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Characterization Of Performance Effects of Operational Conditions on Cowpea Dehulling Machine

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Abstract:
Cowpea is an essential leguminous crop that significantly contributes to the diet and economy of many regions. Actions have been undertaken to enhance the dehulling process to minimize loss, maximize efficiency, and improve product quality. This study focused on a black-eyed variety of cowpeas (*Vigna unguiculata)* to evaluate the effects of various operational conditions, including moisture content, dehulling time, and soaking time, on dehulling efficiency, percentages of un-dehulled and broken. Response Surface Methodology (RSM) was employed, utilizing a 3^2 factorial i-optimal randomized design and analysis of variance (ANOVA) at a 5% significance level, using Design Expert software. A sample weight of 4.08 kg was tested in triplicates, with moisture levels set at 8.3%, 10.32%, and 12.07% (wet basis). The samples were fed into the machine after different soaking durations of 5, 7.5, and 10 minutes for each replicate. The optimization process aimed to achieve optimum dehulling efficiency with reduced percentages of un-dehulled and broken. The optimal conditions were predicted to be a moisture content of 12.07% (wet basis), a dehulling time of 7.6 minutes, and a soaking time of 9.9 minutes, resulting in a dehulling efficiency, percentages of un-dehulled and broken seeds of 87.3%, 5.9% and 6.8% respectively.

Keywords: Cowpea, Dehulling efficiency, un-dehulled, broken, Optimization, Response surface methodology

I. INTRODUCTION

Cowpea (*Vigna unguiculata*), is a leguminous crop commonly referred to as 'beans' in Nigeria. It plays a critical role in the dieting and economy of many regions, particularly in sub-Saharan Africa and Asia [1]. It is an important source of carbohydrates, vitamins, protein, and minerals for lots of people, particularly in areas where animal protein is insufficient or expensive [2]. In Nigeria as well as most West African countries, cowpea seeds are consumed in various forms, including whole seeds, flour, and processed foods [3]. Despite its widespread acceptance as a main food for many Nigerian households, the dehulling process remains a challenge and requires attention [4]. The seed coat, or **hulls**, requires removal (i.e., **dehulling)** to improve the nutritional quality, cooking time, and taste of cowpea-based products.

In Nigeria, cowpeas are still often dehulled by hand, which entails soaking them in water for a predefined time (e.g., 2 to 10 minutes), draining and rubbing them between the palms, or pounding them with a wooden pestle and mortar by food vendors [5]. This method is characterized by **high labour intensity, low efficiency**, and **seed damage** during dehulling [6]By evaluating the **cowpea dehulling process**, researchers aim to optimize dehulling machines and techniques, focusing on factors such as **moisture content, soaking time, dehulling time,** and **mechanical efficiency** to reduce losses and improve the overall quality of dehulled cowpea products. Grain conditioning before dehulling is often performed to break the bonding between the hulls and the cotyledon. Meanwhile, Response Surface Methodology (RSM) has been continuously employed for evaluating and optimization of post-harvest processes such as the dehulling of some agricultural products [7-10] respectively. RSM is a statistical analytics tool used in modelling and optimizing systems with more than two variables, to investigate the interactions between variables on selected responses [11].

Numerous initiatives have been undertaken to enhance the dehulling process to ensure **minimal loss**, **maximum efficiency,** and **improved product quality**. A hydro-separating cowpea dehulling system that incorporated a water tank into the machine to eliminate soaking before dehulling was designed and evaluated by [12]; the machine's capacity, when tested was 18 kg/hr. Ehiem et al. [13] explored the optimal performance of dehulling equipment for African oil bean seeds (AOBS). They found that the maximum throughput of 41.09 kg/hr was achieved at a speed of 700 rpm with a boiling duration of one hour, whereas the minimum throughput recorded was 14.05 kg/hr at 331 rpm. The study used first and second-order response surface models to establish parameter correlations and determine the best conditions for minimizing expenses and increasing output. Ogunnigbo et al. [1] explored how soaking duration, running time, and operating speed affect the performance of a modified flour mixer developed for the wet dehulling of beans. Their findings revealed that these factors significantly influenced the machine's operational efficiency. Remarkably, the study achieved a peak dehulling efficiency of 84.83%, with seed breakage rates of 22.93% for brown beans and 19.66% for black-eyed peas. Kamaldeen et al. [2] assessed a cowpea de-hulling machine using a factorial experiment that examined various speeds, soaking durations, and cowpea varieties. Their findings revealed that speed, soaking time, and cowpea type significantly influenced de-hulling efficiency and output capacity, while only soaking duration and speed were associated with mechanical damage. The ideal de-hulling conditions were determined as a speed of 120 rpm, an 11-minute soaking time, and the Dan-barre variety. Under these optimal conditions, the machine attained a de-hulling efficiency of 90.75%, an output capacity of 74.27 kg/hr, and mechanical damage of just 0.39%.

Olotu et al. [5] evaluated a modified cowpea dehuller using two cowpea varieties, IAR 48 and IAR60/62, by varying machine speed (150-350 rpm) and soaking time (2-10 mins) to assess their effect on dehulling efficiency, cleaning efficiency, feed rate, and output capacity. The study found that both soaking time and machine speed significantly impacted performance. Optimal dehulling efficiency was achieved at 150 rpm with 6 minutes of soaking for both varieties. As machine speed increased to 350 rpm, cleaning efficiency (around 73%) as well as feed rate and output capacity improved, with IAR60/62 showing higher values in these parameters. Lastly, in a study by Egbe and Roland [4], a wet legume dehulling machine was developed to de-hull cowpea and soya beans soaked for 6-30 minutes using shear and friction. However, this method was time and energy-consuming and resulted in dehulled beans unsuitable for long-term storage. It also adversely impacted the nutritional and taste quality of the soaked cowpeas and led to environmental pollution from wastewater.

1.1 STUDY CONTRIBUTION AND NOVELTY

To overcome the gaps inherent in [4], an improved cowpea dehuller that operates on the principle of "abrasion"; which is the rubbing effect of the dehulling drum on the bean grain against the walls of the dehulling chamber is developed and evaluated using RSM. The developed machine is novel as it addresses the former's excessive water usage, environmental sustainability and machine efficiency. Secondly, the machine's dual optimization for manual and electrical operation allows food vendors in areas with inconsistent power supply to maintain high productivity. This flexibility reduces downtime and increases the volume of processed cowpeas, particularly in rural areas with limited access to electricity.

II. MATERIALS AND METHODS

A. Design Consideration

In designing the dehulling machine some important factors like; Mechanical properties of the construction material, cost, ease of construction and dismantling, availability, strength and durability, safety, and the effect of the material used on the food material were considered [14]. Other engineering properties of black-eyed bean cowpea seed as stated by Appiah et al. [15] were also considered in designing the dehulling machine. These included the axial dimensions of the black-eyed bean (length 6.50-7.25 mm, breadth 4.74-5.00 mm, thickness 3.75-4.00 mm). Saima et al [16], have reported the bulk density of black-eye cowpeas (800 kg/m^3).

B. Design computation

- ***Hopper design***

The design of the hopper allows for the convenient flow of the soaked cowpea grains into the machine's dehulling unit. The hopper volume was computed using Eq. 1 [17].

$$\text{Hopper Volume } (H_v) = \frac{\text{M}}{\rho} \qquad (1)$$

where: M = mass of soaked cowpea grains fed into the hopper in (kg) = 4kg

ρ = the mean bulk density of soaked cowpea grains, (kg/m^3) = 800 kg/m^3

$$H_v = \frac{4 \text{ kg}}{800 \text{ kg/m}^3} = 0.005\text{m}^3$$

The hopper dimension as shown in Figure 1 is 301 × 301 × 185mm (0.016m^3).

- ***Power Requirement Design***

The power required for driving the dehulling drum, P_D is the total force needed to rotate the dehulling drum [18].

$$P_D = \tau_t \omega \qquad (2)$$

$$\tau_t = F_{td} \times r_d \qquad (3)$$

Where

τ_t is the toque developed in the dehulling unit

F_{td} total weight of the dehulling drum

r_d radius of the drum in the dehulling unit.

$F_{td} = 88.29N$,

$r_d = 0.1055$ m

$\therefore \tau_t$ = 88.29N × 0.1055m = 9.31Nm

Hence, the power required for dehulling is

$$P_D = \tau_t \omega = \frac{2\pi N\tau}{60} \qquad (4)$$

$$= \frac{2\pi \times 1430 \times 9.31}{60} = 1.394 \text{ kW}$$

τ_t is the torque (Nm), ω is the angular speed, of the soaked black-eyed cowpea seeds, and the dehulling shaft without key way was estimated to be 55 × 10^6 N/m^2 [19]. N is the speed of the motor and dehulling shaft speeds are 1,400 and 565 rpm, respectively. However, a 2 kW (kilowatt) electric motor which exceed the calculated power requirement (1.394 kW) was used to power the machine. This is done to ensure sufficient torque to overcome the initial resistance posed by the soaked seeds.

- ***Determination of Shaft Speed***

The shaft speed was determined as given by [20]:

$$\frac{D_m}{D_d} = \frac{N_d}{N_m} \qquad (5)$$

$$N_d = N_m \times \frac{D_m}{D_d} \qquad (6)$$

Substituting values into eqn. (6) we have:

$$N_d = 1400 \times \frac{17.80}{33.50} = 743.88 \text{ rpm}$$

where N_m = revolution of the motor pulley, rpm;
N_d = revolution of the dehuller shaft pulley, rpm;
D_m = diameter of the motor pulley, mm;
D_d = diameter of the dehuller pulley, mm.

- ***Determination of the diameter of the shaft***

The diameter of the shaft is important in designing and determining the machine's power requirement. This is determined, as reported by [21].

$$\sin \alpha = \frac{d_2 - d_1}{2c} \qquad (7)$$

where d_2 = Diameter of the driven pulley = 0.335 m, d_1 = Diameter of the driving pulley = 0.178 m, c = Centre distance between the driving and driven pulleys 0.41m (approximately)

$$\alpha = sin^{-1}\frac{d_2 - d_1}{2c} \qquad (8)$$

$$\alpha = sin^{-1}\frac{0.335 - 0.178}{2 \times 0.41}$$

$$\alpha = sin^{-1}(0.1915) \approx 11.04^0$$

The angle of contact between the belt and the driven pulley is given as:

$$\theta = (180 - 2\alpha)\frac{\pi}{180} \qquad (9)$$

θ = [180 – 2(11.04^0)] $\frac{\pi}{180}$ = 157.92 × 0.0174533 = 2.755rad

Taking the coefficient of friction as 0.3 for rubber on cast iron or steel [22], the tension between the tight side (t_1) and the slack side (t_2) of the belt is given as;

$$\frac{t_1}{t_2} = e^{\mu\theta} \qquad (10)$$

$$\frac{t_1}{t_2} = e^{0.3 \times 2.755}$$

$$e^{0.8265} = 2.283$$

The ratio of the tension between the tight side (t_1) and slack side (t_2) of the belt is:

$$\frac{t_1}{t_2} \approx 2.283$$

$$t_1 = 2.283t_2$$

But; $(t_1 - t_2)r_p = \tau_t$

$$r_p = \frac{0.3350}{2} = 0.1675 \text{ m}$$

$$\tau_t = 9.31\text{Nm}$$

$$t_1 - t_2 = \frac{9.31}{0.1675} = 55.58\text{N}$$

By substitution

$$2.29t_2 - t_2 = 55.58$$

$$1.21t_2 = 55.58$$

$$t_2 = \frac{55.58}{1.21} = 45.93\text{N}$$

Therefore, t_1 = 2.29t_2

$$= 2.29 \times 45.93 = 105.2 \text{ N}$$

- ***Determination of Belt Length***

The length of the belt for the dehuller was calculated as given by [20]:

$$L = 2C + \frac{\pi}{2}(D_m + D_d) + \frac{(D_m + D_d)^2}{4C} \qquad (11)$$

$$L = 2(405) + \frac{\pi}{2}(17.80 + 33.50) + \frac{(17.80 + 33.50)^2}{4(405)}$$

$$= 890.63 \text{ mm}$$

where L = length of belt for the dehuller pulley, mm; C = minimum centre-to-centre distance, mm.

- ***Design of the dehulling unit clearance***

The design of the dehulling unit clearance is one of the most important aspects in the design of a dehulling machine and this was determined as reported by [22]. This was calculated using eqn. (12)

$$\text{Dehulling Unit Clearance} = \frac{a+b}{2} \qquad (12)$$

$$\frac{7.145 + 6.87}{2} = 7.006 \text{ mm}$$

where a = The major diameter of the seed (mm) b = The minor diameter of the seed (mm)

- ***Shear Stress Requirement (τ)***

The seed dimension was determined according to the description of [23]. Thus, ninety (90) black-eyed cowpea seeds were randomly selected and their axial dimensions of average length (L), width (W), and thickness (T) were measured using a Vanier calliper with a calibration of 0.01 mm. These size means were used to determine the geometric mean diameter (D_g) and the surface area (S_A) in mm^2 using eqn. (13) and (14) as reported by [24].

$$D_g = \sqrt[3]{LWT} \qquad (13)$$

$$D_g = \sqrt[3]{9.17 \times 6.45 \times 6.09}$$

$$D_g = \sqrt[3]{359.55}$$

$$D_g \approx 7.12\text{mm}$$

$$S_A = \pi {D_g}^2 \qquad (14)$$

$$S_A = \pi(7.12)^2 = 159.3\text{mm}^2$$

But **shear stress** (τ) is:

$$\tau = \frac{\text{F}}{S_A} \qquad (15)$$

According to Davies and Zibokere [25], the shearing force of wet beans is related to the moisture content (M_c) based on the following relation:

$$\text{F} = -1.54M_c + 91.9 \qquad (16)$$

$$F_{Mc\ 8.30\%} = -1.54(8.30) + 91.9 = 79.12\text{N}$$

$$F_{Mc\ 10.32\%} = -1.54(10.32) + 91.9 = 76.01\text{N}$$

$$F_{Mc\ 12.07\%} = -1.54(12.07) + 91.9 = 73.31\text{N}$$

where **1.54** = the **slope** of the regression line, indicating that for each 1% increase in moisture content, the shear force decreases by 1.54 N; and **91.9** is the **intercept**, representing the shear force (N) at very low or zero moisture content, where the seeds are dried and require the highest force to dehull [25]. Hence, the mean force (F) required to shear the wet beans is estimated as follows:

$$\mathrm{F} = \frac{F_{Mc=8.30\%} + F_{Mc=10.32\%} + F_{Mc=12.07\%}}{3}$$

$$= \frac{79.12 + 76.01 + 73.31}{3} = 76.14\mathrm{N}$$

Substituting values into eqn. (15), we have:

$$\tau = \frac{76.14}{159.3} = 0.478 \text{ MPa} = 4.78 \times 105 \text{ N}/m^2$$

Other design specifications of the dehulling machine are presented in Table 1.

Table 1. Machine specifications of the developed Cowpea dehulling machine.

No.	Design element	Value	Unit
1	Electric motor speed	1,400	rpm
2	Dehulling shaft speed	565	rpm
3	Weight of dehulling drum	88.29	N
4	Dehulling shaft length	625	mm
5	Shaft bending fatigue factor (k_b)	1.5	
6	Torsional fatigue factor (k_t)	1.0	
7	The angle of the pulley groove	26.57	^{0}
8	The centre-to-centre distance of the pulley	405	mm
9	Coefficient of friction (μ)	0.3	
10	Number of pulley grooves required	1	mm
11	Hopper unit plate thickness	2	mm
12	Concentric cylinder plate thickness	4	mm
13	Torque transmitted to the dehulling drum.	9.31	Nm
14	Bulk density of black cowpeas [16]	800	Kg/m

C. Machine description

As illustrated in Figures 1, 2, and 3, the hopper unit was constructed using a 2 mm stainless steel plate, precisely cut and welded to form a pyramidal frustum with dimensions of 301 × 301 × 185 mm. This hopper was positioned directly atop the feeding chute at the dehuller's centre point. The concentric cylinder surrounding the dehulling mechanism was constructed from 4 mm stainless steel. The intake shaft consists of a rectangular auger wound across 140 mm of its 565 mm length, extending to the very end. The dehulling drum features a belt-like material enveloping its 360 mm length and 211 mm diameter. Dehulled seeds are collected tangentially through a rectangular seed outlet measuring 335.5 × 180 mm, constructed from a 2 mm stainless steel plate. The frame supporting each component was built with angle iron bars measuring 744 mm × 332.6 mm × 251.4 mm.

Figure 1. Orthographic and Isometric view of the designed cowpea bean seed dehuller.

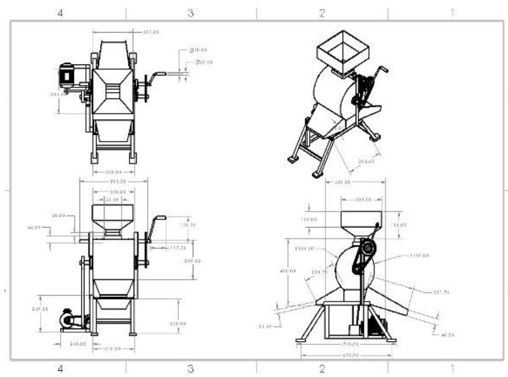
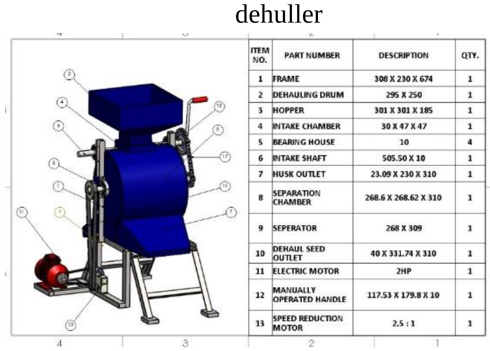


Figure 2. 3D view of the designed cowpea bean seed dehuller



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	FRAME	308 X 230 X 674	1
2	DEHAULING DRUM	295 X 250	1
3	HOPPER	301 X 301 X 185	1
4	INTAKE CHAMBER	30 X 47 X 47	1
5	BEARING HOUSE	10	4
6	INTAKE SHAFT	505.50 X 10	1
7	HUSK OUTLET	23.09 X 230 X 310	1
8	SEPARATION CHAMBER	268.6 X 268.62 X 310	1
9	SEPERATOR	268 X 309	1
10	DEHAUL SEED OUTLET	40 X 331.74 X 310	1
11	ELECTRIC MOTOR	2HP	1
12	MANUALLY OPERATED HANDLE	117.53 X 179.8 X 10	1
13	SPEED REDUCTION MOTOR	2.5 : 1	1

Figure 3. The developed cowpea bean seed dehuller.

D. Machine operation

The designed dehulling machine was developed to have two compartments (dehulling unit and separation) and run by a single shaft, although the separation unit is yet to be fully optimized. After the bean seeds are soaked for a predefined time, the seeds are gradually fed into the machine. The dehulling is attained with the aid of the dehulling drum which revolves about a horizontal axis coupled to the intake shaft (grain collector) run by a 2kW electric motor attached to a speed reduction motor with a ratio of 2.5 :1. The abrasion between the grain and the rough surface of the dehulling drum and the walls resulted in a shear action that removed the hulls from the grain. The dehulled seeds and hulls come out through different outlets with the aid of the rotating dehulling drum.

E. Experiment material

The selected cowpea varieties (*Vigna Unguiculata)* for performance evaluation of the developed dehuller were sourced from a local market in Calabar metropolis, Cross River State, Nigeria. The samples were cleaned manually to eliminate foreign materials, dust, and dirt before samples were prepared for the experiment. After cleaning, 4.08kg of the samples were conditioned under three different levels of soaking time 5, 7.5 and 10 minutes before dulling to ascertain the moisture levels calculated as 8.3%, 10.32%, and 12.07% (w.b) at each level of soaking using eqn. (17) [26].

$$\mathrm{M_c}\ (\%) = \frac{W_d - W_w}{W_d} \qquad (17)$$

$\mathrm{M_c}$ = moisture content (wet basis);

W_w= weight of cowpea seeds before soaking; and W_d = weight of cowpea seeds after soaking.

Following the dehulling, the various fractions of samples were collected and classified into fully dehulled, un-dehulled, and broken seed; and weighed for further examination (Table 2).

Table 2. Performance of the designed cowpea dehulling machine under different processing conditions

Runs	MC (% w.b)	ST (min)	DT (min)	DE (%)	PU (%)	PB (%)
1	8.3	5	14.5	73.53	17.16	9.31
2	8.3	5	14.6	72.79	18.38	8.82
3	8.3	5	14.9	74.51	17.16	8.33
4	8.3	5	15.4	75.25	16.91	7.84
5	8.3	5	15.57	74.02	14.22	11.76
6	8.3	5	14.6	75.00	16.18	8.82
7	8.3	5	14.17	72.30	22.30	5.39
8	8.3	5	15.4	74.51	14.71	10.78
9	8.3	5	14.7	75.25	15.44	9.31
10	10.32	7.5	9.55	87.25	5.39	7.35
11	10.32	7.5	9.16	85.78	4.90	9.31
12	10.32	7.5	9.04	87.25	1.72	11.03
13	10.32	7.5	9.07	87.25	5.64	7.11
14	10.32	7.5	9.36	85.54	4.66	9.80
15	10.32	7.5	9.27	85.54	6.13	8.33
16	10.32	7.5	9.44	87.01	3.68	9.31
17	10.32	7.5	9.25	86.27	5.15	8.58
18	10.32	7.5	10.6	87.25	2.70	10.05
19	12.07	10	7.8	80.64	18.87	0.49
20	12.07	10	7.9	80.64	14.95	4.41
21	12.07	10	7.6	81.37	15.69	2.94
22	12.07	10	7.7	82.60	12.01	5.39
23	12.07	10	7.7	82.11	10.78	7.11
24	12.07	10	7.7	81.62	16.18	2.21
25	12.07	10	7.6	82.35	14.46	3.19
26	12.07	10	7.6	81.86	14.71	3.43
27	12.07	10	7.8	81.37	13.24	5.39

Notes: *MC is Moisture content; ST denotes Soaking time; DT represent Dehulling time; DE is Dehulling efficiency; PU denote Percentage un-dehulled and PB is Percentage broken.*

Experimental Design

A 3^2 - factorial i-optimal randomized design is employed for the experiment conducted. The experimental design was 3×3 having 9 experimental units. The experiment runs (moisture content, dulling time and soaking time) were repeated three times, with 27 test runs (Table 2). The data acquired was analyzed using Design Expert (13.0) software. Analysis of variance (ANOVA), means, and standard deviation were used to determine the significant differences between each response ($p < 0.05$). The assumption is that the independent variables would affect the responses (dehulling efficiency, percentage un-dehulled and broken) factors as follows:

$$\mathrm{D_E} = f(\mathrm{x_1, x_2, x_3}) \qquad (18)$$

$$\mathrm{P_U} = f(\mathrm{x_1, x_2, x_3}) \qquad (19)$$

$$\mathrm{P_B} = f(\mathrm{x_1, x_2, x_3}) \qquad (20)$$

Performance Metrics Analysis

Dehulling efficiency ($\mathrm{D_E}$), percentage un-dehulled ($\mathrm{P_U}$) and percentage broke were used to evaluate machine performance and were calculated using eqs. (21, to 235) [27].

$$\mathrm{D_E}\ (\%) = \left(\frac{\text{Weight of dehulled cowpea grains (kg)}}{\text{Weight of hull + coteledon (kg)}}\right) \qquad (21)$$

$$\mathrm{P_B}\ (\%) = \left(\frac{\text{Weight of un-dehulled Cowpea grains (kg)}}{\text{Weight of hull + coteledon (kg)}}\right) \qquad (22)$$

$$P_B\,(\%) = \left(\frac{\text{Weight of Broken Cowpea grains (kg)}}{\text{Total mass of soaked grains}}\right) \quad (23)$$

RESULTS AND DISCUSSION

Table 3 presents the independent variables and their co--ded levels in terms of moisture content (M_c), soaking time (S_T) and dehulling time (D_T). The sequential model sum of squares suggested the linear effect of conditioning.

Table 3. Independent variables and their coded levels were used for the evaluation of cowpea (*Vigna Unguiculata)* dehulling.

Factor	Name	Units	Low	High
x_1	MC	(% w.b)	8.3	12.07
x_2	ST	min	5	15
x_3	DT	min	6.27	11.17

Dehulling efficiency

From Table 2 above, the impact of moisture content (M_C) on dehulling efficiency (D_E) is significant. At a moisture content of 10.32%, the dehulling efficiency reaches its peak value of 87.25%, indicating that the optimal moisture level softens the seed coat, thereby enhancing the efficiency of the dehulling process. This is further supported by the lower percentage of un-dehulled (P_U) and moderate percentage of broken (P_B) values at this specific moisture level. In contrast, lower DE values, ranging between 72.30% and 75.25%, are observed at 8.3% M_C, possibly due to inadequate moisture, resulting in the hardening of the seed coat and reduced D_E. Soaking time (S_T) is also a significant factor that influences D_E. At 12.07% M_C, longer soaking times (10 minutes) lead to improved D_E, with a peak of 82.60% at 7.7 minutes S_T, although 10.32% M_C performs better overall. Shorter soaking times at 10.32% M_C result in slightly higher D_E, but prolonged soaking can lead to over-softening, increasing P_B and reducing D_E. Furthermore, dehulling time (D_T) has a variable impact on D_E depending on M_C and S_T. Shorter D_T, such as 9.55 minutes at 10.32% M_C and 7.5 minutes ST, result in the highest D_E of 87.25%. Conversely, longer D_T (15.57 minutes at 8.3% M_C) reduced D_E to 74.02%, possibly due to mechanical damage. The interaction between M_C, S_T, and D_T optimizes dehulling efficiency. At 10.32% M_C, combining 7.5 minutes S_T and 9.55 minutes D_T yields the highest D_E, demonstrating that moderate soaking and dehulling times with optimal moisture levels minimize P_U and P_B while maximizing D_E.

Table 4 further presents the analysis of variance (ANOVA) for the regression parameters of the predicted response surface linear model for D_E. The coefficients' sign and magnitude indicate the variable's effect on the response. A negative coefficient indicates that the response decreases as the variable level increases, whereas a positive coefficient indicates that the response increases [27].

Table 4. ANOVA for the regression coefficients of the linear model for Dehulling efficiency.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	708.17	3	236.06	341.37	< 0.0001	significant
M_C	90.87	1	90.87	131.40	< 0.0001	
S_T	105.75	1	105.75	152.92	< 0.0001	
D_T	1.88	1	1.88	2.72	0.1126	
Residual	15.90	23	0.6915			
Lack of Fit	11.96	16	0.7476	1.33	0.3674	not significant
Pure Error	3.94	7	0.5632			
Cor Total	724.07	26				

The model obtained exhibits a correlation coefficient ($R^2 = 0.98$). The high R^2 value suggests that the linear model is suitable; the lack of fit test yields a **p-value of** 0.3674**,** indicating that the model fits the data well, with no significant lack of fit. The model is highly significant **(F-value =** 341.37**, p < 0.0001)** as evident in Table 4, effectively explaining most of the variability in the response variable. Both Moisture Content and Soaking Time exhibit high significance, as evidenced by their p-values which are well below the 0.05 threshold. This indicates the substantial impact of these two factors on DE. The F-values for these factors (131.40 for MC and 152.92 for ST) further emphasize their strong influence on the dehulling process. However, Dehulling Time does not significantly impact DE, with a p-value of 0.113, surpassing the 0.05 threshold. This implies that variations in dehulling time have a lesser influence on the dehulling efficiency compared to MC and ST. These findings are consistent with previous research by Olajide et al. [28], who observed an optimum dehulling rate of 98% efficiency after 6 minutes of soaking, as well as the optimal performance of a developed cowpea dehuller after a running period of 15 minutes with 98% efficiency. Furthermore, Akinfiresoy et al. [29] discovered that increasing the moisture level of the African Locust Bean on a wet basis improves the effectiveness of the de-pulping machine, which can be attributed to the wet quality of the hulls due to water absorption, thereby weakening its walls and making it simpler to dehull.

Percentage un-dehulled

The combined effects of M_C, S_T, and D_T significantly influence the percentage of un-dehulled seeds (D_T), as shown in Table 2 above. When the moisture content is at 10.32%, the lowest PU values of 1.72% and 5.39% are observed, indicating that higher moisture content decreases PU by softening the seed coat. Conversely, at 8.3% MC, PU increases to between 14.22% and 22.30%, suggesting that harder seed coats impede dehulling. At 12.07% MC, PU decreases to 0.49%, confirming the role of moisture in reducing PU. Soaking time (ST) also has a significant impact, as extended soaking times at 12.07% MC reduce PU, while shorter ST combined with 8.3% MC results in higher PU. Dehulling time (DT) affects PU differently, with shorter DTs at 10.32% MC and 7.5 minutes ST yielding a low PU of 5.39%, while longer DTs at 8.3% MC increase PU up to 22.30%. The interaction between these factors shows that a PU of 5.39% is achieved under optimal conditions, while 12.07% MC with 10 minutes ST reduces PU to 0.49%. In contrast, lower MC, shorter ST, and longer DT increase PU, highlighting the need for balance in all factors to achieve efficient dehulling. Overall, higher MC, longer ST, and moderate DT generally enhance dehulling performance, while longer DT without sufficient moisture increases PU. The study's findings align with Barnwal et al. [30] and Babalola et al. [31], indicating that increased moisture levels above thresholds and time can reduce dehulling efficiency and promote product loss.

Table 5 further presents the analysis of variance (ANOVA) for the regression parameters of the predicted response surface linear model. The model shows a significant overall effect, with an **F-value of** 69.67 and **$p < 0.0001$, along with** a correlation coefficient ($R^2 = 0.90$). The moisture content (MC) is of great significance, as indicated by an F-value of 56.15 and a p-value < 0.0001, underscoring the substantial impact of moisture content on the percentage of un-dehulled seeds. Additionally, soaking time exhibits high significance, with an F-value of 65.64 and a p-value of 0.0001, indicating that the duration of seed soaking is another critical factor in minimizing un-dehulled seeds. Although dehulling time (DT) has a smaller but still statistically significant effect on the percentage of un-dehulled seeds, with an F-value of 4.90 and a p-value of 0.0371.

Table 5. ANOVA and regression coefficients of the linear model for Percentage un-dehulled.

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Model	811.08	3	270.36	69.67	< 0.0001	significant
M_C	217.88	1	217.88	56.15	< 0.0001	
S_T	254.69	1	254.69	65.64	< 0.0001	
D_T	19.01	1	19.01	4.90	0.0371	
Residual	89.25	23	3.88			
Lack of Fit	51.69	16	3.23	0.6022	0.8106	not significant
Pure Error	37.55	7	5.36			
Cor Total	900.32	26				

The Lack of Fit F-value of 0.6022 is not statistically significant (p = 0.8106), indicating that the model effectively fits the data without any significant deficiencies. A non-significant lack of fit is desirable as it demonstrates that the model fits well and that any disparities between the model and data are not substantial. These results align with the study of Olotu et al. [5] regarding the significance of soaking time (ST) in the dehulling process. Their research highlights that optimal soaking time improves the efficiency of cowpea dehulling, particularly in minimizing seed breakage and incomplete dehulling.

Percentage broken

The moisture content (MC), soaking time (ST), and dehulling time (DT) significantly impact the percentage of broken seeds (PB) as shown in Table 2 above. Increased moisture levels reduced breakage, with the lowest PB value of 0.49% observed at 12.07% MC, indicating that higher moisture content softens the seeds and reduces brittleness. Conversely, at 8.3% MC, PB values increase, ranging from 5.39% to 11.76%, highlighting the fragile nature of seeds when moisture is insufficient. Prolonged soaking at 12.07% MC decreases PB to 0.49% and 2.94%, underscoring the benefit of extended soaking in reducing breakage. In contrast, shorter soaking times at 8.3% MC lead to higher PB values, such as 11.76%, suggesting that insufficient soaking does not adequately soften the seeds. Dehulling time also affects PB, as shorter DTs at 10.32% MC and 7.5 minutes ST yield a PB of 7.35%, minimizing breakage. However, longer DTs at 8.3% MC, such as 15.57 minutes, result in greater breakage, up to 11.76%. The interaction of these factors is crucial. For instance, at 12.07% MC, 10 minutes ST, and moderate DT, the lowest PB of 0.49% is achieved, indicating that optimal moisture and soaking times, combined with shorter DTs, enhance dehulling efficiency and minimize seed damage. In summary, higher moisture content and longer soaking times result in fewer broken seeds, while longer dehulling times at lower moisture levels increase breakage. Table 6 further presents the analysis of variance (ANOVA) for the regression parameters of the predicted response surface linear model of PB. The model shows a significant overall effect, with an **F-value of** 20.90 and **$p < 0.005$, along with** a correlation coefficient ($R^2 = 0.73$).

Table 6. ANOVA and regression coefficients of the linear model for Percentage broken.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	166.09	3	55.36	20.90	< 0.0001	significan
M_C	27.37	1	27.37	10.33	0.0038	
S_T	32.25	1	32.25	12.17	0.0020	
D_T	8.96	1	8.96	3.38	0.0788	
Residual	60.94	23	2.65			
Lack of Fit	32.13	16	2.01	0.4880	0.8888	not significant
Pure Error	28.81	7	4.12			
Cor Total	227.03	26				

The percentage of broken seeds is significantly affected by moisture content (MC), as evidenced by a p-value of 0.0038 and an F-value of 10.33. Soaking time (ST) also plays a crucial role, with an F-value of 12.17 and a p-value of 0.0020. Dehulling time (DT) has a less substantial impact on broken seeds, with a p-value of 0.0788, slightly above the typical threshold of 0.05. While it contributes to the model, its influence on breakage is relatively insignificant compared to MC and ST. The model's residual sum of squares of 60.94 reflects the unexplained variation. The Lack of Fit F-value of 0.4880 ($p = 0.8888$) is not significant, indicating that the model fits the data well without significant variation due to noise. The significance of both MC and ST aligns with existing literature, which underscores the importance of proper moisture management and soaking times in minimizing seed breakage during dehulling processes.

Optimization of experimental conditions

The optimum parameters levels for dehulling of cowpea (*Vigna unguiculata*) were defined as those yielding maximum dehulling efficiency, minimum percentage un-dehulled, and broken grains, evaluated at a desirability value of 0.704 (Figure 4).

The optimal values predicted for MC, DT, and ST were 12.07 (% w. b), 7.6 minutes, and 9.9 minutes respectively. At these optimal values, the dehulling efficiency, percentage un-dehulled and percentage broken were predicted as 87.3%, 5.9% and 6.8% respectively. To verify the findings, a preliminary experiment was performed in triplicate at optimal conditions. The average dehulling efficiency, percentage un-dehulled and percentage broken were observed to be 80.8, 11.9% and 7.25%, which confirms the optimum conditions.

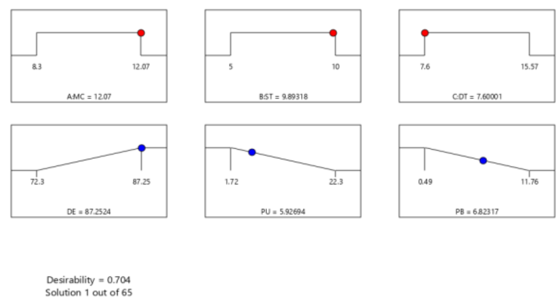


Figure 4. Desirability response surface plot of the performance efficiency at optimal conditions

CONCLUSION

Cowpea (Vigna unguiculata) is a vital crop in many Nigerian households, serving as a key source of nutrients and economic support. This study focused on improving the efficiency of cowpea processing through the optimization of a dehulling machine's operational conditions. Utilizing Response Surface Methodology (RSM), the study analyzed the impacts of moisture content, dehulling time, and soaking time on processing performance, determining optimal conditions of 12.07% moisture (w.b), 7.6 minutes of dehulling, and 9.9 minutes of soaking. These conditions yielded a dehulling efficiency of 87.3% while minimizing un-dehulled seeds and breakage rates by 5.9% and 6.8% respectively.

As an improvement, the study developed a dual manual/electric dehulling machine, particularly beneficial for communities with unreliable power sources, allowing small-scale businesses to flourish without electricity. This development could enhance food security by increasing the availability and quality of dehulled cowpea products. Additionally, the machine's design supports local manufacturing and maintenance, fostering job creation and economic growth in rural agricultural areas. Overall, this innovation offers the potential to reinforce food security and economic stability in resource-limited regions by transitioning from labour-intensive methods to an efficient mechanized system.

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