Umudike Journal of Engineering and Technology (UJET); Vol. 8, No. 2, December 2022, pp. 1 – 12; Michael Okpara University of Agriculture, Umudike, Print ISSN: 2536-7404, Electronic ISSN:2545-5257; http://ujetmouau.net; doi: https://doi.org/10.33922/j.ujet_v8i2_1

DETERMINATION OF OPTIMUM PERFORMANCE PARAMETERS OF A DEVELOPED AFRICAN OIL BEAN SEED DEHULLING MACHINE

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ABSTRACT

The study presents the optimum performance parameters of a developed African oil bean seed (AOBS) dehulling machine. The performance indicators are throughput, dehulling efficiency, mechanical breakage index, and labour requirement. The results indicate that the highest throughput was attained at a speed of 700 rpm, boiling time and throughput of 1 hour, and 41.09 kg/hr, respectively. In contrast, the minimum throughput was obtained at a dehulling speed of 331rpm and a throughput of 14.05 kg/hr. However, first and second-order response surface models were developed to achieve the optimum parameters and their relationship. The relationship between the input variables (time, speed, and labour required) and the output variables (throughput, dehulling efficiency, and mechanical damage index) was evaluated by the use of experimental design methodology with six centre points. The analyses show that the root mean square for the throughput, dehulling efficiency and mechanical damage index was 80.08%, 85.69% and 89.15%, respectively, which correlated well with the input variables. Consequently, the optimal time, speed and labour required were approximated at 4.1053hr (4hr, 6min), 43530rph (726rpm) and 3.85man-hr/kg respectively. Also, the values of the composite desirability and the individual desirabilities of the responses indicate that these results are highly desirable. Conclusively, since the results shows the minimum parameters for maximum production, it will give opportunity for machine scaling which in turn will reduce production cost, downtime and increase output.

***Keywords**: Dehulling, boiling time, machine, African oil bean, throughput.*

1.0 INTRODUCTION

The African oil bean seed (Pentaclethra macrophylla) is a primary tropical zone tree commonly grown in Nigeria and belongs to the *leguminosae* family. The plant is prevalent amongst the Ibo tribes and some ethnic groups in the southern part of Nigeria. The product is also called *Ugba* in the Ibo language and is a popular delicacy, acknowledged as a good food flavour agent (Nurudeen *et al*., 2016). The plant produces its fruit which looks like green pods and gradually darkens at maturity. The fruit is about 0.36 to 0.46 m in length and 0.05 to 0.10 m wide. Each pod holds approximately 10 seeds, which riven open to strew the seeds to a span of about 20 m from the tree at maturity (Akindahunsi *et al*., 2004). The seed's structure is flat in shape, smooth in texture, and hard and brown, as presented in Figure1 (Adekunle *et al*., 2008).

Figure 1: The tree, ruptured and plane pod and seeds of AOBS

Furthermore, some operations are required in African oil bean seed processing, which comprises boiling to ease the separation of the shell from the kernel; the dehulling process needed to extract the kernel from the seed; the slicing process to improve the surface area to facilitate fermentation, and the fermentation process to eliminate the anti-nutritional composition to enhance the taste quality. All these processes are orthodoxly done at present-day. However, the manual or physical dehulling process of the AOBS comes with several challenges. Adekunle al. (2008) presented the drawbacks of the manual procedure of dehulling, which include: drudgery, risk of injury, waste of person-hours and substantial economic losses. Consequently, it is imperative to mechanize the process of dehulling the AOBS to alleviate the accompanying complications of the non-mechanized technique. Besides, the mechanized operation will enhance production, improve quality, reduce drudgery and increase the income capacity of the local farmers engaged in this business (Adejumo, 2012).

Nonetheless, very few studies exist regarding the mechanization of the AOBS dehulling process as contain in the study by (Fadeyibi *et al*. 2018). The study emphasized the relationship between the angular speed and the linear displacement with minimal emphasis on how these parameters relate to the dehulling efficiency and output. Reflections on the dehulling process for some seeds, not AOBS, are reported. For example, (Hussain *et al*. (2018) designed and developed a novel technology for walnut cracking. From the results, the electrically operated cracker, hand operated cracker and the manual cracking method was 15.46 kg/hr, 1.61 kg/hr/ person and 3.42 kg/hr/person for the Kaghazi walnuts while 14.07 kg/hr, 1.29 kg/hr/person and 3.21 kg/ hr/person were achieved for the medium shield nut respectively. Similarly, (Agidi *et al*. (2018) designed and fabricated both the dehuller and separator locust beans machine and attained enhanced efficiency of 63.335 % for the dehuller efficiency and 55.04 % for the separator compartment.

In the last decade, research development of machine systems prediction and optimization has increased significantly. The advantage of this growing area is that it reduces waste in design and manufacturing processes predicated on trial-and-error methodologies. It also removes all rigour from manual processes and takes care of some unattained approximations (Nwankwojike *et al*. 2018; Edeh *et al*. 2018). For example, Malozemov (2015) established a software system for estimating and optimizing the operating methods for fuel and diesel supply. In contrast, Lee and Park (2013) developed software for optimizing the nonlinear dynamic system using a similar static loads technique. Likewise, a mechanistic model was developed by (Nwankwojike *et al*. 2016) to predict optimum value of the specific energy consumption and the throughput of a palm nut–pulp separator. The optimization results obtained from these studies showed a very high prediction accuracy. The study of Isaac *et al* (2017) presented the optimal performance of a centrifugal pump using response surface optimization. The experimental design was divided into 32 factorial points, which comprises 10 centre points and 12 axial points. The results showed optimal points at $417mm$, $70mm$, $366mm$, $36mm$, and $64mm$ and 39°, as the optimum settings of the impeller discharge breadth, impeller blade length, suction pipe diameter, impeller radial tip clearance, blade discharge width and blade discharge angle respectively. Similarly, (Egwuagu *et al*. (2021), presented a multi-objective optimization based on response surface method of an integrated milling-sieving-dewatering machine for grain slurry starch production. The results indicated that about 70L/h, 10rpm, 0.59rpm and 90 kPa optimal settings of the water feed rate, sieving speed, and dewatering speed and pump pressure were achieved, respectively while 87Kg/h, 98.75%, 25.35% and 183kJ/Kg constitute the corresponding throughput, extraction efficiency, cake moisture content and specific energy consumption in that order.

However, from the reviewed literature the African oil bean seed dehuller has not been sufficiently developed and optimized for best operating condition. The study of Fadeyibi *et al*. (2018) provided a conceptual design of AOBS with a horizontal shaft system for dehulling. Moreover, the generated data did not present performance values in terms of the efficiency and other operating parameters that will assist replication. The horizontal shaft design in Fadeyibi *et al*. (2018) may lead to low dehulling efficiency due to low impact force as a result of reduced gravitational force. To close this gap, the current study proposes the design and development of a dehuller for African oil bean seed through a vertical impact. The latter design will enhance impact due to assisted gravitation force as the bean seed falls from the hopper thus increasing processing time and enhance dehulling efficiency. On this note, the objective of this study is to design, develop and optimized the performance of an AOSB based on response surface technique. The study is noteworthy as such references on AOBS are limited in the open literature.

2.0 MATERIALS AND METHOD

The design and development of the AOSB were performed based on the following consideration: (1) Simplicity in design, construction and maintenance, (2) Accessibility, (3) stability, durability and Strength, (4) Safety in the application, (5) Proper material selection that will not contaminate the food, (6) Mechanical and the engineering properties of the materials used for the construction of the AOBS. These include the breadth (37.89 mm), moisture content (15.16 %), volumetric flow rate (2.8m^3/s), bulk density (0.588 g/cm3), angle of repose 32 degrees, rupture force (1.12 kN), rupture stress (7.4 N/mm^2), toughness (1.783 J), coefficient of friction (static) (0.3) for 15.16 % dry bub moisture content (Fadeyibi *et al*. 2018).

2.1 Design calculations

The velocity and belt length are calculated using Eqs (1) and (2) given by (Okokon *et al*. 2010).

$$V_b = \frac{\pi D_m N_m}{60} \tag{1}$$

$$L = \frac{\pi}{2}(D_m + D_d) + 2x + \frac{(D_m - D_d)^2}{4x} \tag{2}$$

Where L is the length and D_m and D_d are diameters of large and the small pulleys respectively.

The following assumption was made in the hopper design, inner and outer radii of 200 mm and 196 mm, respectively. The hopper slant height was chosen at 32^0 (angle of repose). The hopper capacity was estimated in Equation. (3) (Fadeyibi *et al*. 2018). At the same time, other design parameters are depicted in Table 1.

$$V_H = 0.333\pi\,(R^2 - r^2)h \tag{3}$$

Where R^2 = Outside radius of cylinder r^2 = Inner cylinder radius
The required volume for the required of seeds to fill the hopper per unit of time is obtained as follows:

$$V_F = \rho_b \times m \tag{4}$$

Where V_F = volume of seed (m^3), ρ_b = bulk density of seed (kg/m^3), and m = mass of fruit (kg)
The power needed to drive the dehuller shaft (Pd) and the power required to remove the coating of the cotyledon (PF) of the AOBS is estimated by (Owolarafe al. 2011, and Adamu *et al*. 2015).

$$P_F = T_F \omega \quad (5)$$

The power required to drive the driven shaft (Pd) was calculated as Eq. 6

$$P_d = T_d \omega \quad (6)$$

Total power required to dehull African oil bean seed

$$P = P_d + P_F \quad (7)$$

Table 1: Components design dimensions of the dehuller

S/No	Components	Dimension
1	Feeder/hopper height	50 mm
2	Upper hopper diameter	120 mm
3	Hopper base diameter	70 mm
4	Dehauler inside diameter	196 mm
5	Dehauler outside diameter	200 mm
6	Shaft diameter	20 mm
7	Shaft length	300 mm
8	Dehauler blade	30 mm by 20 mm
9	Total height of the machine	460 mm
10	Total width of the machine	255 mm

2.2 Performance analysis

Three performance indices were used, which include Feed rate (throughput), dehulling efficiency and mechanical damage as presented in Equations (8)-(10) (Owolarafe al. 2011)

$$F_r = \frac{3.6M_1}{t_P} \quad (8)$$

Where F_r = feed rate (kg/hr); M_1 = mass of sample before dehulling (kg); t_p = time used for complete dehulling (hr)

$$D_E = \frac{M_D}{M_1} \times 100 \quad (9)$$

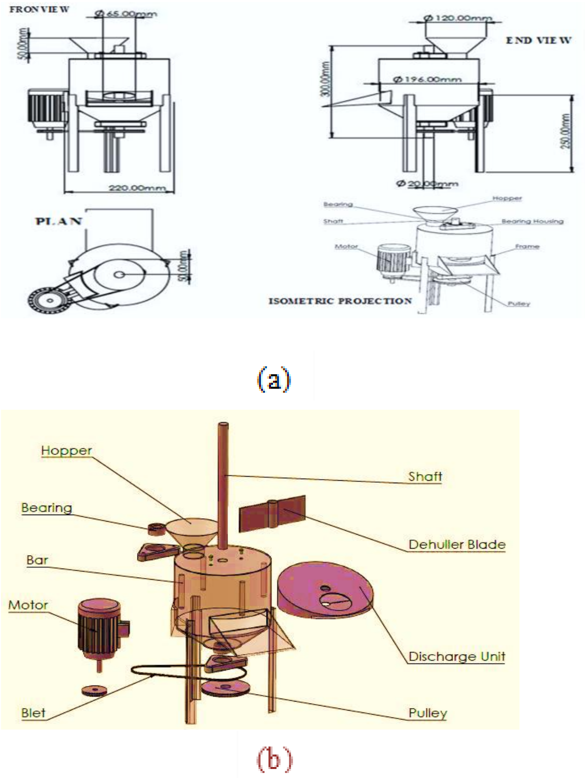
Where M_D = mass of dehulled samples

$$M_i = \frac{M_d}{M_n} \times 100 \quad (10)$$

Where M_d = weight of mechanically damaged kernel received from the outlet (g), M_n = weight of kernel received from the outlet (g)

2.3 Machine description and experimental procedure

The diagram of the dehuller is presented in Figures 2 (a) and (b). The components of the dehulling system are the feeding unit (FU), dehulling unit (DH), and the discharge compartment (DC). The FU is a frustum of 200 mm and 196mm upper and lower base diameters. The DH is made from stainless steel with a shaft of 300 mm long and 20 mm diameter. The DC is a stainless-steel plate of 0.002m. The frame is 0.6m by 0.6m and 0.35 m in length. The oil bean seeds are first washed carefully with water before determining the initial moisture content at 105 ^{O}C for 5 hours after oven-dried. Then prepared seeds were boiled at 100 ^{O}C for four hours and taken at one hour to evaluate the dehuller at five different speeds (700, 580, 488, 380, and 320 rpm). The bean seeds are introduced to the electrically operated rotary dehuller through the hopper. The energy in the rotating dehuller blades pushes the seeds against the attached bars to the wall casing, thereby dehulling the seeds. The soft, stretchy kernel is separated from the seed coat by floating in the water. The dehulling progression is accomplished from the feeding point of the oil bean seed to the exit point of the dehulled seeds by the rotating shaft of the dehuller and the attached iron bar in the dehuller casing. The data collected were analysed.



(a)

(b)

Figure 2: Schematics of the AOBS dehuller (a) Orthographic and isometric views, (b) Exploded diagram

2.4 Experimental design and optimization procedure

The relationship between the input variables (time, speed, and labour required) and the output variables (throughput, dehulling efficiency, and mechanical damage index) was evaluated by the use of experimental design methodology with six centre points (Ede *et al*., 2018, Isaac *et al*., 2017). Thus, the input variables were coded as shown in Equations (11) to (13). The factorial experimental design was also analyzed using MINITAB 16 to formulate the following first-order and second-order surface models showing the relationship between the input variables (time, speed, and labour required) and the output variables (throughput, dehulling efficiency, and mechanical damage index) Equations (14) to (16):

$$x_1 = \frac{t-2.5}{1.5} \qquad (11)$$

$$x_2 = \frac{N-30{,}930}{11{,}070} \qquad (12)$$

$$x_3 = \frac{l_r-2.69}{1.34} \qquad (13)$$

Where t is time (hr), N is speed (rph) and l_r is the labour required $(man-hr/kg)$. The maximum and minimum values of these variables are indicated as follows: $t_{(max)} = 4hr$, $t_{(min)} = 1hr$; $N_{(max)} = 42{,}000rph$, $N_{(min)} = 19{,}860rph$, $l_{r(max)} = 4.03\, man-hr/kg$, $l_{r(min)} = 1.35\, man-hr/kg$.

Six centre points were chosen to ensure robustness and analysis of lack-of-fit. So the factorial design becomes 14 design points at 3 levels (-1, 0 and 1) (Table 2) while the central composite design (CCD) becomes 20 design points at 5 levels (-1.6818, -1, 0, 1, 1.6818) (Table 3). This is to analyze curvature as the factorial design analysis results suggested possible curvature.

Table 2: Full factorial completely randomized single block two level design with six centre points

StdOrder	RunOrder	Blocks	x_1	x_2	x_3	$Q\ (kg/hr)$	$\eta\ (\%)$	$D_I\ (\%)$
2	1	1	1	-1	-1	14.32	27.03	57.8
6	2	1	1	-1	1	31.62	81.2	16.04
1	3	1	-1	-1	-1	14.05	19.15	71.21
8	4	1	1	1	1	41.09	95.6	14.58
4	5	1	1	1	-1	39.38	89.31	52.49
10	6	1	0	0	0	30.31	80.01	16.21
13	7	1	0	0	0	29.22	79.45	17.78
12	8	1	0	0	0	25.09	74.75	18.06
14	9	1	0	0	0	24.39	73.49	18.45
11	10	1	0	0	0	23.18	69.83	20.64
9	11	1	0	0	0	23.01	60.07	20.97
7	12	1	-1	1	1	33.19	86.52	14.99
5	13	1	-1	-1	1	14.6	31.97	57.48
3	14	1	-1	1	-1	15.39	36.45	54.37

Table 2: Single block completely randomize central composite response surface design

StdOrder	RunOrder	Blocks	x_1	x_2	x_3	$Q\ (kg/hr)$	$\eta\ (\%)$	$D_I\ (\%)$
8	1	1	1	1	1	41.09	95.6	14.58
1	2	1	-1	-1	-1	14.05	19.15	71.21
11	3	1	0	-1.6818	0	17.47	40.65	52.36
5	4	1	-1	-1	1	14.6	31.97	57.48
14	5	1	0	0	1.6818	18.29	48.17	43.78
19	6	1	0	0	0	30.31	80.01	16.21
16	7	1	0	0	0	29.22	79.45	17.78
20	8	1	0	0	0	25.09	74.75	18.06
15	9	1	0	0	0	24.39	73.49	18.45
12	10	1	0	1.6818	0	22.88	55.99	25.42
10	11	1	1.6818	0	0	22.53	54.33	26.78
6	12	1	1	-1	1	31.62	81.2	16.04
4	13	1	1	1	-1	39.38	89.31	52.49
13	14	1	0	0	-1.6818	18.03	45.71	43.78
2	15	1	1	-1	-1	14.32	27.03	57.8
18	16	1	0	0	0	23.18	69.83	20.64
17	17	1	0	0	0	23.01	60.07	20.97
3	18	1	-1	1	-1	15.39	36.45	54.37
7	19	1	-1	1	1	33.19	86.52	14.99

9	20	1	-1.6818	0	0	17.93	42.06	46.21

Tables 2 and 3 were analyzed to fit mathematical functions relating for each response Q, η and D_I for first and second order models presented in Equations (14)-(16) and (17) to (19) respectively.

The first-order response surface models:

$$\boldsymbol{Q} = 25.46 + 6.15x_1 + 6.81x_2 + 4.67x_3 \quad (14)$$

$$\boldsymbol{\eta} = 58.40 + 14.88x_1 + 18.57x_2 + 15.42x_3 \quad (15)$$

$$\boldsymbol{D_I} = 42.37 - 7.14x_1 - 8.26x_2 - 16.60x_3 \quad (16)$$

Where Q, η and D_I are throughput, dehulling efficiency and mechanical damage index.
The second-order response surface models:

$$\boldsymbol{Q} = 25.66 + 4.17x_1 + 4.65x_2 + 2.77x_3 - 0.66x_1^2 - 0.68x_2^2 - 1.39x_3^2 + 1.83x_1x_2 + 0.08x_1x_3 + 0.21x_2x_3 \quad (17)$$

$$\boldsymbol{\eta} = 72.54 + 10.23x_1 + 12.76x_2 + 9.34x_3 - 6.19x_1^2 - 6.15x_2^2 - 6.63x_3^2 + 0.60x_1x_2 - 0.30x_1x_3 - 1.33x_2x_3 \quad (18)$$

$$\boldsymbol{D_I} = 18.64 - 6.58x_1 - 8.16x_2 - 9.72x_3 + 6.59x_1^2 + 7.43x_2^2 + 9.16x_3^2 + 6.57x_1x_2 - 3.32x_1x_3 - 2.73x_2 \quad (19)$$

3.0 RESULTS AND DISCUSSION

3.1 Machine performance based on input parameters

The results of the performance of the AOBS are presented in Table 2. The dehuller feed rate capacity or throughput ranged from 15.39 to 41.09 kg/hr, 14.60 to 39.38 kg/hr, 14.32 to 31.62 kg/hr, 14.05 to 29.22kg/hr for the first, second, third and fourth hours of the boiling time. The significant enhancement in the throughput is associated with the resident time reduction in the DC. Conversely, the highest throughput was attained at a speed of 700 rpm, a boiling time of 1 hour, and throughput 41.09 kg/hr. In contrast, the minimum throughput is obtained at a dehulling speed of 331rpm and a throughput of 14.05 kg/hr. The analysis of variance shows that the boiling time and the dehulling speed have a significant effect at ($p \leq .05$) on the throughput capacity. This implies that any increase or decrease in the boiling time, the dehulling speed will affect the output produced in one hour. The correlated results for the throughput occurred at ($R^2 = 0.996$). The dehulling efficiency increased from 19.15 to 95.60 % between the boiling times of the first and the fourth hour. The dehulling efficiency decreases across the boiling time as the speed increases from 331 rpm to 700 rpm. The statistical evaluation of the variance shows that the boiling time has a significant impact ($p \leq .05$) on the dehulling efficiency. The highest dehulling efficiency of 95 % was obtained at a dehulling speed of 448 rpm corresponding to the fourth hour of the boiling time. The least dehulling efficiency occurred at high-speed, corresponding to the fourth hour of the boiling time. Also, the mechanical damage index (Table 2) showed maximum values at 700 rpm (71.21 %) and least values at 388 rpm (14.58%), corresponding to the first and third hours of the boiling time. The variance of the mechanical, index, throughput and labour required parameters are small.

Table 2: Performance of developed African oil bean seed dehuller at varied conditions

Time (hour)	Speed (rpm)	Throughput (kg/hr)	Dehulling Efficiency (%)	Mechanical Damage Index (%)	Labour required (person-hour required/kg)
1	700	41.09 ± 0.42	19.15± 0.27	71.21± 1.16	4.03 ± 0.59
	580	33.19 ± 1.01	27.03 ± 0.71	57.8 ± 0.31	3.27 ± 1.32
	448	24.39 ± 0.52	74.75 ± 0.36	34.65 ± 0.33	2.16 ± 0.31
	388	18.29 ± 0.17	55.99 ± 0.77	25.42 ± o.25	1.78 ± 0.42
	331	15.39 ± 0.72	40.65 ± 0.62	20.64 ± 0.61	1.35 ± 0.33
2	700	39.38 ± 1.11	31.97 ± 0.57	57.48 ± 0.55	3.15 ± 0.11
	580	30.31 ± 0.82	42.06 ± 0.92	54.37 ± 0.71	2.81 ± 0.63
	448	23.18 ± 0.85	81.20 ± 0.49	26.78 ± 1.02	2.21 ± 0.22
	388	18.03 ± 0.58	69.83 ± 0.26	20.97 ± 0.86	1.88 ± 0.50
	331	14.60 ± 0.90	60.07 ± 0.51	18.45 ± 0.59	1.57 ± 0.19
3	700	31.62 ± 0.88	36.45 ± 1.12	52.36 ± 0.11	2.98 ± 0.49
	580	25.09 ± 0.24	45.71 ± 0.45	52.49 ± 0.26	2.26 ± 1.01
	448	22.88 ± 0.37	89.31 ± 0.18	18.06 ± 0.55	2.24 ± 0.32
	388	17.93 ± 0.08	80.01 ± 0.54	14.58 ± 0.74	2.03 ± 0.40
	331	14.32 ± 0.15	73.49 ± 0.73	14.99 ± 0.31	1.80 ± 0.63
4	700	29.22 ± 0.65	48.17 ± 0.94	43.78 ± 1.03	2.31 ± 0.35
	580	23.01 ± 0.21	54.33 ± 0.37	46.21 ± 0.67	2.13 ± 0.83
	448	22.53 ± 0.44	95.60 ± 0.31	17.78 ± 0.12	2.29 ± 0.73

388	17.47 ±0.51	86.52 ± 0.83	16.21 ± 0.43	2.11 ± 0.45
331	14.05 ± 0.43	79.45 ± 0.66	16.04 ± 0.26	2.03 ± 0.62

3.2 Relationship of machine performance parameters

Adequacy tests of each of the first-order models performed by the analysis of variance (ANOVA) indicate that their respective main effects are significant; curvature is not needed for throughput but needed for dehulling efficiency and mechanical damage index, and the lack-of-fit for throughput and dehulling efficiency is significant but insignificant for mechanical damage index. More so, the analyses show that the R-sq. for $\boldsymbol{Q}$, $\boldsymbol{\eta}$ and $\boldsymbol{D_I}$ are respectively 80.08%, 85.69% and 89.15%. These results show that the output variables are strongly correlated with the input variables since the values tend to 100%, though there are 19.92%, 14.31% and 10.85% deviations, respectively. Their respective R-sq (adj) values, which are 71.22%, 79.33% and 84.33%, indicate that there is only 8.86%, 6.36% and 4.82% need for the respective model adjustment. This is because the closer R-sq (adj) approaches R-sq., the less the need for model adjustment. All the first-order model terms are significant in the regression analyses of the model terms for throughput, dehulling efficiency and mechanical damage index. Thus, all the independent variables affect each dependent variable since their respective p-values are less than 0.05. For the second-order model, the R-sq values for $\boldsymbol{Q}$, η and D_I are respectively 56.15 %, 64.78 % and 83.94 % (Table 4).

Table 3: Analysis of variance (ANOVA) of the first order models for $\boldsymbol{Q}$, $\boldsymbol{\eta}$ and $\boldsymbol{D_I}$

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Analysis of Variance for Q (coded units) S = 4.84198, PRESS = 712.933, R-Sq = 80.08%, R-Sq(pred) = 32.69%, R-Sq(adj) = 71.22%						
Main Effects	3	847.54	847.542	282.514	12.05	0.002
Curvature	1	0.58	0.581	0.581	0.02	0.878
Residual Error	9	211.00	211.003	23.445		
Lack of Fit	4	161.85	161.852	40.463	4.12	0.076
Pure Error	5	49.15	49.151	9.830		
Total	13	1059.13				
Analysis of Variance for $\boldsymbol{\eta}$ (coded units) S = 11.5225, PRESS = 5703.37, R-Sq = 85.69%, R-Sq(pred) = 31.70%, R-Sq(adj) = 79.33%						
Main Effects	3	6431.2	6431.2	282.514	12.05	0.002
Curvature	1	723.8	723.8	723.80	5.45	0.044
Residual Error	9	1194.9	1194.9	132.77		
Lack of Fit	4	923.7	923.7	230.92	4.26	0.072
Pure Error	5	271.3	271.3	54.25		
Total	13	8349.9				
Analysis of Variance for $\boldsymbol{D_I}$ (coded units) S = 8.28733, PRESS = 6824.45, R-Sq = 89.15%, R-Sq(pred) = 0.00%, R-Sq(adj) = 84.33%						
Main Effects	3	3158.09	3158.09	1052.70	15.33	0.001
Curvature	1	1923.36	1923.36	1923.36	28.00	0.000
Residual Error	9	618.12	618.12	68.68		
Lack of Fit	4	601.68	601.68	150.42	45.77	0.000
Pure Error	5	16.43	16.43	3.29		
Total	13	5699.57				
Main Effects	3	3158.09	3158.09	1052.70	15.33	0.001

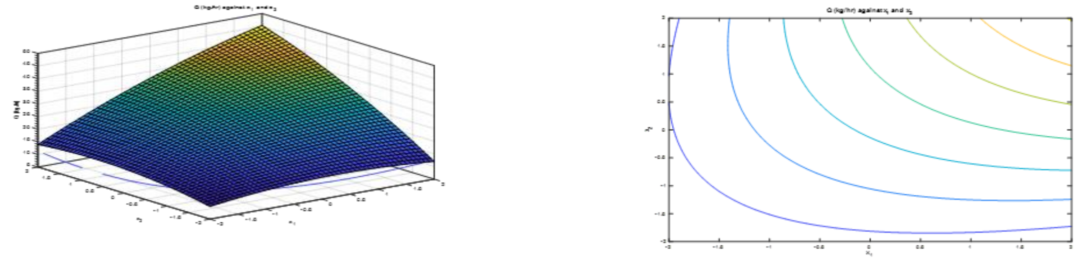
Table 4*: Analysis of variance (ANOVA) of the second order models for $\boldsymbol{Q}$, $\boldsymbol{\eta}$ and $\boldsymbol{D_I}$*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Analysis of Variance for Q (coded units)S = 7.39344, PRESS = 4055.66, R-Sq = 56.15%, R-Sq(pred) = 0.00%, R-Sq(adj) = 16.69%						
Regression	9	700.09	700.091	77.788	1.42	0.294
Linear	3	637.61	637.612	212.537	3.89	0.044

Square	3	35.44	35.435	11.812	0.22	0.883
Interaction	3	27.04	27.044	9.015	0.16	0.918
Residual Error	10	546.63	546.630	54.663		
Lack-of-Fit	5	497.48	497.479	99.496	10.12	0.012
Pure Error	5	49.15	49.151	9.830		
Total	19	1246.72				
Analysis of Variance for η (coded units) S = 18.5160, PRESS = 25776.3, R-Sq = 64.78%, R-Sq(pred) = 0.00%, R-Sq(adj) = 33.09%						
Regression	9	6306.91	6306.91	700.77	2.04	0.140
Linear	3	4844.13	4844.13	1614.71	4.71	0.027
Square	3	1445.01	1445.01	481.67	1.40	0.298
Interaction	3	17.78	17.78	5.93	0.02	0.997
Residual Error	10	3428.42	3428.42	342.84		
Lack-of-Fit	5	3157.16	3157.16	631.43	11.64	0.009
Pure Error	5	271.25	271.25	54.25		
Total	19	9735.33				
Analysis of Variance for D_I (coded units) S = 10.2493, PRESS = 8049.92, R-Sq = 83.94%, R-Sq(pred) = 0.00%, R-Sq(adj) = 69.49%						
Regression	9	5492.28	5492.28	610.25	5.81	0.140
Linear	3	2790.49	2790.49	930.16	8.85	0.027
Square	3	2208.89	2208.89	736.30	7.01	0.298
Interaction	3	492.90	492.90	164.30	1.56	0.997
Residual Error	10	1050.47	1050.47	105.05		
Lack-of-Fit	5	1034.04	1034.04	206.81	62.92	0.000
Pure Error	5	16.43	16.43	3.29		
Total	19	6542.76				

3.3 Optimum performance parameters

The effects of any pair of the input variables on each output variable are shown on the following response surface and contour plots (Figures. 3 to 5). The plots show that the change in any two input variables simultaneously brings about a corresponding change in the output variables. Figures 3(a) and 3(b) show that increasing time and speed increases throughput, Figures 3(c) and 3(d) show that increasing time and reducing labour required increases throughput, while Figures 3(e) and 3(f) show that increasing speed and reducing labour required increases throughput. Furthermore, for multi-objective design optimization, it is expedient to evaluate the effects of all the input variables on all the output variables simultaneously. Thus, the desirability function optimization approach performed with the use of MINITAB 16 provides the optimal settings of the throughput $[Q\ (kg/hr)]$, dehulling efficiency $[\eta\ (\%)]$ and mechanical damage index $[D_I\ (\%)]$ and the coded values of time (x_1), speed (x_2) and labour required (x_3). The optimization plot otherwise referred to as optimplot, is shown in Figure. 6. The plot contains the composite desirability value, the optimal values of the input and output variables and their respective desirability values. It can be seen from the curves that the shift from left to right in the values of each of the input variables increases the throughput and dehulling efficiency but decreases the mechanical damage index. Therefore, the global solutions contained in the optimplot and the iteration result indicate that at$Q = 37.6425\,kg/hr$, $\eta = 85.2146\%$ and $D_I = 20.181\%$; $x_1 = 1.07021$, $x_2 = 1.1382$ and$x_3 = 0.8664$. Hence, the optimal time, speed and labour required are 4.1053hr (4hr, 6min), 43530rph (726rpm) and 3.85man-hr/kg, respectively. The values of the composite desirability and the individual desirabilities of the responses indicate that these results are highly desirable

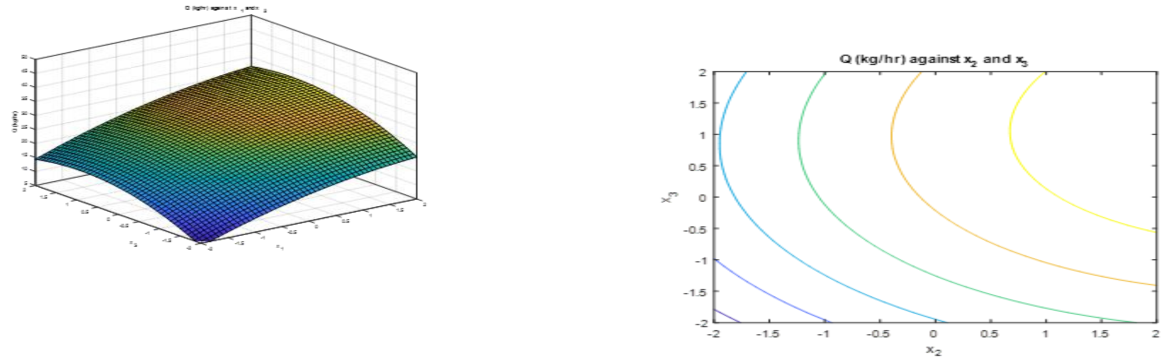


(a) (b)

Figure 3: (a) Response surface and (b) Contour plots of the throughput $[Q\ (kg/hr)]$ against pairs of the coded values of time (x_1) and speed (x_2)

(c) (d)

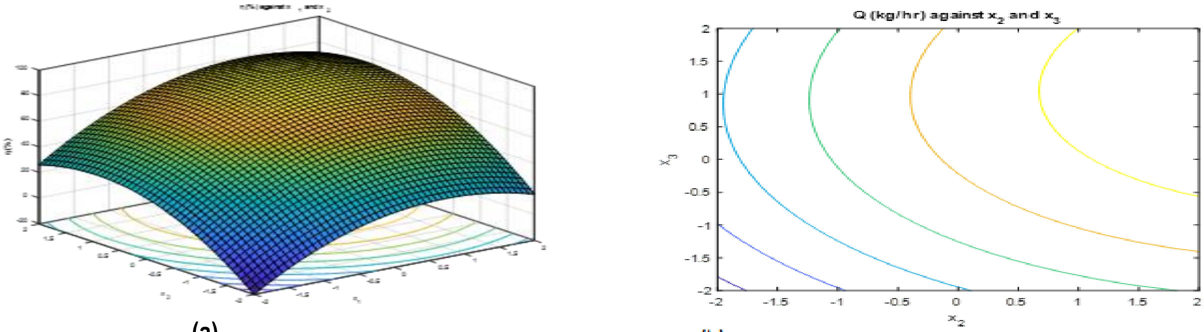
Figure 3: (c) Response surface and (e) Contour plots of the throughput $[Q\ (kg/hr)]$ against pairs of the coded values of time (x_2) and labour required (x_3)



(e) (f)

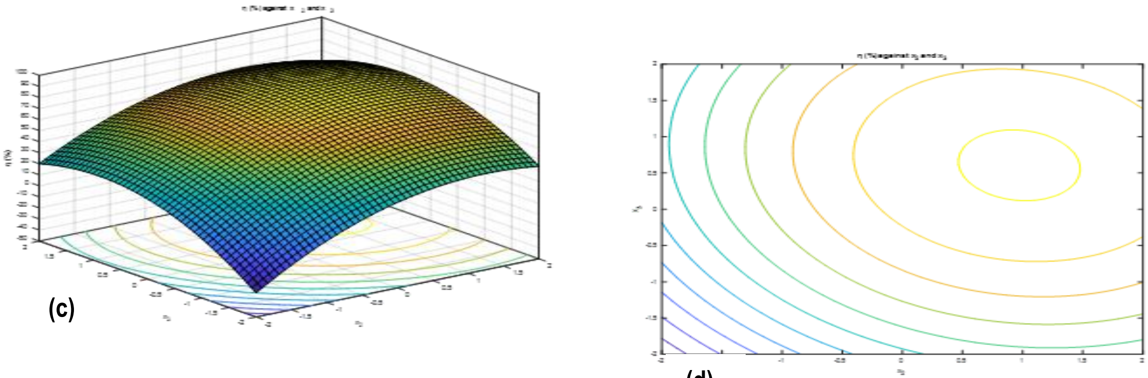
Figure. 3: (e) Response surface and (f) Contour plots of the throughput $[Q\ (kg/hr)]$ against pairs of the coded values of time (x_1) and labour required (x_3)

Also, Figures 4(a) and 4(b) shows that increasing time and speed increases dehulling efficiency, Figures 4(c) and 4(d) show that increasing time and reducing labour required increases dehulling efficiency, while Figures 4(e) and 4(f) show that increasing speed and reducing labour required increases dehulling efficiency



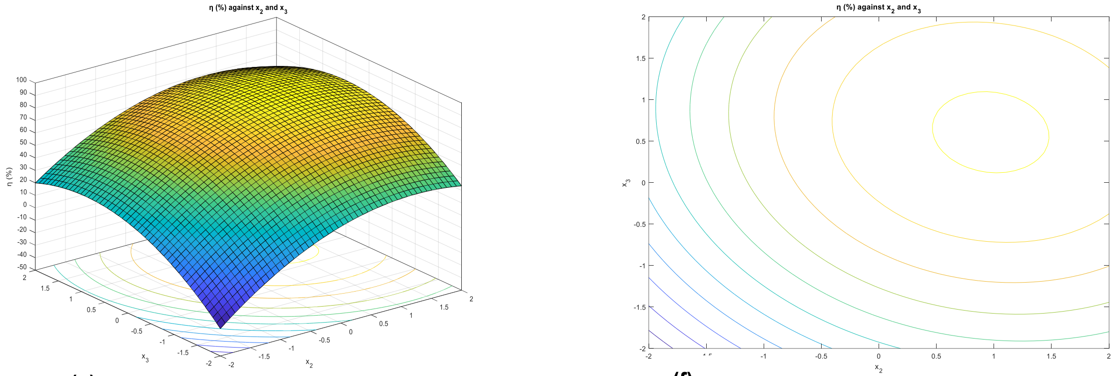
(a) (b)

Figure 4: (a) Response surface and (b) Contour plots of the dehulling efficiency $[\eta\ (\%)]$ against pairs of the coded values of time (x_1) and speed (x_2)



(c) (d)

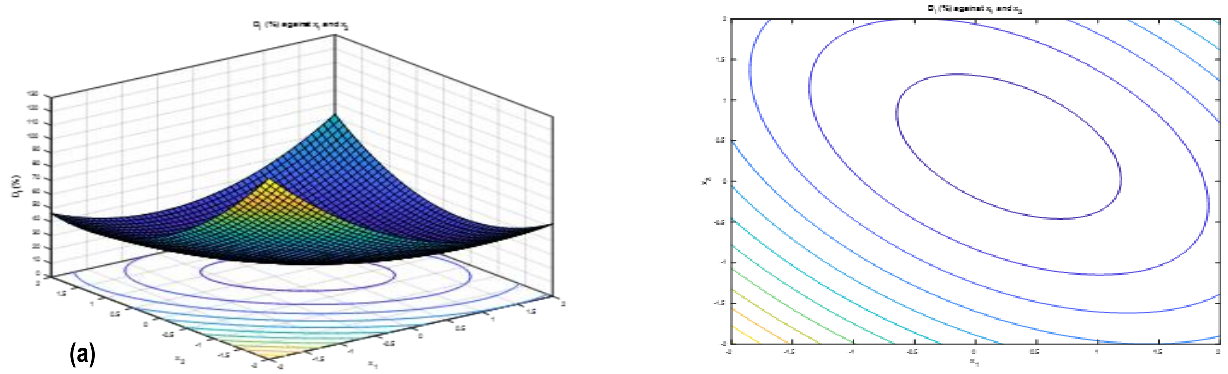
Figure 4: (c) Response surface and (d) Contour plots of the dehulling efficiency $[\eta\ (\%)]$ against pairs of the coded values of speed (x_2) and labour required (x_3)



(e) (f)

Figure 4: (e) Response surface and (f) Contour plots of the dehulling efficiency $[\eta\ (\%)]$ against pairs of the coded values of speed (x_2) and labour required (x_3)

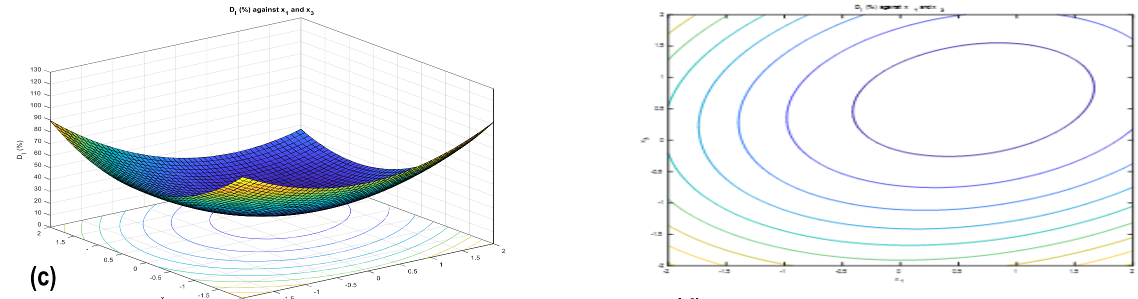
More so, Figures 5(a) and 5(b) shows that increasing time and speed decreases the mechanical damage index, Figures 5(c) and 5(d) show that increasing time and reducing labour required decreases the mechanical damage index, while Figures 5(e) and 5(f) show that increasing speed and reducing the labour required decreases mechanical damage index.



(a)

(b)

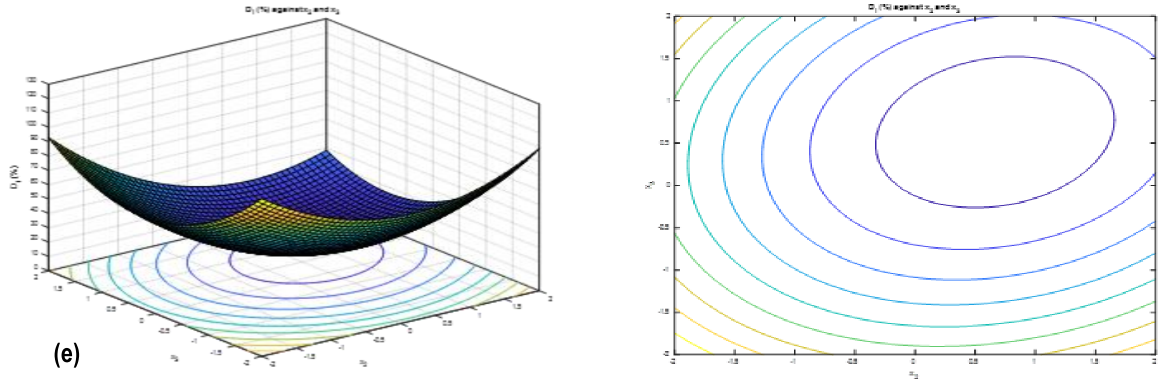
Figure 5: (a) Response surface and (b) contour plots of the mechanical damage index $[D_I\ (\%)]$ against pairs of the coded values of time (x_1) and speed (x_2)



(c)

(d)

Figure 5: (c) Response surface and (d) Contour plots of the mechanical damage index $[D_I\ (\%)]$ against pairs of the coded values of time (x_1) and labour required (x_3)



(e)

(f)

Figure 5: (e) Response surface and (f) Contour plots of the mechanical damage index $[D_I\ (\%)]$ against pairs of the coded values of speed (x_2) and labour required (x_3)

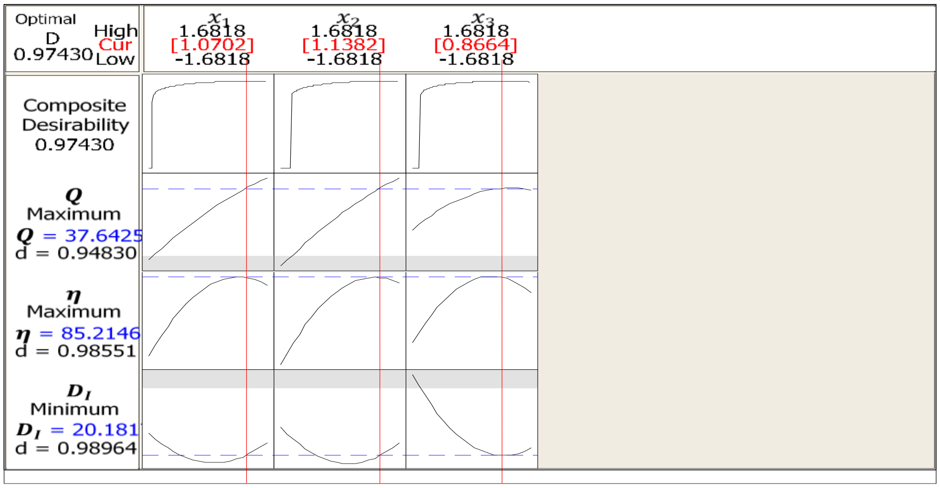


Figure 6: OptimPlot of the throughput $[Q\ (kg/hr)]$***, dehulling efficiency*** $[\eta\ (\%)]$ ***and mechanical damage index*** $[D_I\ (\%)]$ ***and the coded values of time (***x_1***), speed (***x_2***) and labour required (***x_3***).***

4.0 CONCLUSION

The optimum performance parameters of a developed African oil bean seed dehulling machine are presented in this study**.** Four performance indicators were considered: throughput, dehulling efficiency, mechanical breakage and labour requirement. The performance parameters were evaluated at a different speed between 331 rpm and 700rpm. The results indicate that the machine's throughput was highest at the first hour of the boiling time, estimated at 41.09 kg/hr (700rmp). Additionally, maximum dehulling efficiency exists at the fourth hour of the boiling time at 448 rpm and 95 % efficiency, while the highest mechanical breakage index (MDI) occurred at 700 rpm at the first hour of the boiling time. The association between the input variables (time, speed, and labour required) and the output variables (throughput, dehulling efficiency and mechanical damage index) were evaluated. The result shows that (i) increasing time and speed decreases mechanical damage, (ii) increasing time and reducing the labour required decreases the mechanical damage index, and (iii) increasing speed and reducing the labour required decreases the mechanical damage index. Furthermore, the global solutions contained in the optimplot and the iteration result indicate that at the optimal time, speed and labour required are respectively 4.1053hr (4hr, 6min), 43530rph (726rpm) and 3.85man-hr/kg. The values of the predicted response for Q, η and D_I are 37.642, 85.22, and 20.18 with the desirability of 0.948, 0.9855 and 0.989 respectively.

Acknowledgement

We acknowledged the National Research Fund (NRF) of Nigeria, Under the Tertiary Education Trust Fund (TETFund) for the financial support of this research.

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