Development of a modified palm-nut cracker

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Abstract: This study examined the major shortcomings of conventional crackers, and developed a modified palm-nut cracker with the view of reducing the level of mechanical kernel damage. Equation relating the required speed for cracking operation and force requirement in fracturing the nut was expressed, and the force was experimentally determined before machine development. The machine was designed and fabricated based on standard engineering principles for part-sizing and selection of materials. The machine was tested with *dura* nuts classified into four groups of sizes and varied during experimentation. The performance evaluation of the machine show that cracking efficiency ranged between 86.10%-97.27% at an average value of 4.59% kernel breakage and whole kernels ranging between 94.85%-95.97%. Analysis of results using Minitab 17 show that efficiency of the machine was influenced by nut sizes and variation in the selected feed rates. The result indicated that the machine is suitable for processing, palm nuts of all sizes when operated at moderate feed rates.

Keywords: palm-nut cracker, nut cracking, feed rate, cracking efficiency, performance evaluation

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1 Introduction

The cracking of palm nut, a composite biomaterial consisting of an outer hard shell and embedded softer kernel, which is extracted for the production of Palm Kernel Oil (PKO) leaving the palm kernel meal as residue, is a significant step that usually affects the quality of thekernel. Hence, thepreservation of this fragile kernel embedded in the palm nut is very important and depends, among other things, on efficient nut-cracking, which enhances effective kernel-shell separation as well as the subsequent quality of the palm kernel oil (Koya and Faborode, 2005; Gbadam et al., 2009). Cracking occurs when a material breaks without entire separation and nut-cracking, therefore, occurs when palm-nuts are loaded to rupture without crushing the embedded kernel. Prior to cracking, the nuts are dried sufficiently to enable the kernel shrink away from the shell, in order to reduce kernel breakage. The nuts are then cracked in a machine or manually (Manuwa, 1997; Koya and Faborode, 2005).

Palm nut cracking machines are developed on the principle of hurling of the palm nuts at a fairly high speed against astationary hard surface (Okoli, 1997). Generally, there are two types of modern crackers, the hammer-impact and the centrifugal-impact types. The hammer-impact type breaks or cracks the nut by the impact when the hammer falls on the nut, while the centrifugal-impact nut cracker uses centrifugal action to crack the nut.

The economic importance of palm kernel is indicated by its extensive use as food, traditional medicine, and in the cosmetic and confectioneryindustries (Akinoso et al., 2009; Koya et al., 2004). In view of these, its demand in global markets has ever been increasing and interest in the effective palm kernel extraction is growing.

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In the recent years, various researchers and engineers (Ilechie, 1985; Babatunde and Okoli, 1988; Manuwa, 1997; Obiakor and Babatunde, 1999; Olakanmi, 2004; Koya and Faborode, 2005; Koya, 2006; Olukunle et al., 2008; Jimoh and Olukunle, 2012) had developed different types of prototypes and concepts for mechanized palm nut cracking devices. So far, palm nut cracking operation had recorded certain level of feat, the process however has quite a number of deficiencies, notably, high operational speed of the existing cracking devices makes design modification a necessity in order to minimize mechanical damage and improve the recovery of the products. Other defects of the existing crackers include: kernels breakages, which may be due to insufficient nut dryness, uncracked nuts in the finished product, which may be caused by inappropriate spacing of blow bars as well as the high nut feeding rate into the cracking chamber. Fortunately, the knowledge of minimum impact force required for nut cracking relevant to the design improvement of the existing mechanical nutcrackers has been investigated (Ofei, 2007; Koya and Faborode, 2005). The focus of this study was therefore aimed at developing a modified palm-nut cracker that minimizes kernel breakage for enhanced subsequent product separation.

2 Materials and methods

2.1 Analysis of nut cracking process

In order to estimate the impact force on the nut impinging on the cracking ring, the kinetic energy of the moving nut is equivalent to the energy absorbed upon impact (Koya, 2006). Thus; for a centrifugal impact cracker to impinge the palm nuts repeatedly against the stationary wall of the cracking chamber:

Kinetic energy = Energy absorbed upon impact

That is

$$\text{Energy absorbed upon impact} = \frac{1}{2} mv^2 \qquad (1)$$

Where v is the speed of impacted particles, ms^{-1} and m is a mass of the nut, kg.

But energy absorbed upon impact is the average work (denoted as W) required to deform the nut (Khurmi and Gupta, 2005).

Therefore

$$W = \frac{F}{2} \times d \qquad (2)$$

Where F is the applied force (otherwise referred to as cracksforce, N) to the nuts and d is the deformation of the nut, m. Equation 2 expresses the energy of nut deformation, Nm.

Consequently

$$\frac{1}{2} mv^2 = \frac{F}{2} \times d$$

Therefore

$$F = \frac{mv^2}{d} \qquad (3)$$

From Equation 3, the following relationship for the determination of operational speeds required for palm nut cracking applies:

$$v = \sqrt{\frac{Fd}{m}} \qquad (4)$$

2.2 Experimental determination of nut cracking force

The cracking force (F) required to crack different nut sizes were experimentally determined using the Instron Universal Testing Machine (INSTRON 3369, USA) as shown in Figure 1.This was achieved by determining the compressive loads to induce nut breakage, as well as their corresponding energy of nut deformation. The testing machine was connected to a computer equipped with the appropriate software which monitored and plotted the load-deformation curves for the specimen of palm nut being tested.

The required speeds for palm nut cracking shown in Table 1, were then determined using Equation 4.

Hence, for repeated impact on the nut by the modified machine, the speed found suitable to implement palm nut cracking at relatively minimum impact which may minimize mechanical damage, was taken as 10.32 ms^{-1} (86 $rads^{-1}$) when compared with the speed for cracking process whenBuckingham's π theorem was used in a recent study (Alade, 2017).

Figure 1 Loading of palm nut sample for compression load test between two parallel plates

Table 1 Operational speeds determined for palm nut cracking

Nut	*Dura* (Moisture Content, 13.4%)				Remark
Properties/sieve size (mm)	10	14	20	25	
Mass (10^3 kg)	3.02	5.16	10.41	11.88	Koya et al. (2004).
Energy of deformation (Nm)	0.3988	0.9496	1.0516	1.1718	Alade (2017)
Required speed (ms^{-1})	16.25	16.72	14.21	14.05	Computed using Equation 4

2.3 Machine description and development

The modifications made in addressing the identified sho rtcomings were nuts pre-screening and grading into large, medium and small size categories for cracking; repeated impact cracking of the graded nuts using the determined minimum cracking speed and incorporation of external kernel-shell pre-cleaner cum classifier with the cracker. The modified palm-nut cracker therefore mainly consists of a hopper, cracking chamber and pre-cleaner cum classifier. Palm nuts are primarily pre-screened to remove dirt and immature nuts, categorized into four size grades and then loaded into the machine through the hopper, in batches for nut cracking. The cracker mixture is then transported to the external pre-cleaner cum classifier, to further remove dirt, immature kernels and smaller shell particles, before proceeding to classify the mixture of kernel and shell based on their sizes.

2.3.1 The hopper

The hopper (Figure 2) is essentially the inlet for the palm nuts into the machine and regulated through the feed gate. It was made of 2 mm mild steel plate to ensure rigidity, and as a pyramidal frustum (350×100×350 mm) with flanks inclined at 70^o, greater than the dynamic angle of repose of palm nut with mild steel, for free flow of the nuts into the cracking chamber. The volume and holding capacity of the hopper was determined for a batch feeding of 13.5 kg palm nuts into the cracking chamber.

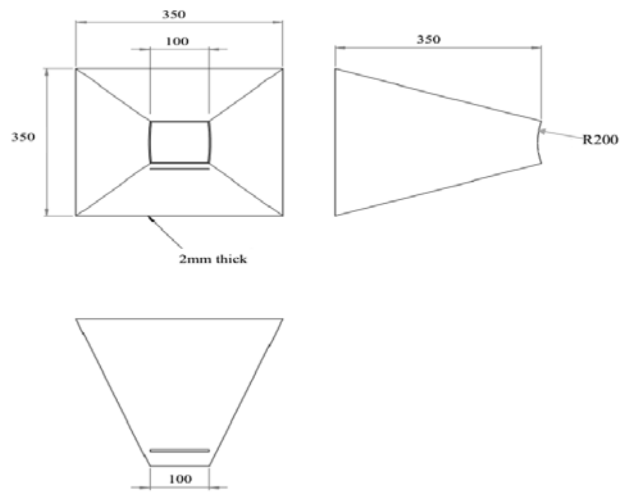

Figure 2 Orthographic projections of the feed hopper

Note: All dimensions in mm.

2.3.2 The cracking chamber

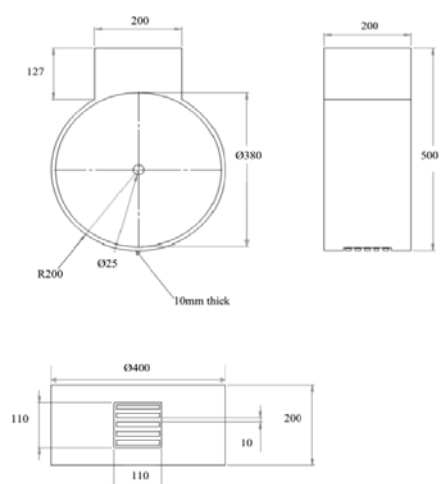

Figure 3 Orthographic view of the cracking chamber

Note: All dimensions in mm.

The cracking chamber (Figure 3), takes the shape of a hollow cylindrical tube with beaters at its core. The cylinder measures380×400 mm in its minor and major diameters respectively, and 200 mm in its length.

The cracking chamber is bored at the circumferential ce ntre through the back surface to enable the passage of the dr iving shaft, to the core of the chamber through the ball beari ng. The cracking chamber is made of mild steel with 10 m m thickness to ensure adequate.

Strength and rigidity to withstand the repeated impact force during cracking. The cracking process is achieved by the impact force exerted on the nuts against the walls of the cracking chamber. As the nuts are being fed to the cracking chamber are struck against the walls of the chamber by the rotating beaters by centrifugal action, the impact force is generated to loosenthe kernels from the shells. The cracked mixtures are then transported to the precleaner cum classifier chamber via the discharge unit.

2.3.3 The cracking beater

The beater is made of mild steel and schematically shown on Figure 4.

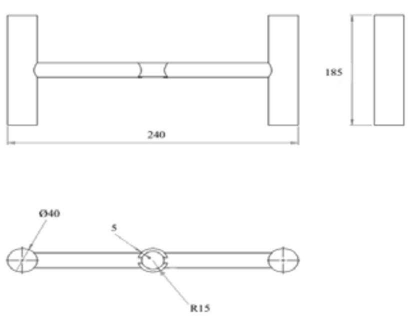

Figure 4 Orthographic view of cracking beaters

Note: All dimensions in mm.

The shape of the beater was adopted to ensure that each palm nut fed into the cracking chamber is impacted against the wall of the chamber by the beater. Also, a radius of 120 mm was selected for designing the beater as it falls within the range of most of the existing designs of commercialized palm nut crackers.

2.3.4 The pre-cleaner and classifier

This section (Figure 5) mainly composes of rotating screen and shaft. A pre-screening section was incorporated to screen out dirt and immature kernels while the other section is designed to classify kernel-shell mixture. This was to enhance better product purity. The physical properties of kernel and shell such as differences in sizes and shapes were considered in the development of this compartment, which mainly consists of rotating cylindrical screen and shaft. In most cases, shells are flat or dish shaped, while kernels vary from nearly spherical to ellipsoidal in shape. Also, it has been established that the least mean diameter of palm kernels is greater than 10 mm (Akubuo and Eje, 2002; Koya et al., 2004; Koya and Faborode, 2005). It was expected that mixture of kernel and shell particles smaller than these kernels will be classified after mechanical cracking process. Consequently, sieve cleaner with regular apertures of 10 mm was used as aclassifier. It was a cylindrical framework 900 mm long with a diameter of 350 mm (Figure 5). A section of the frame, 300 mm long, near the feed-end, overlaid with net of uniform 5 mm apertures, was used as pre-cleaner, to sieve out small shell particles and immature kernels, while the remaining length was the classifier. The unit is mounted on the supporting frame through the driving shaft and directly attached to the outlet discharge of the cracking chamber, and it was made up of galvanized steel and expanded metal.

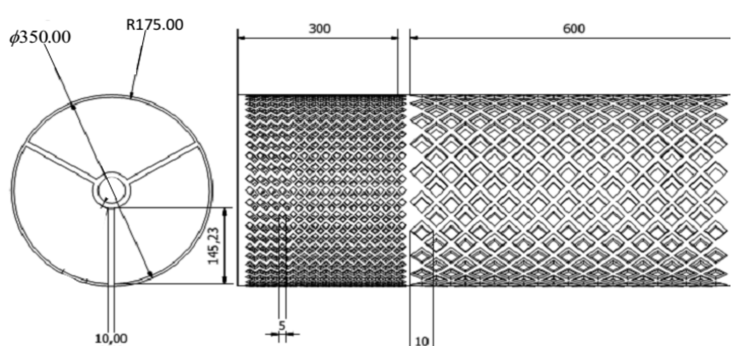

Figure 5 Orthographic views of pre-cleaner and classifier

Note: All dimensions in mm.

2.3.5 Final assembly of the cracking unit

After all the components have been developed, all the unit members were finally assembled (Figure 6), having its dimensions as shown. The drive shaft carrying the pulley and two bearings was coupled to the cracking chamber which had been initially attached to the cracking beater. The hopper is vertically linked to the cracking chamber to ensure the free fall of the palm nuts by gravity into the chamber. The pre-cleaner cum classifier section is also externally attached to the chamber and supported by another shaft carrying its pulley. The entire framework is firmly coupled to the chassis member through welding and bolt and nuts where necessary.

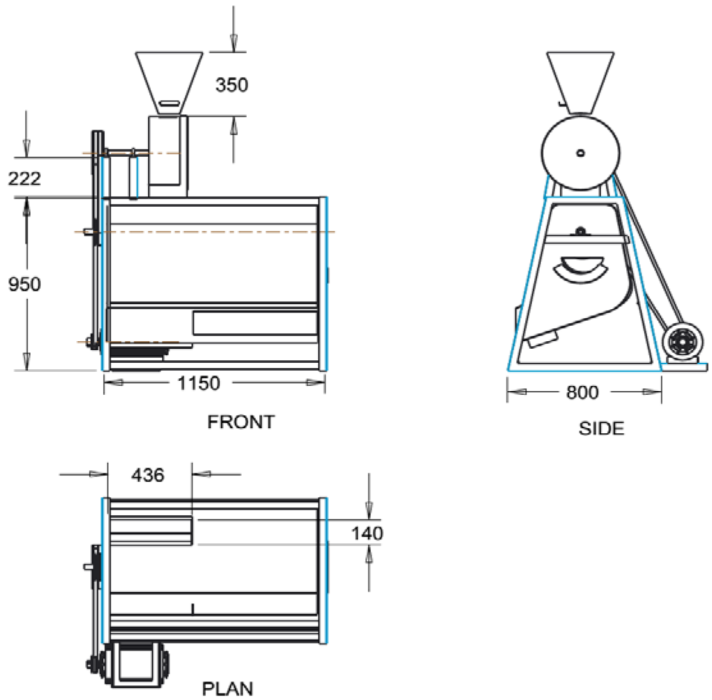

Figure 6 Orthographic views of the cracking unit and pre-cleaner cum classifier of modified machine

Note: All dimensions in mm.

2.3.6 Machine drive

The drive division of the machine consists of the electric motor, the pulleys and the belt drive. The section integrates the basic units of the modified machine and thereby minimizes energy consumption. A single - phase electric motor with initial driving speed of 1410 rpm was firmly mounted on the supporting frame to serve as the power source. Power is transmitted from the motor to the machine through V-belts and pulley arrangements. The pulleys range in diameter of sizes 110 mm (cracking) to 600 mm (pre-cleaner cum classifier).

2.4 Design analysis

2.4.1 Hopper

The hopper was expected to handle nut capacity of 13.5 kg in a batch feeding. Therefore, the volume (V *in* m^3) of the hopper was determined using the following relationship:

$$V = \frac{mass}{density} \quad (5)$$

The density is the nut bulk density, which had been experimentally determined and proposed by researchers (Koya et al., 2004; Ezeoha et al., 2012);

$$V = \frac{13.5kg}{711kgm^{-3}}$$

V=0.019 m^3

To achieve the designed volume the following dimensions were used:

Volume of Hopper (V, m) = Volume of Pyramidal frustum

$$V = \frac{1}{3} h \left(A_1 + A_2 + \sqrt{A_1 A_2}\right) \quad (6)$$

Where;

A_1 is area of upper dimension; (0.35×0.35) m^2

A_2 is arrea of lower dimension; (0.1×0.1)m^2

*h*isheight of hopper; 0.35m

2.4.2 Mechanical power requirement

In order to determine the power requirement for cracking,P_c,W, the centrifugal force to crack the nut F_c, N (John and Stephens, 1999) was determined using:

$$F_c = m\omega^2 r \quad (7)$$

$$\alpha = \omega^2 r = acceleration = \frac{v}{t} = \frac{\omega r}{t}$$

$$\therefore F_c = \left(\frac{m}{t}\right)\left(\frac{\pi dN}{60}\right) \quad (8)$$

The expected mass flow rate of palm nut being processed per batch of time, t = 13.5 kgs^{-1} d = diameter of beater = 0.24 m and N is the rotational speed = 821rpm. Also, ω is the angular speed = 86 $rads^{-1}$.

Hence;

$$F_c = 139.6N$$

Torque to turn the shaft was determined using:

Torque (T) = Fr

Where; r = 0.12 m; obtained from $\frac{d}{2}$

T =16.75Nm

Therefore power requirement (P_c) for nut cracking = $T\omega$ (9)

$P_c = 16.75 \times 86$= 1440.5W= 1.441kW

With the power rating, the recommended minimum pulley pitch diameter D is 75mm (PSG, Tech, 1982).

2.4.3 Minimum power required for pre-cleaner and classifier (P_p)

The following relationship applies between the angular speed (upper limit) and radius of the drum;

$$\omega < \sqrt{\frac{g}{r}} \quad (10)$$

Where; g=9.81ms^{-2}; designing a prototype drum with diameter 0.35 m; r = 0.175 m

Hence;

$$\omega < 7.49 rad/s$$

Similar to cracking process;

$$\therefore F_p = \left(\frac{m}{t}\right)\left(\frac{\pi dN}{60}\right) \quad (11)$$

$$F_p = 17.69N;$$

T= Fr; T= 3.096Nm

Therefore;

$P_p = 3.096 \times 7.49$= 23.19W

2.4.4 Total Power required (P_T)

$$P_T = P_c + P_p \quad (12)$$

Where;

P_T is Total power required, W

P_T = 1463.69W

Considering losses due to friction, and then multiplying by a factor of safety of 1.5, the total power requirement for the machine is computed as:2196W$\approx$ 2.20kW

A standard electric motor of 1.5kW (2hp) was considered adequate for the machine and used for testing. However, taking into consideration factor of safety, a standard electric motor 2.25kW (3hp) is recommended.

2.4.5 Shaft selection

For gradually applied load/steady load as being considered(Hall et al., 2004);

$$M_c = \frac{1}{2}[(K_m \times M_b) + \sqrt{(K_m \times M_b)^2 + (K_t \times M_t)^2} \quad (13)$$

And;

$$d^3 = \frac{32M_c}{\pi\sigma_b} \quad (14)$$

Where; d is shaft diameter (m), M_b is maximum bending moment (Nm), M_t is Maximum torsional moment (Nm), k_m is combined shock and fatigue factor applied to bending moment and k_t is combined shock and fatigue factor applied to torsional moment. Using a shaft material of 0.26 carbon steel with maximum permissible working stress, σ_b is 84MPa (Adzimah and Seckley, 2009).

Thus: K_m=1.5 and K_t=1.0;

Calculated M_b (maximum bending moment) = 43.52 Nm

Calculated T (Torque to be transmitted) = M_t = 16.75 Nm

Calculated shaft diameter is 20.04 mm. Therefore, a standard size shaft of 25 mm was selected.

2.4.7 Determination of performance evaluation values

Sample of *dura* variety of palm nut which is susceptible to kernel breakage was drawn from large tonnage, which had been sun-dried for commercial nut cracking. The sample was classified into four groups of sizes in order to relate the performance of the machine to nut sizes.

2.4.7.1 Determination of mechanical damage

Mechanical damage was expressed as the ratio of the mass of broken kernels to the total mass of the nut sample fed into the hopper:

$$M_d = \frac{M_b}{M_T} \times 100 \quad (15)$$

Where:

M_d is mechanical damage (%)

M_b is mass of broken kernels (kg)

M_T is thetotal mass of the palm nut sample fed into the hopper (kg)

2.4.7.2 Determination of whole kernel

The value of whole kernels was expressed as the ratio of the mass of unbroken kernels to the total mass of the nut sample fed into the hopper:

$$M_w = \frac{M_u}{M_T} \times 100 \quad (16)$$

Such that:

$$M_u = M_T - M_b$$

Where:

M_w is whole kernels in the sample (%)

M_u is a mass of unbroken kernels (kg)

2.4.7.3 Determination of cracking efficiency

Cracking efficiency was defined as the ratio of the mass of completely cracked nut to the total mass of the nut fed into the hopper.

It was calculated as:

$$C_E = \frac{M_T - M_{PC}}{M_T} \times 100 \quad (17)$$

Where:

C_E is cracking efficiency (%)

M_{PC} isa mass of partially cracked and uncracked Palm-Nut (kg).

3 Results and discussions

3.1 Cracking force for palm nut samples

Table 2 shows the mean results of the compression tests depicting the cracking force of palm nut samples and corresponding energy of deformation when loaded between two parallel plates. The values of cracking force are comparable to the results obtained by Koya et al.(2004) on *Dura* nut samples, and Manuwa (1998) on certain palm nut samples of unidentified specie. Also, the results obtained for energy of nut deformation are comparable to the results obtained by Gbadamosi (2006). The graphical presentations are shown in Figures 7-10. The results were replicated three to four times. Each of the curves is composed of two distinct sections. The first division consists of the part from the instigation of load application to the maximum compressive load. The division shows a logical linearity between load and deformation. This represents the main resistance of the palm nut shell to breakage, while the maximum compressive loads mark the inception of initial shell breakage of the palm nut. The average maximum compressive loads range from 1.3 to 2.26 kN based on the nut sizes. These ranges of values are comparable to the results obtained by Kayode and Koya (2012) for palm kernel shell (1.34-1.41 kN), and the range obtained for other hard nuts such as macadamia nut (0.6-1.8 kN) and Dika nut (2.06-3.67 kN) (Wang et al., 1995; Ogunsina et al., 2008).

Table 2 Experimental results of palm nut cracking forceand energy of deformation

Nut sizes (mm)	Cracking force (N) (mean values)	Energy ofdeformation (Nm) (mean values)
10	1306.09 (101.22)	0.3988 (0.195)
14	2171.76 (355.96)	0.9496 (0.312)
20	2262.09 (692.32)	1.0516 (0.566)
25	2266.15 (988.88)	1.1718 (0.424)

Note: Numbers in parenthesis are the standard deviation.

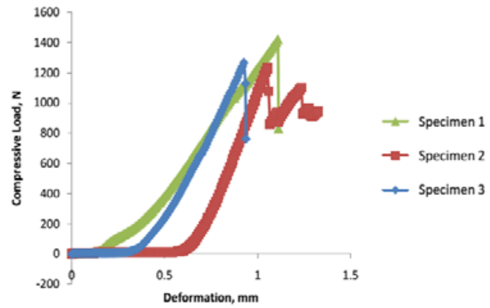

Figure 7 Load-deformation curves for palm nut with average size 10 mm

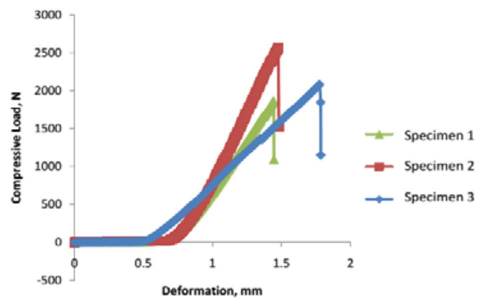

Figure 8 Load-deformation curves for palm nut with average size 14 mm

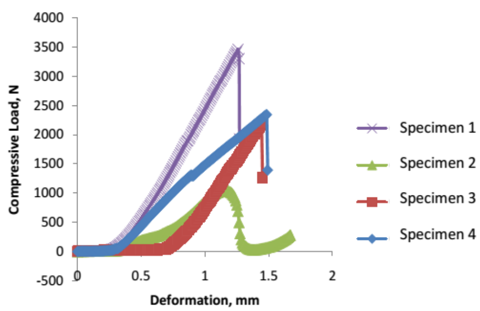

Figure 9 Load-deformation curves for palm nut with average size 20 mm

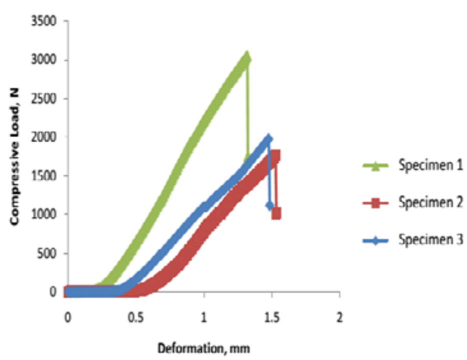

Figure 10 Load-deformation curves for palm nut with average size 25 mm

3.2 Measured performance of the modified palm-nut cracker

Figure 11 is the output prototype showing the assembly of the fabricated modified palm nut cracker; while Table 3 shows the machine performance in terms of its cracking efficiency, mechanical damage and whole kernels. The results from the table show that cracking efficiency and whole kernels increase with increasing nut sizes, and decrease at theincrease in the feed rates.

Figure 11Picture of the fabricated modified palm-nut cracker with pre-cleaner

Note: (1-feed hopper; 2-cracking chamber; 3-pre-cleaner cum classifier chamber; 4-small kernel/shell outlet; 5-dirt outlet; 6-frame; 7-shaft; 8-cracking pulley; 9-belt; 10-pre-cleaner’s pulley; 11-prime mover; 12-big kernel/shelloutlet end)

The result also indicated that mechanical damage decreases slightly as nut size increases, but increases with increasing feed rate. Table 4 also shows the cracking efficiencies and percentage kernel breakages from the machine at different operating conditions. An experiment had shown (Koya and Faborode, 2011) that 100% cracking efficiency was obtained with manual cracking; which appears reasonable, since all the nuts are cracked, though; some kernels (2.0%) are also broken in the process. The experimental mechanical nut cracking unit of the modified machine in the present study gave an average cracking efficiency of 92.35%, but 4.59 % of the kernels were broken when driven at 821 rpm. It appears this efficiency is lower than the 100% cracking efficiency obtained when the nutcracker was initially operated at the speed of 1410 rpm. However the result indicated that mechanical kernel breakage was reduced by about 53 %. This development has addressed to some extent, the limitation of the conventional nutcracker. The results therefore suggestthat mechanical nutcracker will yield better performance in terms of cracking efficiency and whole kernel recovery, if it is operated at such lower speed.

Table 3 Performance indices data for the modified palm nut cracker atmoisture content 13.4% w.b.

Nut retained on sieve-size (mm)	Feed rate (F_r, kgh^{-1})	Mechanical damage (M_d,%)	Whole kernel (M_w, %)	Cracking efficiency (C_E, %)
	85	5.02	94.98	96.80
10	90	5.03	94.97	92.25
	95	5.15	94.85	86.10
	85	5.01	94.99	96.85
14	90	5.10	94.90	92.50
	95	5.15	94.85	87.20
	85	4.09	95.91	97.15
20	90	4.10	95.90	93.10
	95	4.14	95.86	87.85
	85	4.03	95.97	97.27
25	90	4.10	95.90	93.11
	95	4.12	95.88	88.00

Table 4 Efficiencies of palm nut cracking operation of the machine

Speed (rpm)	Mean efficiency (%)	Mean kernel breakage (%)
1410	100(0.0)	9.83(0.4)
821	92.35 (0.4)	4.59(0.5)

Note:Numbers in parentheses are the standard deviations

Figures 12-14 graphically describe the effects of the nut sizes and feed rates on the performance indices (Table 3) of the Modified nut cracker. Data collected on the selected performance evaluation indices at different nut sizes and feed rates were compared. Minitab 17 was the software used in the graphical analysis of the results.

Figure 12 shows the mechanical damage in relation to nut size and feed rate. It is shown that the lower the feed rate, the lower the mechanical damage. It is then understood that to reduce the mechanical damage of thekernel during cracking process, the operation should employ moderately low feed rate. This confirms the findings of Ndukwu and Asoegwu (2010) that mechanical breakage increases with feed rate. It is also demonstrated that higher nut sizes favour lower mechanical damage. From Figure 13, it is shown that whole kernels decreased as the feed rate increased, and it increased with increasing size of the particles. It implies higher nut sizes yield higher whole kernels. Figure 14 shows the comparative effect of the feed rate and nut sizes on the cracking efficiency.

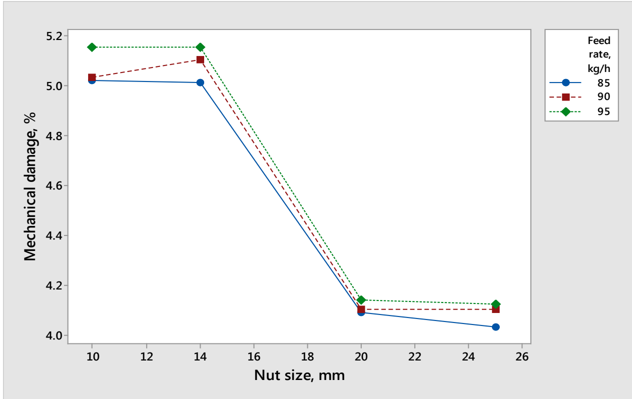

Figure 12 Effectsoffeedrateandpalm-nutsizesonmechanicaldamage

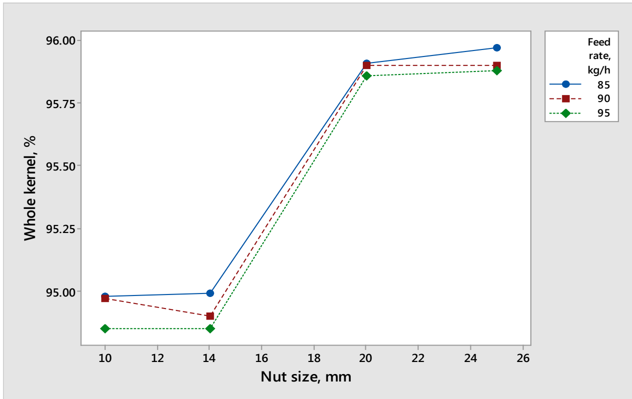

Figure 13 Effectsoffeedrateandpalm-nutsizesonwholekernel

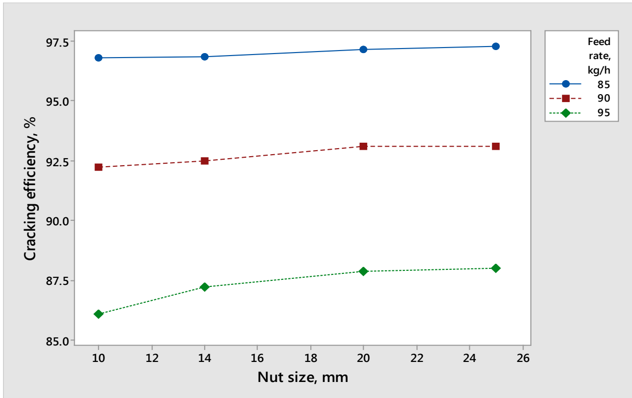

Figure 14 Effectsoffeedrateandpalm –nutsizesoncracking efficiency

It is shown from the curve that cracking efficiency increases with increase in sizes of the nut, in confirmation with the findings of Jimoh and Olukunle (2013). Also, the Figure demonstrated that the lower the feed rate, the higher the cracking efficiency.

4 Conclusion

Modified palm nut cracking machine which incorporated pre-cleaner and classifier with its members has been developed in this study. Palm-nut cracking at a moderately lower speed than the conventional palm-nut crackers yielded satisfactory output in terms of quality based on the observed cracking efficiency, whole kernels recovered and mechanical kernel damage.

The result from the study is therefore a significant step in enhancing subsequent product separation and it is adjudged suitable for small and medium scale application.

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