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Analysis

Performance modelling and validation of palm kernel cracking and separating machine

Tanko Bako[1]✉, **Joseph Daniel Oyigoga**[2], **Japhet Malum Flayin**[2]

[1]Department of Agricultural and Bio-Resources Engineering, Taraba State University, Jalingo, Nigeria
[2]Department of Agricultural and Environmental Engineering, University of Agriculture, Makurdi, Nigeria

✉**Corresponding author:**
Department of Agricultural and Bio-Resources Engineering, Taraba State University, Jalingo, Nigeria
E-mail: engbako@gmail.com. Tel: +234 7064190523

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ABSTRACT

The main objective of this work is to develop simplified palm kernel cracking and cleaning models for the simulation, design and preliminary evaluation of palm kernel cracking and separation machines. The model equations were developed using empirical data obtained from performance evaluation carried out on a motorized palm kernel cracking and separating machine. The factors investigated were shaft speed, feed rate and moisture content of palm nuts, while cracking efficiency, machine performance efficiency and cleaning efficiency constituted the response variables. The models have been validated using experimental data showing good agreement between experimental and predicted data. Experimental results show that the developed models described the performance parameter of the machine adequately at 95% prediction interval. ANOVA revealed that the main effects of all the factors influence the three responses variables significantly.

Key words: Performance, palm nuts, model, efficiency.

INTRODUCTION

The fruit of the oil palm *(Elaeis guineensis)* is well known for its economic importance and nutritive values. After the palm oil has been extracted, the palm nut can further be processed to produce other valuable substances like palm kernel oil which is used in producing chemicals for the pharmaceutical, cosmetics and laundry industries. The cracked shell can be used for road constructions, brake pads and coarse aggregate in concrete for building [1]. The chaffs and shells are locally utilized for producing candles and also as fuel for domestic heating and cooking. Thus, every part of the palm fruit or its by-products is economically useful [2]. The nuts of oil palms are cracked and the shells separated to obtain the palm kernels. In the overall process palm kernel oil production, separation of palm kernels from the shells is a vital process. Cracking has always posed a major problem in the processing of bio-material as a result of the shape and brittleness of the kernels of the nuts; rendering them susceptible to damage during cracking. Hammer impact type and centrifugal impact type nut crackers are the two major types of modern nut crackers generally in use today. The hammer-impact type nut cracker breaks or cracks the nut by impact when the hammer falls on the nut, while the centrifugal-impact nut cracker hurls the palm nut at a fairly high speed against a stationary hard surface to crack the nut using centrifugal action [3]. In existing and emerging agro-economy, proper separation of the cracked palm nut mixture is a vital process for profitable utilization of the constituent palm nut kernel and palm nut shell. Palm kernels can only be utilized when they are separated from the shell. The wet and dry processes are the two main methods generally used for separation of the mixture. In the wet method, separation is done in a liquid medium like water based on the difference in specific gravities of the constituents; while in the dry method, equipments such as carpets fans, blowers and sieves are employed to separate palm kernels from the shells. The usage of wet methods further complicates the separation process as heat would be needed in order to dry the shell before they can be stored. The moisture absorbed during the wet separation process must be removed by re-drying and the palm kernels sterilized against the growth of moulds [4]. Palm nut cracking and separation is therefore, a process that involves a great deal of energy. At present, many research works are geared towards modelling of functional variables that determine the efficiency of processing machines. Most of these models are machine specific and are basically related to the particular features, types and designs the machine. Therefore the present study is undertaken to establish a mathematical model for predicting the cracking, performance and separation efficiencies of a palm nut cracking and separating machine.

MATERIALS AND METHODS

Materials

The *Dura* palm variety was selected for this study. The palm kernel nuts were obtained from the Nigerian Institute for Palm oil Research (NIFOR), Edo State, Nigeria.

Methodology

Determination of experimental variables

The major properties investigated as factors influencing cracking and separation operations in the palm nut cracking and separating machine were moisture content of the palm nut, cracking shaft speed, separating shaft speed, and feed rate. A quartz stopwatch was used for measurement of time during the performance evaluation of the machine. A digital tachometer (DT 2235B) was used to determine the peripheral speed of the impeller shaft and electronic balance of 0.01 kg sensitivity was used in weight measurements.

Moisture content: Three moisture content of 9, 11 and 13 % [5] of the palm kernel nuts were preselected for use in this study. The oven drying method was employed in moisture content determination. Palm kernel nuts were initially weighed and placed in the oven at a temperature of 105°C for 18 h [6]. The samples were removed and allowed to cool before reweighing. Respective moisture contents of samples were determined on dry basis using Equation 1.

$$\text{Moisture content (\%)} = \frac{W_1 - W_2}{W_2} \times 100 \qquad (1)$$

Where; W_1= Initial weight (g), W_2 = Final weight (g).

The samples were soaked in a calculated quantity of water and mixed thoroughly to be conditioned to the desired moisture content. The mixed samples were sealed in polyethylene bags at 5°C in a refrigerated cold room for 15 days to allow the moisture to distribute evenly throughout the sample [3]. The quantity of water required to condition the samples to the desired moisture content was calculated using Equation 2.

$$Q = \frac{W(M_f - M_t)}{100 - M_f} \qquad (2)$$

Where; Q = Mass of water added (g), W = Initial mass of the sample (g), M_t = Initial moisture content of the sample in dry basis (%) and M_f = Final moisture content of the sample in dry basis (%).

The feed rate: The feed rate is the total mass of palm kernel nuts loaded into the cracking unit per time. The weight of samples was determined using a top loading electronic weighing balance. The stop watch was used to determine the time to completely empty the nuts into the cracking chamber. Three feed rates of 400, 500 and 500 kg/hr [7] were preselected for use in this study. The nut cracker was regulated to obtain different feed rates by adjusting the feed rate control (gate) to three points to reduce the diameter of the feeding chute into the cracking chamber. The feed rate was calculated from Equation 3 [3].

$$\text{Feed rate} = \frac{W}{T} \qquad (3)$$

Where; W - weight of the palm kernel that filled the hopper (kg), T - time taken to empty the whole palm kernel into the cracking chamber (hr)

Rotational speed of the impeller and blower: Three speed levels of 600, 800 and 1000 rpm [7] were used for both the cracking and separating shafts speed during the testing. The desired speeds were obtained by using different sizes of V-belts and driven pulleys. The estimated speed of the rotor was determined using speed ratio in Equation 4 [8].

$$\frac{N_1}{N_2} = \frac{D_2}{D_1} \qquad (4)$$

Where; N_1 is the driver speed in rpm, N_2 is the driven speed in rpm, D_1 is the driver pulley diameter in mm and D_2 is the driven pulley diameter in mm.

The three speeds were attained with help of set of driver pulley of 30 mm and driven pulleys of different sizes of 73, 55 and 44 mm. The actual shaft rotational speeds of the palm kernel cracker during its evaluation was determined using a digital tachometer (DT 2235B) which has a sensitivity of 1.0 rpm.

Test procedure

The palm kernel cracker powered by an electric motor was set into operation and a known weight (1000 g) of each prepared sample was fed into the machine through the feeding hopper for cracking and separation. The cracking and separation time for each test was recorded by a stop watch. The quantities of cracked and un-cracked palm kernel nuts; broken and unbroken kernels were sorted, weighed and recorded.

Performance indicators

The machine cracking efficiency, performance efficiency and cleaning efficiency were calculated based on the Equations according to Ndukwu and Asoegwu [3].

Cracking efficiency (%): This is the ratio of completely cracked nuts to the total cracked and uncracked nuts. The cracking efficiency was computed using Equation 5.

$$E_{CR} = \frac{W_C}{W_C + W_{UC}} \times 100\ \% \qquad (5)$$

Where; E_{CR} = cracking efficiency (%), W_C = weight of cracked kernel (damaged and undamaged) (kg), W_{UC} = weight of uncracked kernel (kg).

Machine performance efficiency (%): This is the ratio of completely cracked and undamaged nuts to the total weight of undamaged cracked kernels, damaged cracked kernels and uncracked kernels. The performance efficiency was calculated using Equation 6.

$$E_M = \frac{W_{UD}}{W_{UD}+W_D+W_{UC}} \times 100\ \% \qquad (6)$$

Where; E_M = machine performance efficiency (%), W_{UD} = weight of undamaged cracked kernel (kg), W_D = weight of damaged cracked kernel (kg), W_{UC} = weight of uncracked kernel (kg).

Cleaning efficiency (%): This is the ratio of weight of shells separated to the total weight of shells separated and unseparated. The cleaning efficiency was obtained using Equation 7.

$$E_C = \frac{W_S}{W_S+W_{US}} \times 100\ \% \qquad (7)$$

Where; E_C = cleaning efficiency (%), W_S = weight of palm kernel shells separated (kg), W_{US} = weight of palm kernel shells unseparated (kg).

Experimental design and statistical analysis

A split-plit-plot factorial design with Completely Randomized Design (CRD) involving a three-way classification. The experimental unit comprises three factors; three machine speeds of 600, 800 and 1000 rpm, three feed rates of 400, 500 and 600 kg/hr and three moisture content of 9, 11 and 13 %; giving a twenty seven (27) treatment combinations. The choice of variable levels was selected with respect to preliminary trials. Regression models were generated by subjecting the data obtained to ANOVA. The process was optimized using a commercial statistical package (Design Experts, *version 10*, Stat- Ease, Inc., Minneapolis, USA). A response surface method with an I-Optimal design was used to optimize the machine performance. Optimum process parameters were achieved by maximizing the machine performance efficiency. The adequacy and accuracy of the model equation was demonstrated by a comparison between the experimental values and the predicted values based on regression analysis. To measure how well the suggested model was able to fit the experimental data, parameters such as correlation coefficient, coefficient of determination and probability value (p-value) were determined.

RESULTS AND DISCUSSION

Machine performance

From the results (Table 1), it is evident that the highest cracking efficiency (98.10 %), machine performance efficiency (79.68 %) and cleaning efficiency (68.76 %) were achieved at the machine speed of 1000 rpm, feed rate of 400 kg/h and moisture content of 9 ^oC while the lowest cracking efficiency (72.82 %), machine performance efficiency (65.40 %) and cleaning efficiency (32.60 %) were obtained at the machine speed of 600 rpm, feed rate of 600 kg/h and moisture content of 13 ^oC.

Table 1: The experimental design and obtained values of the responses

Shaft peed, rpm	Feed rate, kg/h	Moisture content, %	Cracking efficiency, %		Performance efficiency, %		Cleaning efficiency, %	
			Measured	Predicted	Measured	Predicted	Measured	Predicted
600	400	9	84.63	84.89	71.00	71.61	44.10	42.99
600	400	11	80.80	81.12	69.86	69.89	41.40	39.32
600	400	13	77.94	77.35	68.43	68.17	37.68	35.65
600	500	9	82.72	81.79	70.10	70.31	40.55	39.09
600	500	11	78.59	78.02	68.97	68.59	38.49	35.42
600	500	13	75.15	74.25	67.30	66.87	35.12	31.75
600	600	9	78.58	78.69	68.80	69.01	35.95	35.19
600	600	11	76.36	74.92	67.22	67.29	34.57	31.52
600	600	13	72.82	71.15	65.40	65.57	32.60	27.85

800	400	9	89.10	91.09	74.30	75.01	48.86	54.19
800	400	11	84.81	87.32	72.14	73.29	44.19	50.52
800	400	13	81.50	83.55	71.45	71.57	39.89	46.85
800	500	9	86.22	87.99	73.27	73.71	45.64	50.29
800	500	11	82.60	84.22	71.64	71.99	41.70	46.62
800	500	13	79.28	80.45	70.33	70.27	38.52	42.95
800	600	9	83.87	84.89	72.81	72.41	41.24	46.39
800	600	11	78.74	81.12	71.24	70.69	37.78	42.72
800	600	13	75.26	77.35	69.80	68.97	34.66	39.05
1000	400	9	98.10	97.29	79.68	78.41	68.76	65.39
1000	400	11	95.43	93.52	76.21	76.69	66.28	61.72
1000	400	13	92.68	89.75	74.84	74.97	61.53	58.05
1000	500	9	94.00	94.19	77.55	77.11	64.11	61.49
1000	500	11	90.16	90.42	75.90	75.39	59.88	57.82
1000	500	13	85.85	86.65	72.43	73.67	55.20	54.15
1000	600	9	92.84	91.09	75.28	75.81	61.98	57.59
1000	600	11	88.30	87.32	72.96	74.09	53.73	53.92
1000	600	13	81.72	83.55	71.87	72.37	49.93	50.25

Development of models

The data for the response variables (cracking efficiency, machine performance efficiency and cleaning efficiency) obtained from the 27 experimental points (Table 1) were used for a statistical analysis to optimize the process variables of shaft speed, feed rate and moisture content. The cracking efficiency ranged from 72.82 to 98.10 %, machine performance efficiency varied from 65.40 to 79.68 % and cleaning efficiency ranged from 32.60 to 68.76 %. The best-fitting model was determined by multiple regressions with backward elimination. The insignificant factors and interactions were also removed from the model. The relationship between the three variables (shaft speed, feed rate and moisture content) and the important process responses (cracking efficiency, machine performance efficiency and cleaning efficiency) for mechanical palm kernel cracking and cleaning process was analyzed using Response Surface Methodology (RSM). The study utilized RSM to develop prediction models for optimizing the mechanical cracking and separating of palm kernel from palm nuts. Significance model terms are required to get a good output in a particular model. The experimental conditions and the corresponding responses from the experimental design are depicted in Table 1. The values of the independent and dependent variables were analyzed to obtain a linear regression equation that could predict the response within the experimental range. Using the obtained empirical data, model equations to predict the effects of shaft speed, feed rate and moisture content on cracking efficiency, machine performance efficiency and cleaning efficiency were developed. Based on lack of fit test and coefficient of determination (R^2), linear model was found to be suitable to express the cracking efficiency, performance efficiency and cleaning efficiency of the machine. The model equations for the cracking efficiency, performance efficiency and cleaning efficiency of the palm kernel cracking and separating machine are as follows:

$$E_{CR} = 95.656 + 0.031S - 0.031F - 1.885M \quad (8)$$

$$E_{M} = 74.340 + 0.017S - 0.013F - 0.859M \quad (9)$$

$$E_{C} = 41.503 + 0.056S - 0.039F - 1.835M \quad (10)$$

Where; E_{CR} = Cracking efficiency (%), E_M = Machine performance efficiency (%), E_C = Cleaning efficiency (%), S = Speed of the impeller or blower (rpm), F = Feed rate (kg/h), M = Moisture content of palm nuts (%)

Validation of the models

The model was validated using data obtained from laboratory experimentations. The ANOVA of the measured and predicted data for cracking efficiency, performance efficiency and cleaning efficiency of the machine is shown in Table 2. The ANOVA ($P \geq 0.01$) of the difference between the experimental data and the predicted values for cracking efficiency and performance efficiency shows that the p-value (0.905) obtained exceeds the p-value level (0.01) and the calculated F-value of 0.014 obtained is far less than the theoretical (Tabulated) F-value of 7.17. The ANOVA ($P \geq 0.01$) of the difference between the experimental data and the predicted values for cleaning efficiency shows that the p-value (0.955) obtained exceeds the p-value level (0.01) and the calculated F-value of 0.003 obtained is far less than the theoretical (Tabulated) F-value of 7.17. This indicates that there were no significant ($P \geq 0.01$) differences between the experimental data and the predicted values for the cracking efficiency, performance efficiency and cleaning efficiency of the machine. These validate the models. A graphical comparison of the measured and predicted data for cracking efficiency, performance efficiency and cleaning efficiency of the machine using the models developed in Equations (8, 9 and 10), is presented in Figure 1. For cracking efficiency of the machine, the model prediction showed about 97.5% correlation with the measured data. For performance efficiency of the machine, the model prediction was about 98.4% in correlation with the measured data. For cleaning efficiency of the machine, the model prediction was about 93.5% in correlation with the measured data. This indicates that the models can be used effectively to tract efficiencies of the palm kernel cracking and separating machine with various levels of shaft speed, feed rate and moisture content of palm nuts.

Table 2 ANOVA of experimental and predicted values

Source	DF	SS	MS	F-cal	F-tab	P-value
Cracking efficiency	1	0.642	0.642	0.014	7.17	0.905
Error	52	2304.214	44.312			
Total	53	2304.857				
Performance efficiency	1	0.161	0.161	0.014	7.17	0.905
Error	52	580.105	11.156			
Total	53	580.266				
Cleaning efficiency	1	0.359	0.359	0.003	7.17	0.955
Error	52	5926.658	113.974			
Total	53	5927.017				

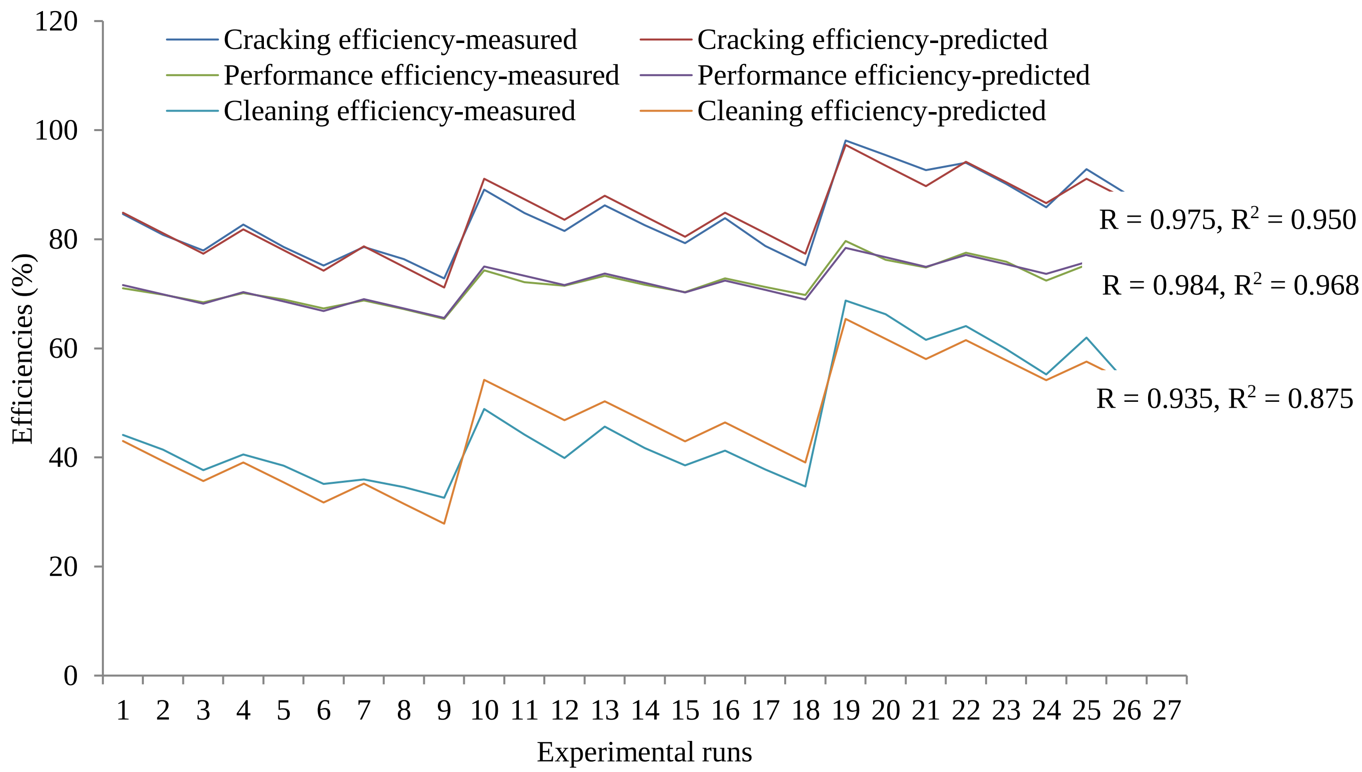

Figure 1 Validation of the predictive models with experimental data

Effects of Independent Variable on Responses

The results showed that machine speed, feed rate and moisture content significantly affected the cracking efficiency, performance efficiency and cleaning efficiency at $P \leq 0.05$. From the results it was found the cracking efficiency, performance efficiency and cleaning efficiency of the machine had positive relationship with the machine speed but had negative relationship with the feed rate and moisture content of palm kernel. The cracking efficiency, performance efficiency and cleaning efficiency of the machine increased with increasing operation speeds but decreased with increasing feed rate and moisture content. The increase in machine efficiency with machine speed results from an increase in impact velocity which also increases the impact energy. The decrease in efficiency with increased feed rate is a result of too much palm nuts entering the cracking chamber at a time, thus decreasing the impinging velocity of the palm nuts due to their collision with one another, and reducing the impact energy. The machine efficiency increased with decrease in palm nut moisture content because the kernel loosed from its shell to create sufficient gap between kernel and shell to absorb impact during cracking. Cracks are even initiated in the shell as the kernel shrinks. This is in line with Omoruyi and Ugwu [5] that optimized and evaluated the performance of an electrically operated palm nuts cracking machine and reported that the cracking efficiency of the machine increase as the speed of the rotor increases but the cracking efficiency decrease as the feed rate and moisture content increases using *Tenera* palm nuts. This is also in agreement with Ndukwu and Asoegwu [3] that evaluated the performance of a vertical-shaft centrifugal palm nut cracker and reported an increased efficiency with increase in cracking speed, a decreased efficiency with increase in feed rate and a decreased efficiency with increase in palm nut moisture content.

CONCLUSION

Mathematical models for palm kernel cracking and separation were developed in order to relate the process control parameters to the process response characteristics. The process control parameters investigated were shaft speed, feed rate and moisture content of palm nuts, while cracking efficiency, machine performance efficiency and cleaning efficiency constituted the response variables. The models have been validated using experimental data showing good agreement between experimental and predicted data. The results obtained in this study showed that shaft speed, feed rate and moisture content affect cracking efficiency, machine performance efficiency and cleaning efficiency of the machine significantly at $P \leq 0.05$. The cracking efficiency, performance efficiency and cleaning efficiency of the machine increased with increasing operation speeds but decreased with increasing feed rate and moisture content. The highest cracking efficiency (98.10 %), machine performance efficiency (79.68 %) and cleaning efficiency (68.76 %) were achieved at the machine speed of 1000 rpm, feed rate of 400 kg/h and moisture content of 9 ^{o}C while the lowest cracking efficiency (72.82 %), machine performance efficiency (65.40 %) and cleaning efficiency (32.60 %) were obtained at the machine speed of 600 rpm, feed rate of 600 kg/h and moisture content of 13 ^{o}C.

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The authors declare that there are no conflicts of interests.

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Data and materials availability:
All data associated with this study are present in the paper.

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