International Journal of Advances in Engineering and Management (IJAEM)
Volume 3, Issue 5 May 2021, pp: 1211-1217 www.ijaem.net ISSN: 2395-5252

Predicting Cracking Efficiency and Kernel Breakage of Centrifugal Nut Cracker

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Submitted: 05-05-2021 Revised: 18-05-2021 Accepted: 22-05-2021

ABSTRACT:Quest for optimal production of marketable quality palm kernel requires, in addition to other parameters, the modelling of cracking efficiency with respect to nut moisture content and the nut cracker rotor speed. In this study, performance index data generated from centrifugal palm nut cracker relating a combination of nut moisture content and cracker rotor speed with cracking efficiency and kernel breakage were gathered. Mathematical models were developed from the data using Non-Linear Regression Statistics embedded in Statistical Package for Social Scientists (SPSS) Version 20. Technical analysis showed that the values of coefficient of determination (R^2) were approximately equal the coefficient of correlation (r). The values of reduced Chi-square (χ_c^2), root mean square error (RMSE) and mean bias error (MBE) were lesser than the values of R^2. The coefficients of residual mass (CRM) were close to zero, and that of modelling efficiency (EF) were approximately one. The developed models were verified, validated and considered to be rationally good for predicting optimum % cracking efficiency and kernel breakage.

KEYWORDS: Cracking, Efficiency, Palm Kernel, Moisture Content, Rotor Speed.

I. INTRODUCTION

Modelling aids to predict the effect of perturbations in a system. To obtain optimum working conditions of a system, simulation is necessary. Simulation is simply the evaluation of an existing or a proposed system performance under various forms of interest and over a long period [1]. The system in this study was a centrifugal palm nut cracker. The palm nuts are obtained when palm fruits are subjected to stripping, sterilization, digestion and palm oil extraction. However, they are three major varieties of palm fruits, namely: the Dura, the Tenera and the Pisifera. Dura have large kernel and a very thin pericarp; Tenera have medium kernel with a thick pericarp; and Pisifera possess about 95% mesocarp, and with little or no kernel [2]. Many products are derived from the fruit. These include palm oil, kernel oil and cake, shell fragments, etc [3]. In order to obtain these products, which have so many domestics and industrial applications, the dried nuts are cracked to release whole kernels for crushing and kernel oil extraction. Cracking of nuts is a challenging issue which sometimes may result in split kernels due to certain influences. The split kernels are likely to cause kernel oil rancidity. The optimum performance of a nut cracker depends on nut moisture content, size, variety, cracker rotor speed, clearance between the rotor and the cracking wall, force, energy, etc [4, 5, 6]. Besides, the cracker optimum performance could be achieved within a certain range of these parameters. Hence, modelling would enable the incorporation of selected parameters into the system so as to allow room for quick and easy performance test of different alternatives that may lead to optimal solution. Several models have been developed by many researchers which could be used in food and crop processing, equipment design and operation optimization [7, 8, 9, 10, 11, 12, 13, 14, 15]. However, in formulating optimization function, the objective function and constraints have to be spelled out. Objective function is the response (value) to be minimized or maximized with respect to the decision variables, whileconstraints are sets of decision variables in which an optimal condition is to be found. These are given in Equations 1 and 2 [8].

Optimize $Y_0 = K_0\,(X_1, X_2, \ldots . X_n)$ (1)

Subject to:

$u_0 < X_i < v_1$, and i = 1, 2, 3,…, n (2)

Where, Y_0 = objective function, K_0 = a certain relationship existing between Y_0 and X, X_i = decision variables, u_0 and v_1 are the lower and upper limits, respectively. Some of the indices used in assessing the performance of a nut cracker are rate of feed, throughput capacity, efficiency of cracking, nut speed, rotor speed, kernel breakage, nut moisture content, etc. In this study, cracking efficiency, rotor speed and moisture content were considered in order to assess kernel breakage; since it contributes to the production of quality marketable kernels. In this work, % cracking efficiency (C_{eff}) is described as the ratio of completely cracked nuts to the total nuts fed into the hopper [5]. It is given as Equation 3.

$$\% \ C_{eff} = \left(\frac{M_T - M_p}{M_T}\right) \times 100\% \qquad (3)$$

Similarly, % kernel breakage, (K_b) is expressed as the mass of damaged kernels ($M_{k.d}$) divided by mass of the mixture of whole and damaged kernels, ($M_{k.w/d}$):

$$\% \ K_b = \left(\frac{M_{k.d}}{M_{k.w/d}}\right) \times 100\% \qquad (4)$$

Where, M_T = total mass of palm nuts fed into the nut cracker (kg) and M_p = mass of partially cracked and un-cracked nuts (kg).

The high % cracking efficiency with the corresponding low % kernel breakage factor is regarded as the optimum nut cracker performance index [16]. Therefore, it is essential to develop mathematical models that could be used to predict nut cracking efficiency and kernel breakage with respect to rotor speed and nut moisture content.

II. MATERIALS AND METHODS

Sourcing of Palm Nut

Fresh palm nuts of mixed varieties of the Dura and Tenera were obtained from a palm oil processing mill at Abak Road, Uyo, Nigeria.

Determination of Nut Moisture Content and Cracker Rotor Speed

The nuts were cleaned and the moisture content determined according to ASAE [17] and [18]. The nuts were initially weighed as M_i using electronic digital weighing balance of 0.001g precision and dried in a hot air convection oven at a temperature of 105 ^{0}C for 5, 6, 7 and 8 hours. 1200 nuts per drying time were removed, cooled in a desiccator for 5 minutes, re-weighed as M_f, and moisture content foundusing Equation 5.

$$\% \ MC_{wb} = \frac{M_i - M_f}{M_i} \times 100 \qquad (5)$$

where, % MC_{wb} = percent moisture content, wet basis, M_i = initial nut mass (g) and M_f = final nut mass at the stipulated drying time (g).

The nuts were then wrapped in black polyethene bags. Based on the established nut speed range of about 25.0 to 33.0 m/s for effective cracking and release of high percentage of whole kernel [19, 20, 6]; the cracker rotor speeds of 20.70, 25.50, 31.80 and 37.60 m/s were employed and read using tachometer from rpm to m/s. 100 nuts were fed into the cracker at each run. The total mass of palm nuts fed into the cracker, mass of partially cracked and un-cracked nuts, mass of a mixture of whole and damaged kernels, and damaged kernels obtained at each run were noted and recorded. The experiment was done in three replicates. Hence, the total of number of nuts used was 4800. The mean values were used in calculating the % cracking efficiency and % kernel breakage given in Equations 3 and 4, respectively.

Model Formulation

Based on the data generated, the following models in form of polynomial of degree 3, linear-power, hyperbolic and exponential functions were proposed as given in Equations 6 to 9.

$$Y = a(X)^3 + b(X)^2 + c(X) + d \qquad (6)$$

$$Y = a(X)^b + c \qquad (7)$$

$$Y = \frac{1}{a + b(X)} \qquad (8)$$

$$Y = ae^{bX} \qquad (9)$$

where, Y = percent cracking efficiency (% C_{eff}) or percent kernel breakage (% K_b), X = possible best combination of cracker rotor speed, S_r (m/s) and nut moisture content, M_c (% w.b.); and a, b, c and d are constants of the model equations.

Formulation of Optimization Function

The objective functions maximized and minimized were cracking efficiency and kernel breakage, respectively. The decision variables were the nut moisture content (M_c) and cracker rotor speed (S_r). The lower and upper boundaries of the constraints were as follows:

i. $9.01 \leq M_c \leq 12.10$ (% w.b.) (10)
ii. $20.70 \leq S_r \leq 37.60$ m/s (11)

Model Development

The experimental data obtained were fitted into the proposed model Equations 6 to 9 using Non-Linear Regression Statistics embedded in Statistical Package for Social Scientists (SPSS) Version 20. Each model and its respective constants were found. The model(s) with reasonable and highest value of coefficient of determination (R^2) were selected and subjected to verification and validation.

Model Verification and Validation

The models obtained were verified and validated using the following statistical computations and analyses:

(i) The correlation coefficient (r) and coefficient of determination (R^2) found by employing regression analysis [21];

(ii) Scattered plot of predicted and experimental values; and determination of the degree to which the predicted and experimental values are associated [22]; and

(iii) Reduced Chi-square (χ_c^2), mean bias error (MBE), root mean square error (RMSE), coefficient of residual mass (CRM) and modelling efficiency (EF) analyses [23, 24, 25, 26]. Thus, these values were obtained using Equations 12 to 16:

Reduced Chi-square (χ_c^2)

$$(\chi_c^2) = \frac{\sum_{i=1}^{\hat{N}}(MR_{exp} - MR_{pre})}{\hat{N} - Q} \quad (12)$$

Mean bias error (MBE)

$$MBE = \frac{1}{\hat{N}}\sum_{i=1}^{\hat{N}}(MR_{exp} - MR_{pre})^2 \quad (13)$$

Root mean square error (RMSE)

$$RMSE = (MBE)^{1/2} \quad (14)$$

Coefficient of residual mass (CRM)

$$CRM = \frac{\sum_{i=1}^{\hat{N}} MR_{exp} - \sum_{i=1}^{\hat{N}} MR_{pre}}{\sum_{i=1}^{\hat{N}} MR_{exp}} \quad (15)$$

Modelling efficiency (EF)

$$EF = 1 - \frac{\sum_{i=1}^{\hat{N}}(MR_{exp} - MR_{pre})^2}{\sum_{i=1}^{\hat{N}}(MR_{exp} - MR_{exp.mean})^2} \quad (16)$$

Where, MR_{exp} = experimental values, MR_{pre} = predicted values, $MR_{exp.mean}$ = mean experimental values, $\hat{N}$ = number of observations, and Q = number of constants. For accurate goodness of fit, the value of r should be equal to R^2, and also greater than the values of χ_c^2, RMSE and MBE. Besides, the value of CRM must be close to zero and EF approximately equal to 1.

III. RESULTS AND DISCUSSION

The results of nut moisture content attained at each drying time are presented in Table 1 while that of performance parameters for centrifugal palm nut cracker are given in Table 2. However, the initial nut moisture content was found to be 18.6% wb.

Table 1: Nut moisture content attained at each drying time

Drying Time (hours)	**MC (% w.b.)**
5	12.10
6	11.35
7	10.40
8	9.01

As observed in Table 1, nut moisture content decreased with increase in drying time. At the drying time of 8 hours, 9.01% MC (w.b.) was obtained.

Table 2: Performance Parameters for Centrifugal Palm Nut Cracker

		X_1	**X_2**	**Y_1**	**Y_2**
S/N	**Code**	**M_c (% w.b.)**	**S_r (m/s)**	**Response 1 (%)**	**Response 2 (%)**
1	1	12.10	20.70	54.90	7.70
2	1	12.10	25.50	59.47	10.45
3	1	12.10	31.80	64.74	13.20
4	1	12.10	37.60	68.91	15.72
5	1	11.35	20.70	55.21	8.41
6	1	11.35	25.50	62.00	10.05
7	1	11.35	31.80	69.81	11.44
8	1	11.35	37.60	72.00	14.48
9	1	10.4	20.70	60.09	6.30
10	1	10.4	25.50	64.26	7.11
11	1	10.4	31.80	70.32	8.15
12	1	10.4	37.60	75.45	11.99
13	1	9.01	20.70	64.18	4.08
14	1	9.01	25.50	76.00	4.23
15	1	9.01	31.80	78.39	6.24
16	1	9.01	37.60	80.00	8.80

From Table 2, the optimum performance parameters for the centrifugal palm nut cracker were obtained by simulating the combination of moisture content (M_c) and cracker rotor speed (S_r) within a specified range. The designations, X_1 and X_2 are independent variables while the responses, Y_1 and Y_2 are the % cracking efficiency and kernel breakage, respectively. Based on the statistical analysis, the models that best described the relationships in Table 2, were the hyperbolic and linear-power functions and are given in Equations 17 and 18.

$$\% C_{eff} = \frac{1}{k_1 + k_2\left(\frac{S_r{}^a}{M_c{}^b}\right)} \qquad (17)$$

$$\% K_b = c_1\left(\frac{S_r{}^d}{M_c{}^e}\right) + c_2\left(\frac{M_c{}^f}{S_r{}^g}\right) + h \qquad (18)$$

where k_1, k_2, c_1, c_2 and h are constants given as 0.009, 0.004, 0.022, 1.545×10^{-15} and -3.459, respectively while a, b, d, e, f and g are indices given as -0.945, -1.555, 0.586, -1.833, -0.229 and -9.734, respectively.

The predicted values of % cracking efficiency and % kernel breakage using the model Equations 17 and 18 and their respective constants/indices are presented in Table 3.

Table 3: Mean Experimental and Predicted Values of Cracking Efficiency and Kernel Breakage

Exp. Values (%)		**Pred. Values (%)**	
C_{eff}	K_b	C_{eff}	K_b
54.90	7.70	53.48	8.98
59.47	10.45	59.12	10.63
64.74	13.20	65.06	12.90
68.91	15.72	69.45	16.60
55.21	8.41	56.33	7.60
62.00	10.05	61.96	9.80
69.81	11.44	67.83	11.31
72.00	14.48	72.15	14.31
60.09	6.30	60.22	5.97
64.26	7.11	65.81	7.23
70.32	8.15	71.55	9.04
75.45	11.99	75.71	11.85
64.18	4.08	66.53	3.79
76.00	4.23	71.93	4.77
78.39	6.24	77.36	6.25
80.00	8.80	81.23	8.82

Note: Exp. = Experimental, Pred. = Predicted

The curves fitness of mean predicted % cracking efficiency and kernel breakage against mean experimental % cracking efficiency and kernel breakage are shown in Figures 1 and 2.

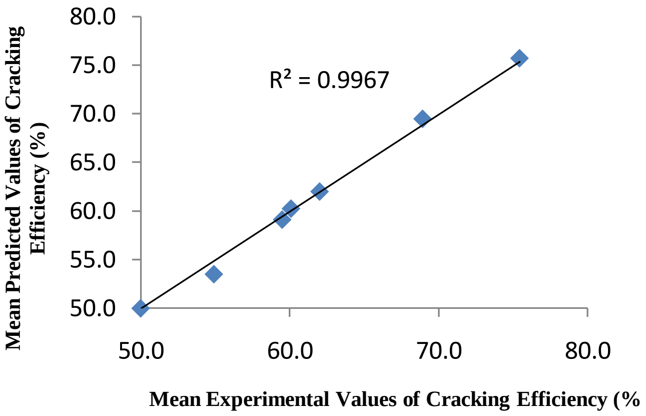

Fig. 1: A plot of mean predicted values against experimental values of % cracking efficiency

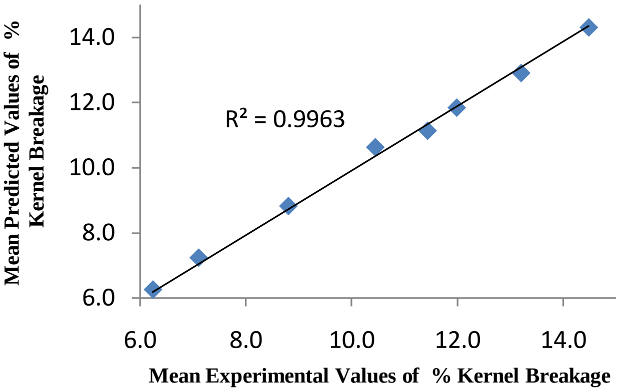

Fig. 2: A plot of mean predicted values against experimental values of % kernel breakage

The plots vividly show that the points for mean predicted and experimental values have positive correlation (r ≈ 1). The line for the slope equal one is the one for which mean experimental values would be equal to predicted values. The calculated statistical parameters for goodness of fit from Figures 1 and 2 are presented in Tables 4.

Table 4: Statistical Parameters for Goodness of Fit for the Model Equations

Parameters	**Values** Model Equation 17	Model Equation 18
Coefficient of correlation, r	0.9983	0.9981
Coefficient of determination, R^2	0.9967	0.9963
Reduced Chi-square, χ_c^2	0.4350	0.4000
Mean bias error, MBE	0.4216	0.0317
Root mean square error, RMSE	0.6493	0.1780
Coefficient of residual mass, CRM	0.0020	0.0070
Modelling efficiency, EF	0.9908	0.9957

From Table 4, the values of R^2 were approximately equal r, and r ≈ 1. The values of reduced Chi-square (χ_c^2), root mean square error (RMSE) and mean bias error (MBE) were lesser than the values of R^2. The values of coefficient of residual mass (CRM) were close to zero, and that of modelling efficiency (EF) were approximately equal to 1. These are characteristics of a satisfactory quality fit. From Tables 1 and 2, the optimum nut moisture content of 9.01% w.b. and cracker rotor speed of 25.50 m/s were found to give appreciable experimental cracking efficiency and kernel breakage of 76.00% and 4.23%; while that of the predicted values were 71.93% and 4.77%, respectively. Therefore, the model Equations 17 and 18 are rationally good for predicting % cracking efficiency and kernel breakage.

IV. CONCLUSION

Based on some reasonable degree of correlation between the predicted and experimental values, it was deduced that the model Equations 17 and 18 are rationally good for predicting the optimum % cracking efficiency and kernel breakage of a centrifugal palm nut cracker, respectively if the nut moisture content and cracker rotor speed are known.

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