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# DESIGN MODIFICATIONS AND PERFORMANCE EVALUATION OF A CENTRIFUGAL IMPACT PALM NUTS CRACKER

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**Abstract-** This study presented a modified centrifugal impact palm nuts cracker that will enhance cracking efficiency of the existing prototypes in traditional and small-scale oil palm mills in Southwestern Nigeria. This study focused on the effect of modified centrifugal impact blades and cracking ring at higher speed on physical properties, cultivar differences and drying period of the palm nuts. The physical properties of *Dura* and *Tenera* cultivars palm nuts were investigated prior to machine design. The modified prototype was developed and evaluated using palm nuts of three categories of geometrical mean diameters (GMD) at steady condition of 80 °C and drying periods of 15, 18 and 21 hrs. The results of the physical properties such as length, breadth, thickness, mass, GMD and sphericity were in the range 25.19-35.84 (mm), 18.69-26.44 (mm), 15.05-21.71 (mm), 4.60-11.57 (g), 19.10-27.58 (mm) and 0.75-0.77 (%); 26.90-33.97 (mm), 17.89-24.57 (mm), 14.32-20.44 (mm), 3.28-8.84 (g), 18.50-25.84 (mm) and 0.71-0.75 (%) for *Dura* and *Tenera* palm nuts cultivars, respectively. The optimum throughput at 15, 18 and 21 hrs drying periods were: 200 and 180, 240 and 218, 235 and 230 (kg/hr) for *Dura* and *Tenera* cultivars, respectively. The optimum cracking efficiency of 88% was obtained across all level of GMD, while the predicted value above threshold of 94% for *Dura* cultivar only. The damaged percentage and recovery efficiency have threshold of 8% and 6% for both cultivars, respectively. Hence, the determination of physical properties and drying condition prior to development and evaluation of this machine enhances its performance efficiently.

**Keywords:** Design modification, industrial revolution, cracking rings, throwing force, optimization.

## I. INTRODUCTION

The oil palm is a perennial tree crop that originated from West Africa but is now cultivated in plantations across tropical Africa, Southeast Asia and Southern America more than its origin (Mutsaers, 2019). It is botanically

known as *Elaeis guineensis*. The major varieties are *Dura*, *Tenera* and *Pisifera* (Adzimah and Seckley, 2009), but the commercial and most prominent cultivars are *Dura* and *Tenera* (Morakinyo and Bamgboye, 2015). The primary products of palm tree are palm fruits, palm wine, broom and timber. However, the secondary products are palm oil, palm nut; palm kernel and shells likewise palm kernel oil and cake. A palm fruit is made of a smooth outer skin (exocarp), a fibrous pulp (mesocarp) which contains palm oil, a centrally placed palm nut with hard shell (endocarp) and the kernel in which palm kernel oil is derived. Palm kernel oil is useful in making soap, biodiesel, glycerin, margarine, candle, pomade, oil paint and polish. The shells are used as biomass to fuel boiler and brake pad composite for automobile, while palm kernel meals or cakes are utilized to produce animal feeds (Gbadamosi, 2006; Adebayo, 2004; Emeka and Olomu, 2007). Palm kernel oil processing mills are not common as oil palm fruit processing mills in Nigeria, due to inadequate technological advancement in this sector. However, exportation of palm nut and kernel into Europe and North Asia countries from Nigeria and Indonesia is highly prolific (FAO, 2002). Recently, there is an industrial revolution that necessitated for increase in the demand of palm kernel and shell in the Southwestern Nigeria. This necessitated for promulgation of government policy by placing embargo on importation of palm kernel oil. The industrialization of this section has become desirable coupled with astronomical increase in the selling price of palm kernel oil. In order to meet up with high demand of this product, there is an urgent need to modify indigenous palm nut crackers for optimum cracking efficiency and durability. Previously, some researchers reported on the development of various palm nut crackers of different cracking mechanism such as centrifugal impact, hammer or rod impact and roller crackers (Adejuge et al., 2017; Kayo, 2006). Antia et al. 2014, investigated the optimum moisture content value and drying period that enhanced palm nut cracker efficiency. They reported that the optimum moisture content value and drying period were 2.5% (dry basis) and 18 hrs, respectively for both *Dura* and *Tenera* palm

nuts cultivars at maximum cracking efficiency of 84%. Most of the palm nuts crackers are indigenous prototypes installed in the traditional and small-scale oil palm mills. They were observed to lack engineering contents, basic engineering design procedures, the selection of appropriate materials of construction, precision in

machining of critical working components, applications of fits and tolerances in-between bearing housing and bearings. A typical palm nut cracker is shown in Figure 1, with a lot of leakages and undue vibration. However, for industrialization, critical modifications and optimization are still necessary in order to achieve higher efficiencies, durability and reliability. Hence this study.



Figure 1: Palm nuts cracker at Eleweeran, Ile-Ife

## II. MATERIALS AND METHODS

### 2.1 Materials

The materials for this study were *Dura* and *Tenera* palm nuts. The *Dura* cultivar palm nuts were obtained from oil palm mill at Eleweeran, Ede Road, Ile-Ife, Osun state, Nigeria with initial moisture content of about 23.5% (wet basis) while *Tenera* cultivar palm nuts of initial moisture content of about 22.8% were obtained from oil palm mill at Elere Adubi, Itori, Ogun State, Nigeria. The palm nuts of each cultivar were sorted and graded into three categories of axial dimensions: small, medium and large sizes. From the population of individual sizes were selected 100 pieces of palm nuts randomly to form eighteen samples in triplicates to be dried in three distinctive periods of 15, 18 and 21 hrs. Each category of small, medium and large sizes was kept inside labeled black polyethylene bag to determine physical properties using standard procedures according to their respective cultivar (Morakinyo and Bamgboye, 2015). The corresponding axial dimensions such as: length, breadth and thickness, geometric mean diameter, sphericity of each cultivar were measured using digital caliper while

their corresponding mass was determined using electronic digital weighing balance, model: Scout Pro SPU 401 with standard error of 0.001 mm. The average values of the geometrical mean diameters of both cultivars were calculated to categorize their sizes (18.80 mm, 22.46 mm and 26.72 mm) to reduce the experimental runs. The data obtained were used as machine design parameters for the prototype modifications.

All materials of construction were procured from Owode Onirin, Iron market, Ikorodu, Lagos. The exiting force convection biomass-fired cabinet drier of three tray compartments was used for the drying of eighteen samples at steady temperature of 80 °C to the final moisture content ranges from 3-5% (wet basis) at retention periods of 15, 18 and 21 hrs for *Dura* and *Tenera* cultivars consecutively. The drying operation was carried out for each drying period sequentially by loading 100 pieces of each sample of the geometrical mean diameter category in three replicate inside tray. However, for each drying period, six experimental runs were observed concurrently which summed up to eighteen experimental runs. The dried samples were kept inside desiccators for cooling and then cracked using modified centrifugal impact palm nuts cracker. The machine characteristics evaluated were throughput, the cracking efficiency, damaged percentage and the recovery efficiency for optimum purpose.

### 2.2 Method

#### 2.2.1 Mechanical Properties

The breaking force along longitudinal and axial directions of palm nut previously reported by Davies (2012) was adopted as 2.83 and 11.00 kN, respectively.

#### 2.2.2 Machine Design Considerations

The following factors were considered while designing the new prototype. The average geometrical mean diameter of the two palm nuts cultivars was used to determine the clearance between the beater and the cracking ring. However to eliminate high rate of abrasion of the cracking ring, high carbon steel material was hardened and tempered to the hardness value of 65 HRC. To achieve optimum impact force for effective cracking, high speed electric motor of 2850 rpm with the propelling impact of 3 ph was adopted. Four beaters impeller type was designed to ensure adequate and uniform cracking of the nuts. The beaters were arranged at quadrant pattern in equal inter-distance to each other. The driven shaft and bearing housings were machined using appropriate fits and tolerances. Balancing of impeller was achieved by grinding and re-weighing the individual beater as centrifugal arm on a digital weighing scale until equal weight was achieved to eliminate throwing force. After welding, the impeller was re-calibrated on the lathe machine for accuracy to avoid undue throwing forces.

## 2.3 Machine Design Calculations for the Modified Centrifugal Palm Nuts Cracker

### 2.3.1 The philosophy of cracking principle for modification

A palm nut falling vertically under a gravitational force through a hopper into a cracking mechanism exercising the potential energy was considered. This palm nut was assumed to fall on the surface of a rotating impeller blade at a horizontal level under a centrifugal force. It is assumed that this palm nut travelled at a distance equivalent to the cracking ring radius ( $r$ ). Its initial motion under the influence of propelling force of the impeller resulted to a centrifugal force, impacting kinetic energy on the dried palm nut blowing it against the inner diameter of a circular cracking ring (hard core) at a constant velocity resulting into rupture of the dried palm nut shell instantaneously. The optimization of cracking efficiency was conceptualized by increasing the impeller speed (2850 rpm) and impeller blades width (140 mm). This arrangement enables the four impeller blades to release their kinetic energies for cracking at least once and sequentially along their circular motion at varying angle impact before dried palm nut escape through discharge chute. The clearance between the tip of impeller blade and inner diameter of the cracking ring was determined using maximum geometrical mean diameter of palm nut. However, to avoid abrasion between two nuts, this value was doubled to arrive at equal clearance of 60 mm as shown in Figure 2.

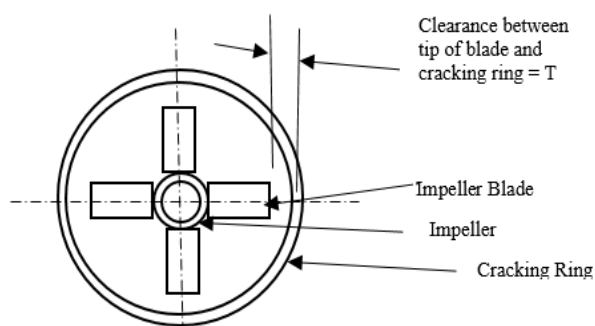


Figure 2: Cracking mechanism of palm nut cracker

Hence, Let  $M$  = mass of the palm nut in kg,  $r$  = radius of the circular cracking ring in mm,

$v$  = constant angular velocity of the palm nut.

The Equations 1-3 were adopted as reported by Khurmi (2005)

$$\text{Centrifugal acceleration of a body} = a = \frac{v^2}{r} \left( \frac{m}{\text{sec}^2} \right) \quad (1)$$

$$\text{The centrifugal force, } P_e = m \times \frac{v^2}{r} = m\omega^2 r \text{ (N)} \quad (2)$$

$$\text{However, } \omega = \frac{2\pi N}{60} \quad (3)$$

The application of increasing impeller speed as one of the design modification factors was considered.

The impeller speed selected was  $\frac{2850}{2}$  rpm = 1425 rpm,

$$\text{Hence } \omega = 149.3 \frac{\text{rad}}{\text{sec.}}$$

For the inner radius of the cracking ring of 130 mm and with *Dura* palm nut mass of 0.01157 kg, The centrifugal force =  $0.01157 \times 149.3^2 \times 130 = 33.521$  kN.

For *Tenera* of 8.84 g = 0.00884 kg, the centrifugal force generated = 25.62 kN.

These centrifugal forces calculated from above were generated from the proposed speed of the electric motor and average mass of *Dura* and *Tenera* palm nuts cultivars. These values were found to be higher than the longitudinal and axial breaking forces of palm nut previously reported by Davies (2012) as 2.83 and 11.00 kN, respectively; hence the design calculated values were adequate for effective cracking of both *Dura* and *Tenera* palm nuts cultivars.

### 2.3.2 Rotor/impeller shaft diameter determination.

Shaft length = 320 mm, rotor pulley selected =  $\Theta 100 \times 50$  mm,

Pulley Weight ( $W_P$ ) = 68.1 N, Palm Nut Weight ( $W_N$ )

$$W_N = \rho_N \times V_N \times g \quad (4)$$

where:  $g = 9.81 \text{ ms}^{-2}$ ,  $\rho_N$  = Bulk density of palm nut =  $38.5 \text{ kg/m}^3$ ,  $V_N$  = Volume of hopper =  $0.010125 \text{ m}^3$ , Hence,  $W_N = 3.824$  N, Hub and beater weight ( $W_B$ ).

$$W_B = \rho_B \times V_B \times g \quad (5)$$

where:  $\rho_B = 7850 \text{ kg/m}^3$  (steel),  $g = 9.81 \text{ ms}^{-2}$

$$V_B = (\pi r^2 \times t_p) + 3(l \times w \times t) \quad (6)$$

$$W_B = 47.81 \text{ N}$$

Hence, the point of contra-flexure is the point where shear force changed from negative to positive value, and has a corresponding maximum bending moment  $M$  at point E of a value 4.771 Nm in Figure 3 and Table 1. where:  $P = 2 \text{ hp} = 1490 \text{ W}$ ,  $N = 2880 \text{ rpm}$  and  $\tau = 42 \text{ MPa}$ , Torque transmitted by impeller shaft  $T = \frac{P \times 60}{2\pi N} = 4.94 \text{ Nm}$

The equivalent twisting moment  $T_e$  is then evaluated as

$$T_e = \sqrt{M^2 + T^2} = 6.887 \text{ Nm} \quad (7)$$

$$T_e = \frac{\pi \times \tau \times d^3}{16} \quad (8)$$

$$d^3 = 832.82 \text{ mm}^3, d = 9.41 \text{ mm},$$

Taking factor of safety as 3 (Khurmi and Gupta, 2006).

$$\text{Hence } d = 9.41 \times 3 \approx 30 \text{ mm.}$$

### 2.6.3 Bearing selection

In assumptions of these parameters where: number of rows of balls ( $i$ ), Number of balls per row ( $Z$ ) = 10, Diameter of balls ( $D$ ) = 10 mm, Radial load factor ( $f_0$ ) = 12.3, Nominal angle of contact ( $\alpha$ ) =  $20^\circ$ . The basic static radial load rating for roller bearing ( $C_o$ ) was calculated as shown in Equation 9.

$$C_o = f_0 i Z D^2 \cos \alpha = 12.3 \times 1 \times 10 \times 10^2 \cos 20 = 11558.22 \quad (9)$$

For a bore of 30 mm and outer diameter 72 mm, with corresponding width of 19 mm, the corresponding roller bearing number selected was 306 (Khurmi and Gupta, 2006).

### Determination of impeller speed, v-belt pitch length and type.



The impeller speed was obtained from v-belt drive ratio as depicted in Equation 10.

$$\frac{N_1}{N_2} = \frac{D_2}{D_1} \quad (10)$$

Where:  $N_1$  = Speed of electric motor in rpm,  $N_2$  = Speed of impeller shaft in rpm,  $D_1$  = Diameter of electric motor pulley in mm,  $D_2$  = Diameter of impeller shaft in mm.

The speed of a 3-phase, 50 Hz induction electric motor used was 2850 rpm. If  $D_1 = 200$  mm,  $D_2 = 100$  mm, hence,  $N_2 = 1425$  rpm (Enemuoh et al., 2013).

However, the distance 'C' between the centers of the two pulleys was taken as 270 mm being the smallest distance between the two pulleys. Morakinyo *et al.* (2014) reported the pitch length of an open v-belt drive in mm as shown in Equation 11.

$$L = 2C + \frac{\pi(D-d)}{2} + \frac{(D-d)^2}{4C} \quad (11)$$

By applying Equation 11,  $L = 660.4$  mm = 26 inches. This value is correspond to v-belt number A-26, as reported in the Table for v-belt and load selection reported by Shigley et al. (2004).

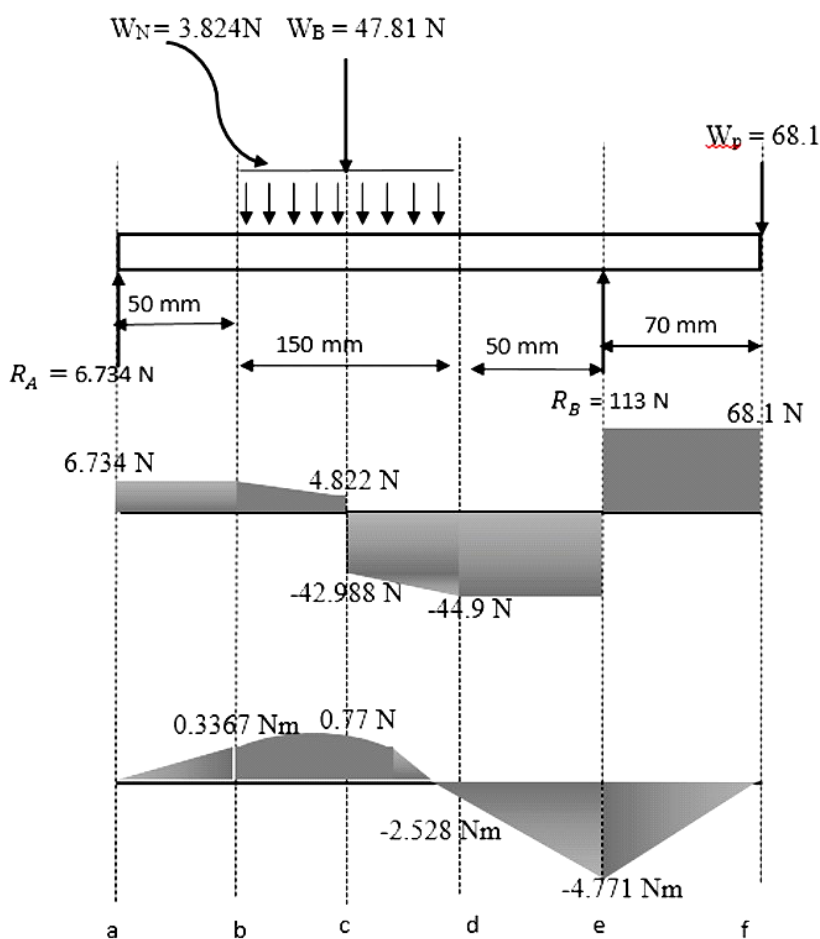


Figure 3: The Shear force and bending moment diagrams

Table 1: Table of shear force and bending moment diagram

Parameter	A	B	C	D	E	F
Shear Force (N)	6.73	6.73	4.82	-42.99	-44.90	68.10
Bending Moment (Nm)	0	0.34	0.77	-2.53	-477	0



**2.7 Description of Modified Centrifugal Palm Nuts Cracker**

The modified centrifugal palm nut cracking machine consists of centrifugal impeller, impeller shaft, cracking ring, cracking ring housing, roller bearing and bearing housing, hopper and discharge chute, pulleys, V-belt, support frame and high speed electric motor as shown in Figures 4 and 5.

**i. Centrifugal impeller**

It was made of high-carbon steel material; consist of a bushing and four equal weights of impeller as shown in Figure 5. The bushing was of  $\Theta 60 \times \Theta 30 \times 140$  mm, while

Impeller blades were of rectangular shape of  $75 \times 140 \times 15$  mm. Both were machined to accurate shape and hardened and tempered to the hardness value of 65 HRC.

**ii. Impeller shaft**

This was made of medium-carbon steel of  $\Theta 30 \times 320$  mm as shown in Figures 4 and 5. It was stepped turned at both sides to accommodate roller bearings. Appropriate fits and tolerances were observed in the assembly of the shaft, impeller bushing, bearings and pulley.

**iii. Cracking rings**

The cracking rings were made out of leave springs, forged into two half-rings of  $\Theta 290$  mm  $\times$  180 mm width, having thickness of 15 mm with perforated holes for mushroom fasteners fittings at four quadrant locations in each half -ring. They were screwed to the cylindrical housing. Beneath these rings and ring housing, a discharged opening of  $70 \times 70$  mm hole was created to discharge cracked shell and kernel out of the cracking rings.

**iv. Cracking rings housing**

$$M_t = \frac{\text{Weight (kg)}}{\text{Time Taken (hr)}} \tag{11}$$

**2.2.2 Cracking efficiency**

The cracking efficiency is the ratio of the number of cracked nuts to the total number of nuts fed into the cracker expressed in percentage. This was determined using the

where,

$C_{EFF}$  is the Cracking efficiency (%),

$N_C$  = the number of the cracked;  $N_T$  is the initial total number of the nuts

was made of low-carbon steel material of a cylindrical shape as shown in Figures 4 and 5. It has diameter of 300 mm, width of 150 mm and thickness of 5 mm. There are two outer cover plates made of low-carbon steel of  $\Theta 300 \times 5$  mm thickness with a center hole which accommodate impeller shaft. At the upper part,  $150 \times 150$  mm hole was made to position hopper.

**v. Hopper**

The hopper was made of low-carbon steel material of 2.5 mm thickness of a trapezoidal shape; through which the materials were fed into the cracking unit. It has dimensions of  $300 \times 150 \times 150$  (mm) equivalent to a volume of  $0.010125 \text{ m}^3$  using Equation 10.

$$V_h = \frac{1}{2} (a + b) \times h \times l \tag{10}$$

**vi. The frame**

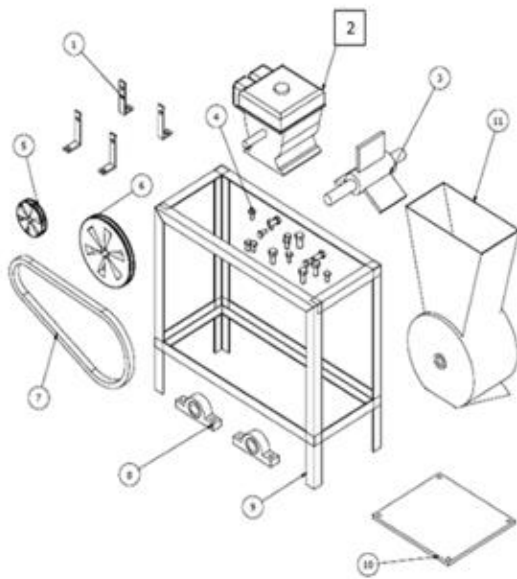
This was made of angle iron of  $60 \times 60 \times 4$  (mm) having a vertical height, breadth and length of  $410 \times 270 \times 620$  (mm), for the positioning of cracking ring housing, bearings and electric motor.

**2.8 Performance Evaluation of the Machine**

The throughput of the machine was evaluated by weighing 100 pieces of palm nuts and feeding them into the machine through the hopper. The cracker was operated at a constant speed of 2850 rpm, as one of the modifications factor in this prototype, higher than the speed of electric motor previously reported ( Koya, 2006, ; Antia et al., 2014). The cracking period was recorded for each cracking operation. This procedure was replicated for each sample from three trays for the corresponding size and cultivar. The average machine throughput ( $M_i$ ) was calculated using Equation 11.

mathematical expression reported by Gbabo et al. (2013) depicted as Equation (12).

$$C_{EFF} = \frac{N_C}{N_T} \times 100 \tag{12}$$



PARTS LIST		
ITEM	QTY	PART NUMBER
1	4	Guide
2	1	Prime Mover
3	1	Beater
4	16	Bolts and Nuts
5	1	Prime Mover Pulley
6	1	Beater Pulley
7	1	Belt
8	2	Bearing
9	1	Frame
10	1	Slab
11	1	Hopper



Figure 4: Exploded view of a modified palm nuts cracker Figure 5: The developed centrifugal palm nuts cracker

This

### 2.2.3 Damaged percentage

The damaged percentage is the ratio of the number of broken nuts to the total number of nuts fed into the cracker expressed in percentage. This was determined using the expression reported by Gbabo et al. (2013) depicted as Equation 13.

$$D_{DP} = \frac{N_B}{N_T} \times 100 \quad (13)$$

where,

$D_{DP}$  is the damaged percentage (%),  $N_B$  = the number of the broken nuts

$N_T$  is the initial total number of the nuts

### 2.2.4 Recovery efficiency

The recovery efficiency is the ratio of the un-cracked nuts to the total number of the nuts before cracking. This is expressed in percentage as reported by Gbabo et al. (2013). This was determined using Equation (14).

$$R_{EFF} = \frac{N_{UN}}{N_T} \times 100 \quad (14)$$

where,

$R_{EFF}$  is the recovery efficiency (%),  $N_{UN}$  = the number of unbroken shelled nuts

$N_T$  is the total number of nuts

### 2.3 Data Analysis

The experimental data of the physical properties were analyzed using descriptive and inferential statistics to determine means and standard deviation. However, experimental design for the performance characterizations of the modified centrifugal palm nut cracker was generated using Response Surface

Method with Multilevel-Categoric Factors of Design-Expert 11.1.0 (Stat-Ease, Inc., 2019). Table 1 showed the 3 Categoric factors of  $2 \times 3 \times 3$  factorial design as cultivar, geometrical mean diameter (size) and drying period, respectively. Eighteen experimental runs were generated and corresponding four responses (cracking efficiency, throughput, and damage percentage and recovery efficiency) were obtained during each run. The optimum performance characterizations of this machine were established.

## III. RESULTS AND DISCUSSIONS

### 3.1 Physical properties of the palm nuts

Tables 3 -4, showed the results of the physical properties of palm nuts such as length, breadth, thickness, mass, geometrical mean diameter and sphericity ranges of both palm nuts cultivars at their respective initial moisture contents.

### 3.2 Results of performance evaluation of the machine

The performance characterizations of the machine evaluated were the responses of the experimental design which were: throughput, the cracking efficiency, damaged percentage and the recovery efficiency. The results of the performance evaluation are shown in Table 5.

#### 3.3.1 The throughput

It was observed that increased in the weight of the palm nut increased the throughput and likewise the optimum throughput occurred at 18 hrs of drying period. This observation could be validated by considering Figures 3-5, in which the throughputs



of *Dura* and *Tenera* palm nuts cultivars increase relatively to the increase in their geometrical mean diameters. More importantly, throughputs of the *Dura* palm nuts cultivar were found to be higher at geometrical mean diameter and drying period of 26.72 mm and 18 hrs, respectively. This same trend was reported by Antia et al. (2014). Considering Table 6 of ANOVA, all categorical factors such as cultivar, geometrical mean diameter and drying period influenced significantly the throughput of the modified centrifugal palm nuts cracker. In Table 6, the p-values was less than 0.0500, likewise the Model F-value of 15.35 implies that the model was significant. Furthermore, since the predicted  $R^2$  of 0.6958 obtained was reasonably agreed with the Adjusted  $R^2$  of 0.8084 and their differences was less than 0.2, hence categorical factors A, B, C were significant model terms for optimizing throughput value. The adequate signal to noise ratio of 13.681 was also obtained which was highly desirable since the value was greater than 4. Considered Figures 6-8, the throughput increased relatively to geometrical mean diameters (GMD) of both cultivars. At 15, 18 and 21 hrs drying period, the optimum throughputs were: 200 and 180, 240 and 218, 235 and 230 (kg/hr) for *Dura* and *Tenera* cultivars, respectively. In all the Figures red points indicated design points above predicted values, while pink points indicated design points below the predicted values and black points symbolized predicted values. Considering Figure 9, the predicted throughput for *Dura* and *Tenera* was 235 and 215 (kg/hr), respectively. However, design point above predicted value for *Dura* and *Tenera* cultivars was 255 and 205 (kg/hr), respectively. The variability may be due to their shell thickness as reported by Ebunilo and Ojariafe, (2014) and Koya, 2006. They reported the cracked shell thickness of the fresh palm nuts of *Dura* and *Tenera* as 7.0 and 6.0 (mm) respectively. They also reported that the average cracked shell thickness after drying operations at 180 °C and 170 °C of *Dura* and *Tenera* cultivars palm nuts were 4.5 mm and 3.3 mm, respectively. This shows that *Tenera* cultivar shell has tendency of higher moisture migration that *Dura* cultivar even at almost the same drying temperature and retention time. This was the reason why *Tenera* cultivar has higher optimum throughput and cracking efficiency at 18 hrs drying period while *Dura* cultivar occurred at 21 hrs drying period. In summary, as the drying period increased from 15 -21hrs, the throughput for both cultivars increased from 140 to 255 kg/hr.

### 3.3.2 Cracking Efficiency

It also observed that as the geometrical mean diameter increased which correlated to the increase in weight of *Dura* and *Tenera* palm nuts cultivars, the cracking efficiency at each drying period almost remain constant, but *Dura* palm nut cultivar was found to be higher at 18 hrs of drying period than *Tenera*. In Table 7, the P-values were less than 0.0500 while Model F-value of 9.93, both indicated that the model was significant. In this case only drying period among all categorical factors has significant model term. The Predicted  $R^2$  of 0.3802 was reasonably agreed with the Adjusted  $R^2$  of

0.5122; since their difference was less than 0.2. However, only 0.18% chance that an F-value could occur due to signal to noise ratio of 5.797, which indicated adequate signal occurred within all categorical factors. In Figure 10, the optimum cracking efficiencies at drying period of 15 hrs for both cultivars were almost the same of an average value of 74%. However, in *Dura* cultivar, the design points above predicted values were on increased relative to GMD of palm nuts samples, hence the cracking efficiency increased from 74% to 80%. But contrary to that in *Tenera* cultivar, in Figure 10 of drying temperature of 15 hrs, the design point below predicted value of the cracking efficiency decreased relative to geometrical mean diameters from 26.22 to 18.80 (mm). Considering Figure 11, as drying temperature increased to 18 hrs, the optimum cracking efficiencies were almost at the threshold value of 88% in all three levels of GMD of both cultivars. However, the cracking efficiencies design points above predicted were almost equal to that of the optimum value across all the GMD of *Dura* cultivar palm nuts. In contrary to this observation, in *Tenera* cultivar, the design points above predicted value of cracking efficiency increased to 94% from design point of 88%, most especially at the GMD of 26.22 mm. In Figure 12, as drying temperature increased to 21 hrs, the optimum cracking efficiency decreased to 87% across the cultivars and GMD, while design points above predicted values increased to 94% in *Dura* cultivar only but contrary to this observation, in *Tenera*, design points below predicted values occurred and it decreased as the GMD of palm nuts decreased. The variability in their cracking efficiencies at equal drying temperature may be due to difference in their physical and mechanical properties regards to mass and thickness of the palm nut shell which ultimately influenced differences in their cracking force requirement as reported by Gbadamosi, (2006) and Ebunilo and Ojariafe, (2014).

In Figure 13, it was observed that *Tenera* has optimum cracking efficiency of 95% occurred at 18 hrs of drying period, while that of *Dura* cultivar occurred at 21 hrs. Furthermore, in Figure 13, the optimum cracking efficiency increased linearly from 75-90% in both cultivars relatively to the drying period from 15 hrs to 18 hrs, but decreased to 87% and 85% for *Dura* and *Tenera* cultivars, respectively. These observations were earlier reported by Ndukwu and Asoegwu, (2011); Morakinyo and Bamgboye, (2015); Morakinyo and Bamgboye, (2019).



Table 3: Results of the physical properties of Dura cultivar palm nuts at 23.5% (wet bases) moisture content.

Palm nuts size	Length (mm)	Breadth (mm)	Thickness (mm)	Mass (g)	Geometric Diameter (mm)	Mean	Sphericity (%)
Small	25.19±4.30	18.69±2.07	15.05±1.75	4.60±0.75	19.10±1.32		0.75±0.05
Medium	30.24±4.47	22.44±2.26	17.36±2.03	7.08±1.14	23.05±1.40		0.82±0.03
Large	35.84±4.80	26.44±2.53	21.71±2.27	11.57±2.09	27.58±3.30		0.77±0.02

Table 4: Results of the physical properties of Tenera cultivar palm nuts at 22.8% (wet bases) moisture content

Palm nuts size	Length (mm)	Breadth (mm)	Thickness (mm)	Mass (g)	Geometric Diameter (mm)	Mean	Sphericity (%)
Small	26.90±4.21	17.89±1.90	14.32±1.62	3.28±0.62	18.50±2.86		0.71±0.02
Medium	28.34±4.21	20.90±2.10	16.53±1.52	5.35±0.68	21.86±3.06		0.72±0.06
Large	33.97±5.23	24.57±2.72	20.44±1.93	8.84±1.59	25.84±3.15		0.75±0.07

TABLE 5: Result of the performance characterizations of the modified palm nut cracker

Run	Factor 1 Cultivar	Factor 2 Geometrical Mean Diameter	Factor 3 Drying Period	Response 1 Throughput	Response 2 Cracking Efficiency	Response 3 Damage Percentage	Response 4 Recovery Efficiency
		Mm	Hr	kg/hr	%	%	%
1	TENERA	26.72	15.00	180	75	5	20
2	TENERA	18.80	21.00	140	72	16	2
3	DURA	26.72	21.00	255	95	2	3
4	DURA	18.80	21.00	190	92	7	1
5	DURA	26.72	15.00	195	76	20	4
6	DURA	18.80	18.00	180	88	3	9
7	DURA	22.46	18.00	225	90	3	7
8	TENERA	18.80	15.00	150	70	16	14
9	TENERA	26.72	21.00	205	85	12	3
10	DURA	26.72	18.00	230	90	4	6
11	DURA	18.80	15.00	165	78	5	7
12	TENERA	22.46	18.00	210	90	8	2
13	DURA	22.46	15.00	182	80	14	6
14	TENERA	26.72	18.00	235	95	1	5
15	TENERA	22.46	21.00	195	86	12	2
16	DURA	22.46	21.00	230	94	3	3
17	TENERA	18.80	18.00	175	82	4	4
18	TENERA	22.46	15.00	160	72	16	2

Table 6: ANOVA for selected factorial model Response 1: Throughput

Source	Sum of squares	Df	Mean square	F-Value	P-Value
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Model	14779.44	5	2955.89	15.35	< 0.0001	Significant
A-Cultivar	2266.89	1	2266.89	11.77	0.0050	
B-Geometrical Mean Diameter	7800.44	2	3900.22	20.25	0.0001	
C-Drying Period	4712.11	2	2356.06	12.23	0.0013	
Residual	2311.00	12	192.58			
Cor. Total	17090.44	17				

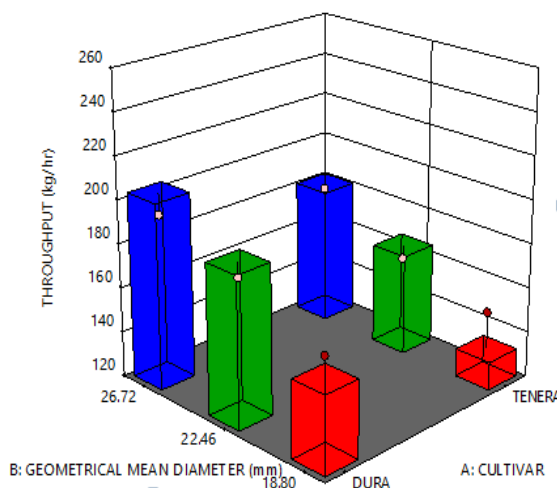


Figure 6: Optimum throughput at drying period of 15 hrs for both cultivars.

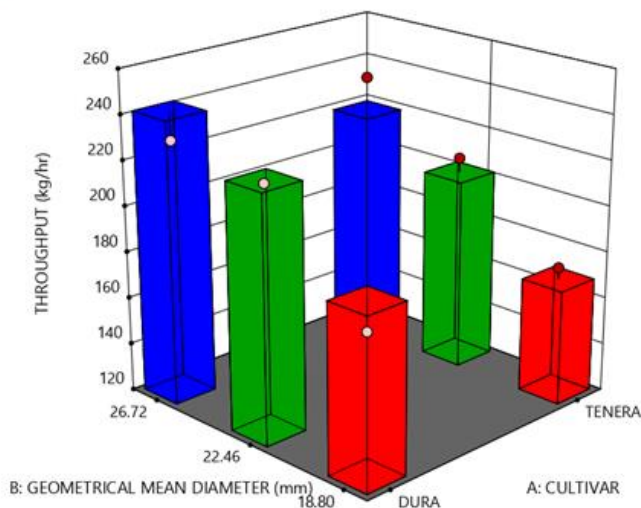


Figure 7: Optimum throughput at drying period of 18 hrs for both cultivars.

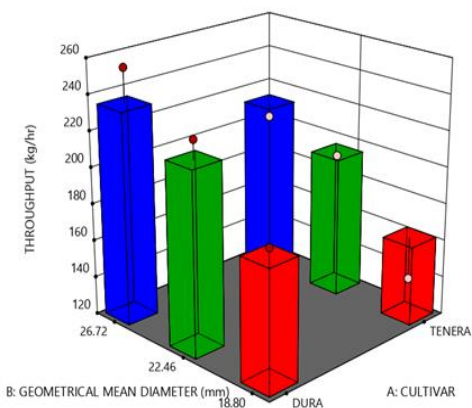


Figure 8: Optimum throughput at drying period of 21 hrs for both cultivars

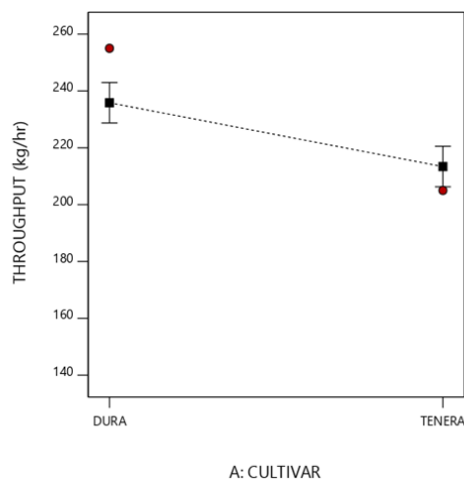


Figure 9: Comparison of throughput predicted design points and actual values at maximum categorical factors values for the cultivars



### 3.3.3 The Damage percentage

The damage percentage was almost constant irrespective of varying in the experimental factors in both *Dura* and *Tenera* palm nuts cultivars. For example in Table 8, there were no P-values, likewise no significant model terms among the categorical factors. The Predicted R<sup>2</sup> was negative, which implies that the overall mean may be a better predictor of response than the current model. This was the reason why in Figure 17, a horizontal line indicating a uniform damaged percentage value of 8% that cut across both cultivars. These could be validated by considering Figures 14-16, where there was no significant difference in their damaged percentage across the GMD and drying temperature. However, design points above predicted values were on increased to a value of 19% in *Dura* cultivar at GMD of 26.72 mm during constant

drying period of 15 hrs, while that of *Tenera* cultivar was at 15% on both GMD of 18.80 and 22.46 mm. Conversely, in Figures 14 - 16, the design points were below predicted values except in *Tenera* cultivar.

Table 7: ANOVA for selected factorial model Response 2: Cracking Efficiency

Source	Sum of Squares	Df	Mean Square	F-value	p-value
Model	694.78	2	347.39	9.93	0.0018 Significant
C-Drying Period	694.78	2	347.39	9.93	0.0018
Residual	525.00	15	35.00		
Cor Total	1219.78	17			

Table 8 : ANOVA for selected Factorial Mode Response 3: Damage Percentage

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	0.0000	0			
Residual	612.28	17	36.02		
Cor Total	612.28	17			

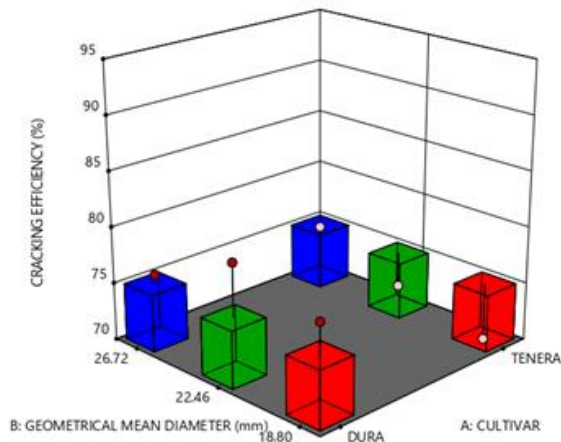


Figure 10: Optimum cracking efficiency at drying temperature of 15 hrs for both cultivars.

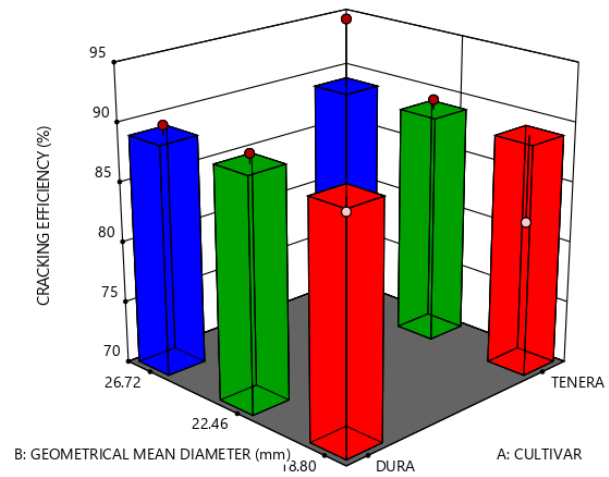


Figure 11: Optimum cracking efficiency at drying period of 18 hrs for both cultivars.

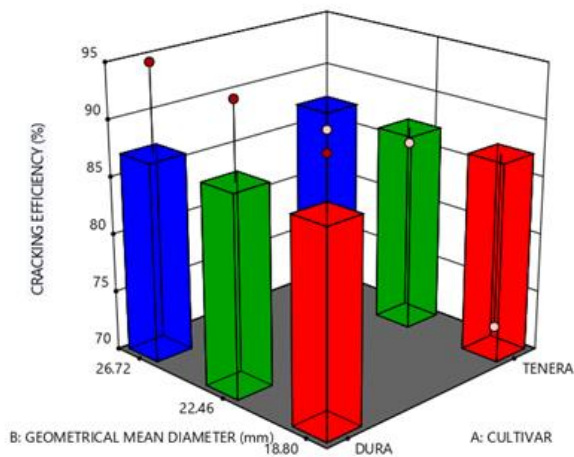


Figure 12: Optimum cracking efficiency at drying period of 21 hrs for both cultivars

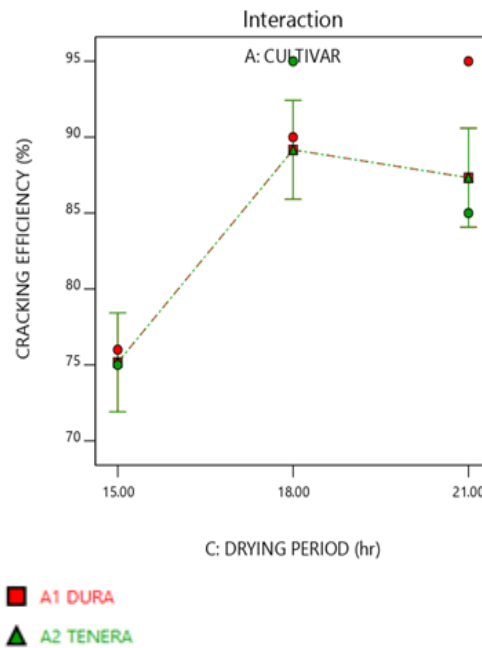


Figure 13: Comparison of cracking efficiency for Dura and Tenera cultivars at varying drying temperatures and 26.72 mm geometrical mean diameter.

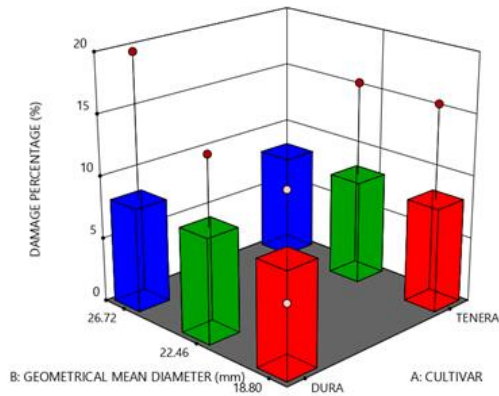


Figure 14: Optimum damaged percentage at drying temperature of 15 hrs for both cultivars.

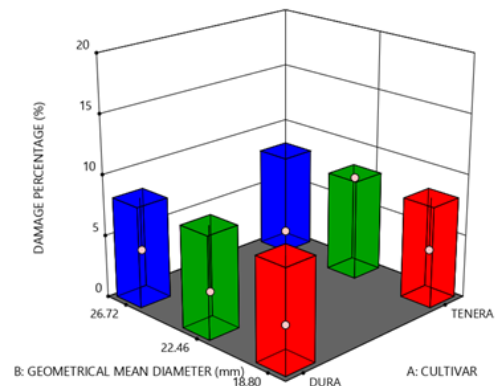


Figure 15: Optimum damaged percentage at drying period of 18 hrs for both cultivars.

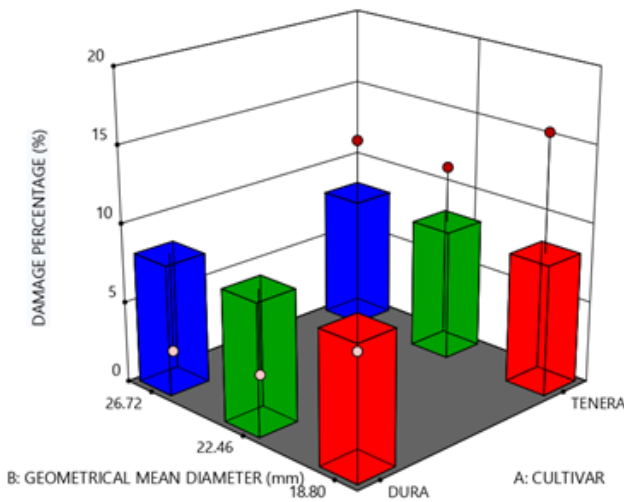


Figure 16: Optimum damaged percentage at drying period of 21 hrs for both cultivars

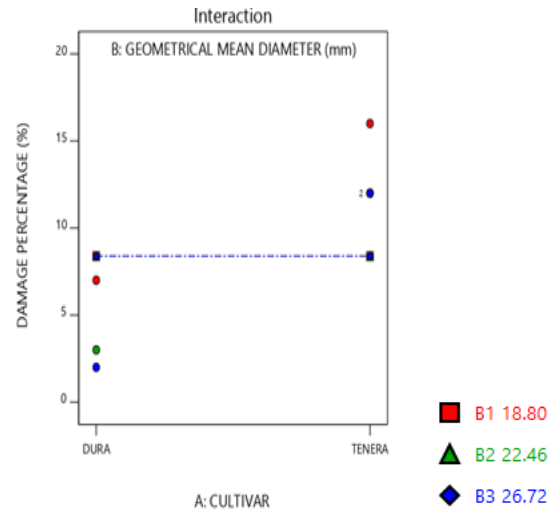


Figure 17: Comparison of damaged percentage for *Dura* and *Tenera* cultivars at varying drying temperatures and 26.72 mm geometrical mean diameter.

Table 9: ANOVA for selected factorial model Response 4: Recovery Efficiency

Source	Sum of Squares	Df	Mean Square	F-value	p-value
Model	0.0000	0			
Residual	392.44	17	23.08		
Cor Total	392.44	17			

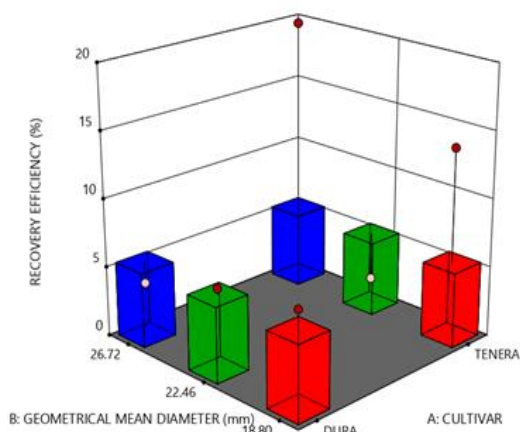


Figure 18: Optimum recovery efficiency at drying temperature of 15 hrs for both cultivars.

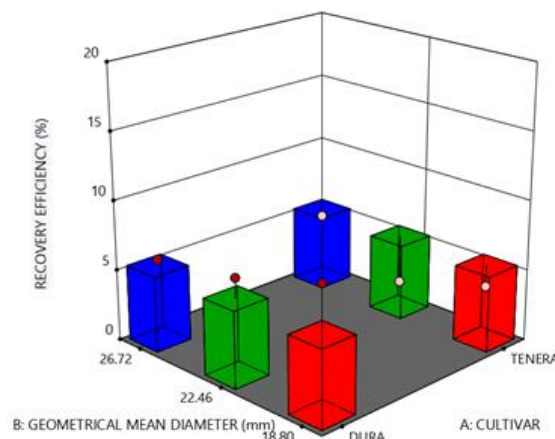


Figure 19: Optimum recovery efficiency at drying period of 18 hrs for both cultivars.

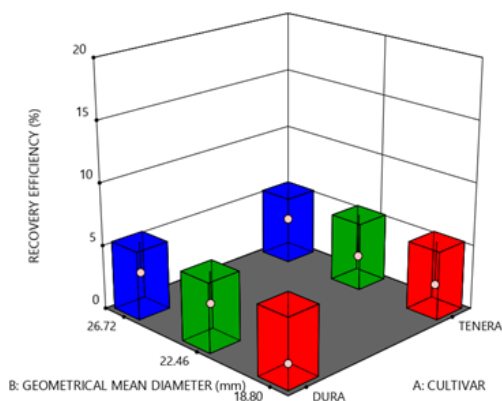


Figure 20: Optimum recovery efficiency at drying period of 21 hrs for both cultivars

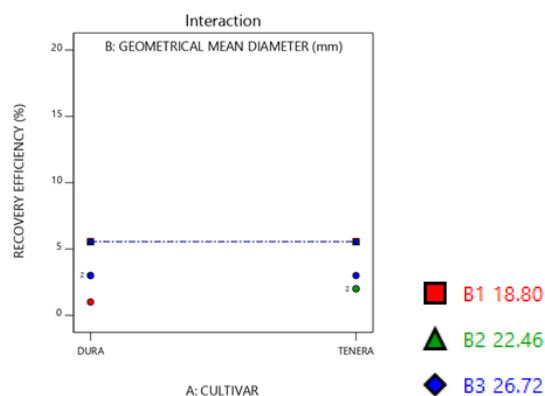


Figure 21: Comparison of recovery efficiency for *Dura* and *Tenera* cultivars at varying drying temperatures and 26.72 mm geometrical mean diameter.

#### IV. CONCLUSIONS

The determination of the physical properties has enhanced appropriate configuration of clearance between the tip of centrifugal impeller to the inner diameter to achieve optimum throughput, cracking efficiency, minimum damaged and recovery percentages. The optimum throughput increased relatively to geometrical mean diameters (GMD) of both cultivars. At 15, 18 and 21 hrs drying period, the optimum throughputs were 200 and 180, 240 and 218, 235 and 230 (kg/hr) for *Dura* and *Tenera* cultivars, respectively. The optimum cracking efficiency of 88% was obtained across all level of GMD, while predicted value above this threshold was 94% for *Dura* cultivar only, which were found higher than values obtained by previous researchers reported. Among all categorical factors, only throughput and cracking efficiency influenced optimization model terms to be significant at level of  $P > 0.0500$ , while others such as damaged percentage and recovery efficiency were insignificant factors. Damaged

percentage and recovery efficiency have threshold of 8% and 6%, respectively. Hence, the determination of physical properties and inferential statistical analysis, before embarking on development of the modified centrifugal palm nuts cracker improved performance characteristics and reduced damaged percentages.

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