rotational speed of the machine, the dehulling process is slowed down resulting in reduced Q_c due to reduced impact of mechanical forces on the seed products. The trough put capacity of the dehulling machine was found to be within the limit of $1.9 \leq Q_c \leq 9.82$ kg/h.

The prediction equation (in coded terms) for the throughput capacity is given in Eq. (11):

$$Q_c = 6.5 + 3.85\delta - 0.0875m + 0.19n - 0.025\delta m - 0.02\delta n - 0.223\delta^2 - 0.453m^2 - 0.398n^2$$

$$[R^2 = 0.8947] \quad (11)$$

The high coefficient of correlation, $R^2 = 0.8947$ indicates that the model can account for 89.47% of the changes in the throughput capacity depending on the input parameters (δ , m , and n). Thus, high prediction reliability in the specified operational settings. The positive coefficients indicate the synergistic impact of feed rate and machine speed on throughput capacity. The linear, interaction, and quadratic negative coefficients suggest diminishing returns on Q_c at increased input parameters (Nwakuba, 2019).

B. Dehulling Optimization

The principle of total desirability function, \mathcal{F}_d (Eq. 4) of the Design Expert version 11.1.0.1 statistical software was applied to establish the optimal dehulling conditions of African breadfruit seeds. The desirability function or desired goal for the numerical response surface optimization is to minimize the energy demand (Q_d) and seed damage rate (ζ_d) while maximizing dehulling efficiency (η_d) and throughput capacity (Q_c). Fig. 7a and Fig 7b shows the desirability function values for each response variable and the overall optimization with an \mathcal{F}_d - value of 0.62. The desirability values for each of the input variables (feed rate, moisture, and machine speed) are equal to 1 as their targeted outcomes/objectives are fixed 'in-range'.

This practically shows that the input/operational parameters have been tuned to the optimal state for the machine's maximum performance. It further implies that, within the limit of the experimental factors, the machine's performance satisfies the desired targets for economy, efficiency, and quality. The response/output parameters (energy demand, Q_d ; dehulling efficiency, η_d ; seed damage rate, ζ_d ; and throughput capacity, Q_c) have their

corresponding values of \mathcal{F}_d which are 0.729, 0.727, 0.671, and 0.414, respectively.

Table 5 presents the values predicted response parameters (0.661 kW/h, 88.907%, 8.6%, and 5.178%) with optimal input parameters of 4.678 kg/h feed rate, 15.38% w.b moisture content, and 14.51 rpm machine speed and a 0.95 level of confidence. To confirm that the predicted values were accurate, dehulling experiments were conducted (three times) under optimum dehulling settings, despite the degree to which the predicted values fitted the minimum energy demand (Q_d) and seed damage rate (ζ_d) and the maximum fitting dehulling efficiency (η_d) and throughput capacity (Q_c), and their mean

values computed as shown in Table 5. Therefore, it is evident that the predicted and observed values for the response parameters differ by $< 5\%$ (0.05); hence, the process variables are accurately described and validated (Bangphan *et al.*, 2013; Uzoma *et al.*, 2020). Three varying colour groups — red, green, and blue—often called design points were used to represent the response variables' level of desirability on the 3D plot. Red, green, and blue stand for maximum, average and, minimum levels of the process variables, respectively. Using the 3-dimensional response surface desirability plot of the combined feed rate, moisture content, and machine speed parameters, Fig. 7 illustrates the optimum dehulling conditions for African breadfruit seeds.

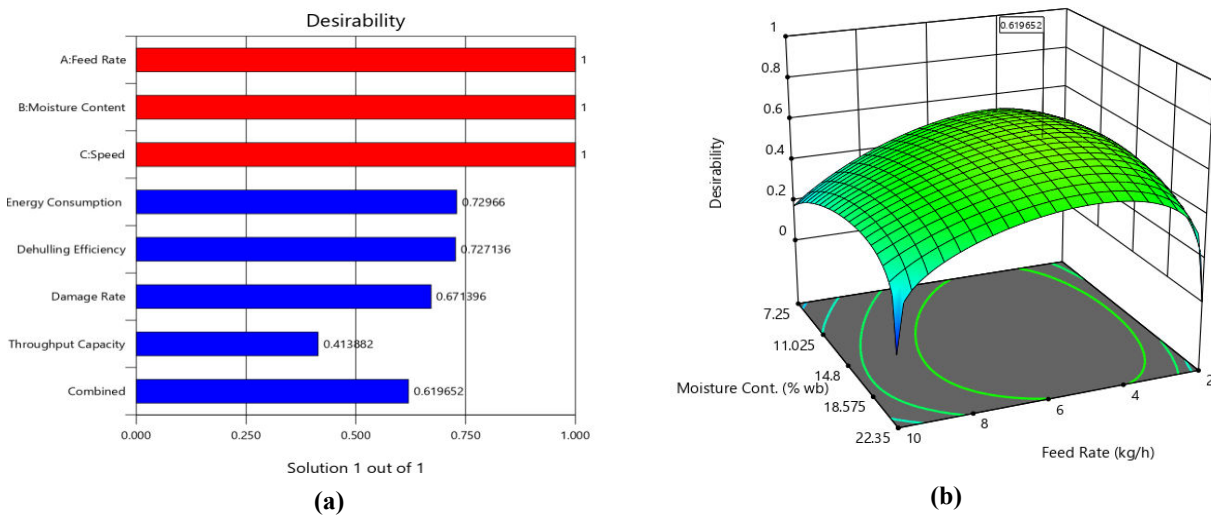


Fig. 7: (a) Optimized desirability values of process/input, response/output, and combined parameters; (b) Response surface desirability plot of the input parameters.

Table 5: Spectrum of desirability for optimum dehulling of African breadfruit seed.

Source	Input/process parameter			Output/response parameter				\mathcal{F}_d
	δ (kg/h)	m (% w.b)	n (rpm)	Q_d (kW/h)	η_d (%)	ζ_d (%)	Q_c (kg/h)	
Simulated values	4.678	15.380	14.510	0.729	72.70	0.671	0.414	0.620
Experimental values				0.761	75.4	0.702	0.439	
Error (%)				4.21	3.58	4.42	3.94	

IV. CONCLUSION

The energy needs for dehulling African breadfruit (*Treculia Africana*) seeds using response surface methodology were investigated in this work in relation to the feed rate, moisture content, and machine speed at varying levels. The findings showed that feed rates and machine speeds are the

most indispensable variables influencing energy demand with notable linear and quadratic effects, whereas, moisture content dramatically lowers energy use at higher levels. The energy demand for dehulling of African breadfruit seeds at varying studied process parameters is $0.35 \leq Q_d \leq 1.5$ kW/h range. Energy demand is reduced by feed rate-moisture and moisture-speed interactions, but increased by feed rate-speed interactions. There are clear antagonistic and synergistic impacts as energy demand is increased by feed

rate-speed interactions and decreased by feed rate-moisture content and moisture content-speed interactions. At varying process factors, the dehulling efficiency, seed damage rate, and throughput capacity were obtained in the ranges of $78 \leq \eta_d \leq 93\%$, $4 \leq \zeta_d \leq 18\%$, and $1.9 \leq Q_c \leq 9.82 \text{ kg/h}$.

Three-dimensional response surface graphs were developed to show the interactions between the process variables and the experimental results. With an optimal energy demand of 0.73 kW/h, a dehulling efficiency of 72.7%, a seed damage rate of 0.67%, and a throughput capacity of 0.41 kg/h, the desirability index (0.62) showed a 95% confidence level within the range of the optimal process parameters of 4.68 kg/h, 15.38% w.b, and 14.51 rpm. With an R^2 value of 0.9996, the proposed energy model demonstrated exceptional prediction accuracy. The optimized dehulling conditions established an equilibrium between energy economy, dehulling performance, and kernel quality and throughput capacity.

The findings of this study provide a basis for developing energy-efficient dehulling equipment for African breadfruit seeds, which would add to sustainable food processing techniques. Potential avenues for further research include integrating electronic control systems to automatically modify operational parameters for increased performance efficiency and lower energy demand. Furthermore, examining how these factors affect machine longevity, upkeep needs, and the nutritional value of African breadfruit seeds might yield insightful information for industrial uses. A cost-benefit analysis of the optimized dehulling process would enhance the practical applicability of the findings for manufacturers and farmers. Benchmarking the designed dehuller against alternative dehulling techniques would provide deeper insights into its advantages and limitations. The results, therefore, contribute to sustainable agricultural processing by promoting energy-efficient machinery.

AUTHOR CONTRIBUTIONS

N. R. Nwakuba: Conceptualization, Writing – original draft, & Validation; **V.C. Okafor:** Methodology, Writing – review & editing, Supervision; **E.C. Abba:** Writing – original draft, Validation & Writing – review & editing; **A.N. Ofoma:** Supervision, Methodology, & Writing – review & editing; **A.U. Onuruka:** Methodology, Supervision, & Writing – review & editing.

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