Performance efficiency model of an integrated palm-nut cracker and kernel-shell separator

E. I. Alade*, O. A. Koya, B. V. Omidiji

(*Department of Mechanical Engineering, Obafemi Awolowo University, Ile-Ife 22005, Nigeria*)

Abstract: A mathematical model for predicting the performance efficiency of an integrated palm-nut cracker and kernel-shell separator was developed using dimensional analysis based on Buckingham's π theorem. The developed performance model was iterated in Matrix Laboratory (MATLAB), to predict the efficiencies, by varying the parameters of the materials in contact. The predicted performance efficiencies ranged between 88.26%-99.98%, while the evaluated performance efficiencies were in the range of 56.16%-96.57%. The correlation between the predicted and experimental numerical values using MINITAB17 suggested relationship and validity of the developed model (optimum r^2 = 99.6%).

Keywords: performance efficiency, cracking efficiency, separation efficiency, dimensional analysis, palm nut

Citation: Alade, E. I., O. A. Koya, and B. V. Omidiji. 2019. Performance efficiency model of an integrated palm-nut cracker and kernel-shell separator. Agricultural Engineering International: CIGR Journal, 21(3): 218–225.

1 Introduction

Palm nut industry had remained immensely relevant in many nations of the world due to the dependency of different companies on its products as raw materials (Hartley, 1987; Oke, 2007). However, the production of palm kernel, a major product of palm nut extraction, had been reported far below the projected demand, because more discoveries are being made on its numerous technical, domestic and economic values (Ituen and Modo, 2000).

Over the years, different researchers had carried out investigations on various techniques to facilitate the extraction of whole kernels from the shells, which have remained an arduous challenge in the industry due to huge damages on the kernels during the cracking process which in variably reduces its market value (Singh and Bargale, 2004). The development of effective route for the production of palm kernels and shells is therefore very crucial in order to meet up with their increasing demand industrially (Oke, 2007).

Various modelling techniques had been explored for finding solutions to problems of practical significance by different researchers. The behavior of biomaterials to different physical handling conditions during processing requires full comprehension in order to maximize yield and efficiency of machines associated with various unit operations (Ojolo et al., 2010). Also, survey from the literatures showed that researchers have engaged system modelling in enhancing the performances of processing equipment using several approaches. Most of these involve modelling of the variables to determine the functionality of processing machines, and they are usually specifically related to a particular design of a machine (Ndukwu and Asoegwu, 2010). Many a times, several process parameters are involved, and to tackle this phenomenon, a semi empirical modelling approach, such as dimensional analysis seems suitable, as it is a robust engineering tool that has recently shown efficiency in modelling such processes (Delaplace et al., 2012; Hassan et al., 2012; Petit et al., 2013).

This was demonstrated by Ndukwu and Asoegwu (2011). A mathematical model for predicting the cracking efficiency of vertical-shaft palm nut cracker using dimensional analysis based on the Buckingham's π theorem was developed. The model was validated with data from existing palm nut cracker and there was agreement between the experimental cracking efficiency

Received date: 2018-09-26 **Accepted date:** 2018-11-11

***Corresponding author:** E. I. Alade, ph.D., Department of Mechanical Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria. Tel: +2348038323045. Email: eyifemikate@gmail.com.

with the predicted values. Similarly, Okafor et al. (2016) developed a mathematical model for predicting the extrusion efficiency of a vertical column shaft palm oil extrusion machine using dimensional analysis based on the Buckingham's π theorem. Idowu and Owolarafe (2017) also presented a mathematical model for the prediction of shelling efficiency of an impact snake gourd seed decorticator using dimensional analysis based on the Buckingham's π theorem. The verification of the model by comparing the theoretical prediction with experimental values showed agreement between the predicted and the experimental numeral values. Other researchers (Degrimencioglu and Srivastava, 1996; Shefii et al., 1996; Mohammed 2002; Ndirika, 2006) had also used dimensional analysis based on the Buckingham's π theorem as veritable instrument in establishing prediction equations of various systems.

Collectively, their results suggested significant potential of accuracy and efficiency for system developments via modelling approaches. It thus appeared reasonable that this approach may be employed in combating the current challenge being faced in kernel-shell processing industry, by exploring the dominant factors influencing the processing of palm kernel and shell in principle, in order to build a functional device for the process. The focus therefore, of this study was to assess and correlate the factors defining the performance of an integrated palm nut cracker and dry kernel-shell separation system.

2 Materials and methods

2.1 Performance efficiency modelling of the modified machine

The parameters assumed to influence the performance of the proprietary device were deduced from the crop, machine, and operational parameters of the materials in contact. The interrelationships between the dependent and independent variables were then established using dimensional analysis, based on Buckingham's π theorem. This was with the view to develop a useful predicting equation for the system performance.

2.2 Modelling of cracking performance

Considering the cracking process, the parameters that were considered dominant are the shaft speed, ω_c, feed rate, λ_1, nut's size, d_n, moisture content, φ, cracking force, F_c, diameter of cracking drum, d_d and diameter of beater, d_i (Table 1).

The general relationship for nut-cracking was expressed as,

$$\eta_{ce}^{p} = f(\omega_c;\lambda_1;d_i;\varphi;F_c;d_d;d_n) \quad (1)$$

where, η_{ce}^{p} is Predicted cracking efficiency, (%).

The total number of independent variables for the determination of cracking performance efficiency (dependent variable) is 7, while the fundamental units (M, L, and T) are three. It is therefore necessary to determine the number of dimensionless groups into which the variables maybe combined. According to Buckingham π theorem (Douglas et al., 1995), the equation relating the variables will be of the form:

$$f(\pi_1,\pi_2,\pi_3,\ldots,\pi_{n-r})=0 \quad (2)$$

Where the number of dimensionless groups arising from a particular matrix formed from 'n' variables is given as (n-r) where 'r' is the largest non-zero determinant that can be formed from the matrix. Hence, the number of π terms is 4, indicating the need to form π_1; π_2; π_3 and π_4. Meanwhile, since φ is already dimensionless, it is therefore excluded (Simonyan et al., 2006) from the dimensionless terms determination, but later added when other dimensionless terms are determined.

$$\eta_{ce}^{p} = f(\omega_c;\lambda_1;d_i;F_c;d_d;d_n) \quad (3)$$

Table 1 Modelling parameters of palm-nut cracking and separation process

Variables	Symbols	Dimensions
Cracking parameters		
Predicted Performance efficiency	η_{PE}^{p}	dimensionless
Shaft speed	ω_c	T^{-1}
Feed rate (cracker)	λ_1	MT^{-1}
Nut size (diameter)	d_n	L
Moisture content	φ	dimensionless
Cracking force	F_c	MLT^{-2}
Diameter of cracking drum	d_d	L
Diameter of beater	d_i	L
Separation parameters		
Predicted Separation efficiency	η_{se}^{p}	dimensionless
Speed of rotating drum	ω_s	T^{-1}
Length of the slide	L_s	L
Gravitational acceleration	g	LT^{-2}
Coefficient of friction	μ	dimensionless
Diameter of the drum	d_s	L
Feed rate (separator)	λ_2	MT^{-1}
Shape of the particle	γ	dimensionless

The repeating variables were chosen to reflect dynamic, geometric and inertia similarities. Hence, ω_c, d_d and λ_1 were chosen, respectively, as repeating variables and are dimensionally related as;

$[\lambda_1]$=[MT^{-1}]; $[\omega_c]$=[T^{-1}]; and $[d_d]$=[L]

Consequently, the dimensionless terms are defined in terms of the repeating variables as foljhlow:

$$d_i=f[\lambda_1, \omega_c, d_d] \quad (4)$$

$$=\pi_1[\lambda_1^{a}, \omega_c^{b}, d_d^{c}] \quad (5)$$

Dimensionally,

$$L^1 = \pi_1(M^aT^{-a})(T^{-b})(L^c)$$

$$\therefore a = 0, b = 0, c = 1$$

So that,

$$\pi_1 = \frac{d_i}{d_d} \quad (6)$$

Similarly,

$$\pi_2 = \frac{F_C}{\lambda_1 d_d \omega_c} \quad (7)$$

$$\pi_3 = \frac{d_n}{d_d} \quad (8)$$

$$\pi_4 = \varphi \quad (9)$$

By modelling, the predicted cracking efficiency is then having the relationship below:

$$\eta_{ce}^{p} = f(\pi_1; \pi_2; \pi_3; \pi_4) \quad (10)$$

Hence;

$$\eta_{ce}^{p} = f(\frac{d_i}{d_d}; \frac{F_C}{\lambda_1 d_d \omega_c}; \frac{d_n}{d_d}; \varphi) \quad (11)$$

Douglas etal. (1995) stated that any dimensionless groups maybe combined by multiplication or division or both to form a new valid group. This will condense the dimension terms (Shefii et al., 1996) to a manageable level.

Based on these, new group was therefore formed by setting;

$\pi_1' = \pi_1 \times \pi_2 \times \pi_3 \times \pi_4$; or $\frac{\pi_1}{\pi_2} \times \frac{\pi_3}{\pi_4}$; or $\frac{\pi_1}{\pi_2} \times \frac{\pi_3}{\pi_4}$; or $\frac{\pi_2}{\pi_1} \times \frac{\pi_4}{\pi_3}$; or $\frac{\pi_3}{\pi_1} \times \frac{\pi_4}{\pi_2}$; or $\frac{\pi_3}{\pi_1} \times \frac{\pi_2}{\pi_4}$; or $\frac{\pi_1}{\pi_3} \times \frac{\pi_4}{\pi_2}$; or $\pi_1 \div (\pi_2 \times \pi_3 \times \pi_4)$; or $\pi_2 \div (\pi_1 \times \pi_3 \times \pi_4)$; or $\pi_3 \div (\pi_1 \times \pi_2 \times \pi_4)$; or $\pi_4 \div (\pi_1 \times \pi_2 \times \pi_3)$; or $(\pi_1 \times \pi_2 \times \pi_3) \div \pi_4$; or $(\pi_1 \times \pi_2 \times \pi_4) \div \pi_3$; or $(\pi_1 \times \pi_3 \times \pi_4) \div \pi_2$; or $(\pi_2 \times \pi_3 \times \pi_4) \div \pi_1$

Equation (10) then becomes:

$$\eta_{ce}^{p} = f(\pi_1') \quad (12)$$

Implying that;

$\eta_{ce}^{p} = f\left(\frac{F_c d_i d_n \varphi}{d_d^3 \lambda_1 \omega_c}\right)$; or $f\left(\frac{d_i d_n \lambda_1 \omega_c}{F_c d_d \varphi}\right)$; or $f\left(\frac{F_c d_i}{\lambda_1 d_n d_d \varphi \omega_c}\right)$; or $f\left(\frac{F_c d_d \varphi}{\lambda_1 \omega_c d_i d_n}\right)$; or $f\left(\frac{F_c d_n}{\lambda_1 d_i d_d \omega_c \varphi}\right)$; or $f\left(\frac{d_n d_d \varphi \lambda_1 \omega_c}{F_c d_i}\right)$; or $f\left(\frac{d_i d_d \varphi \lambda_1 \omega_c}{F_c d_n}\right)$; or $f\left(\frac{d_i d_d \lambda_1 \omega_c}{F_c d_n \varphi}\right)$; or $f\left(\frac{F_c d_d}{\lambda_1 d_i d_n \omega_c \varphi}\right)$; or $f\left(\frac{d_d d_n \lambda_1 \omega_c}{F_c d_i \varphi}\right)$; or $f\left(\frac{\lambda_1 \omega_c d_d^3 \varphi}{F_c d_i d_n}\right)$; or $f\left(\frac{F_c d_i d_n}{d_d^3 \lambda_1 \omega_c \varphi}\right)$; or $f\left(\frac{F_c d_i \varphi}{\lambda_1 \omega_c d_d d_n}\right)$; or $f\left(\frac{\lambda_1 \omega_c d_i d_n \varphi}{F_c d_d}\right)$; or $f\left(\frac{F_c d_n \varphi}{\lambda_1 \omega_c d_d d_i}\right)$

Some typical values of some properties that are relevant in nut cracking and product separation had been determined by different researchers which are available in relevant literatures (Koya et al. 2004; Koya and Faborode, 2006). Moreover, the combination of values for optimizing the models, to obtain the expression providing the best promise for the predicted performance are shown on Table 2.

It was expected that cracking efficiency would increase as the feed rate reduces. Also, operating the machine at a reasonably low speed was expected to reduce the mechanical breakage of the nut, thereby enhancing the efficiency of the nut cracking, which is desirable for better product separation. This was suited by Equation (13) for the prediction of cracking efficiency when tested and optimized with the cracking parameters on Table 2.

$$\eta_{ce}^{p} = \frac{F_c d_i \varphi}{\lambda_1 \omega_c d_d d_n} \quad (13)$$

2.3 Modelling of separation performance

Based on the materials in contact of experimental separator, the significant factors considered for products separation were, speed of rotating drum, ω_s, length of the slide, L_s, shape of the particle, γ, coefficient of friction, μ, diameter of the drum, d_s, acceleration due to gravity, g, and feed rate, λ_2 (Table 2).

Similar to the cracking process, the total number of independent variables for the determination of separation performance efficiency (dependent variable) is 7. The relationship for predicted separation efficiency was therefore expressed as,

$$\eta_{se}^{p} = f(\omega_s; \gamma; L_s; g; \mu; d_s; \lambda_2) \tag{14}$$

where, η_{se}^{p} =Predicted separation efficiency, (%).

Table 2 Values of parameters for predicting performance efficiency

Parameters	Values at different particle sizes			
	10 mm	14 mm	20 mm	25 mm
Cracking				
Shaft speed, ω_c (rad s^{-1})	83-152	83-152	83-152	83-152
Feed rate, λ_1 (kg h^{-1})	85, 90, 95	85, 90, 95	85, 90, 95	85, 90, 95
Moisture content, φ (%)	13.4	13.4	13.4	13.4
Cracking force, F_c (N)	1306.09	2171.76	2262.06	2266.15
Diameter of beater, d_i (m)	0.24	0.24	0.24	0.24
Diameter of cracking drum, d_d (m)	0.4	0.4	0.4	0.4
Separation				
Speed of rotating drum, ω_s (rad s^{-1})	1.0-6.2	1.0-6.2	1.0-6.2	1.0-6.2
Length of the slide, L_s (m)	0.127	0.127	0.127	0.127
Gravitational acceleration, g (m s^{-2})	9.81	9.81	9.81	9.81
Coefficient of friction, μ	0.68	0.68	0.68	0.68
Shape of the particle, γ	0.71	0.68	0.74	0.67

Hence, π_{1b}, π_{2b}, π_{3b}, and π_{4b} are formed. Meanwhile, γ and μ are dimensionless, and were excluded from the dimensionless terms determination (Simonyan et al., 2006).

$$\eta_{se}^{p} = f(\omega_s; g; L_s; d_s; \lambda_2) \tag{15}$$

Similar to cracking process, the parameters ω_s, d_s and λ_2 were selected as repeating variables and are dimensionally related as;

$$\omega_s = T^{-1},\ d_s = L,\ \lambda_2 = MT^{-1}$$

Therefore,

$$g = \pi_{1b}[d_s \omega_s^2] \tag{16}$$

$$\pi_{1b} = \frac{g}{\omega_s^2 d_s} \tag{17}$$

Similarly,

$$\pi_{2b} = \frac{L_s}{d_s} \tag{18}$$

Also

$$\pi_{3b} = \gamma \tag{19}$$

$$\pi_{4b} = \mu \tag{20}$$

Hence, by modelling, the predicted separation efficiency becomes:

$$\eta_{se}^{p} = f(\pi_{1b}; \pi_{2b}; \pi_{3b}; \pi_{4b}) \tag{21}$$

$$\eta_{se}^{p} = f(\frac{g}{\omega_s^2 d_s}; \frac{L_s}{d_s}; \gamma; \mu) \tag{22}$$

Reducing the relationship by applying combination rule of multiplication and/or division or both to form a new valid group (Douglas et al., 1995; Shefii et al., 1996):

$\eta_{se}^{p} = \pi_{1b} \times \pi_{2b} \times \pi_{3b} \times \pi_{4b}$; or $\frac{\pi_{1b}}{\pi_{2b}} \times \frac{\pi_{3b}}{\pi_{4b}}$; or $\frac{\pi_{1b}}{\pi_{2b}} \times \frac{\pi_{3b}}{\pi_{4b}}$; or $\frac{\pi_{2b}}{\pi_{1b}} \times \frac{\pi_{4b}}{\pi_{3b}}$; or $\frac{\pi_{3b}}{\pi_{1b}} \times \frac{\pi_{4b}}{\pi_{2b}}$; or $\frac{\pi_{3b}}{\pi_{1b}} \times \frac{\pi_{2b}}{\pi_{4b}}$; or $\frac{\pi_{1b}}{\pi_{3b}} \times \frac{\pi_{4b}}{\pi_{2b}}$; or $\pi_{1b} \div (\pi_{2b} \times \pi_{3b} \times \pi_{4b})$; or $\pi_{2b} \div (\pi_{1b} \times \pi_{3b} \times \pi_{4b})$; or $\pi_{3b} \div (\pi_{1b} \times \pi_{2b} \times \pi_{4b})$; or $\pi_{4b} \div (\pi_{1b} \times \pi_{2b} \times \pi_{3b})$; or $(\pi_{1b} \times \pi_{2b} \times \pi_{3b}) \div \pi_{4b}$; or $(\pi_{1b} \times \pi_{2b} \times \pi_{4b}) \div \pi_{3b}$; or $(\pi_{1b} \times \pi_{3b} \times \pi_{4b}) \div \pi_{2b}$; or $(\pi_{2b} \times \pi_{3b} \times \pi_{4b}) \div \pi_{1b}$

Then;

$\eta_{se}^{p} = f\left(\frac{\mu\gamma g L_s}{\omega_s^2 d_s^2}\right)$; or $f\left(\frac{\gamma g}{\mu\omega_s^2 L_s}\right)$; or $f\left(\frac{g L_s}{\gamma\mu\omega_s^2 d_s^2}\right)$; or $f\left(\frac{\mu L_s \omega_s^2}{\gamma g}\right)$; or $f\left(\frac{\mu\gamma\omega_s^2 d_s^2}{g L_s}\right)$; or $f\left(\frac{\gamma\omega_s^2 L_s}{\mu g}\right)$; or $f\left(\frac{\mu g}{\gamma\omega_s^2 L_s}\right)$; or $f\left(\frac{g}{\gamma\mu L_s \omega_s^2}\right)$; or $f\left(\frac{L_s \omega_s^2}{\mu\gamma g}\right)$; or $f\left(\frac{\gamma\omega_s^2 d_s^2}{\mu g L_s}\right)$; or $f\left(\frac{\mu\omega_s^2 d_s^2}{\gamma g L_s}\right)$; or $f\left(\frac{\gamma g L_s}{\mu\omega_s^2 d_s^2}\right)$; or $f\left(\frac{\mu g L_s}{\gamma\omega_s^2 d_s^2}\right)$; or $f\left(\frac{\mu\gamma g}{\omega_s^2 L_s}\right)$; or $f\left(\frac{\mu\gamma L_s \omega_s^2}{g}\right)$

It was expected that separation efficiency would increase as operational speed decreases. This was justified with Equation (23):

$$\eta_{se}^{p} = \frac{\mu\gamma g}{\omega_s^2 L_s} \tag{23}$$

Hence, for the integrated process, the overall predicted performance efficiency of the modified machine was computed as:

$$\eta_{PE}^{p} = \frac{\eta_{ce}^{p}\eta_{se}^{p}}{100} \tag{24}$$

Therefore the prediction expression becomes;

$$\eta_{PE}^{p} = 0.01\left[\left(\frac{F_c d_i \varphi}{\lambda_1 \omega_c d_d d_n}\right)\left(\frac{\mu\gamma g}{\omega_s^2 L_s}\right)\right] \tag{25}$$

The prediction of the performance efficiency was executed using the Matrix Laboratory (MATLAB, R2013a). The software was used to obtain a series of performance cracking and separation efficiencies using Equations (13) and (23). These were used to compute the prediction of overall performance efficiency of the system in conformation to Equation (25). The ranges of speed for the iteration were 83-152 rad s^{-1} and 1.0-6.2 rad s^{-1} for cracking and separation processes; based on range of the speed limits of conventional crackers and prototype separator respectively. The trend shows that fixing a comparative lower speed for repeated impact nut cracking, as well as separation process, would ensure improved efficiency.

The model was verified by numerically analyzing and comparing the performance efficiency results obtained experimentally with the predicted values using MINITAB17 software.

2.4 Determination of measured performance efficiency parameter

The experimental performance was measured in terms of its products recoveries, cracking efficiency, separation efficiency and overall performance efficiency. Sample of *dura* variety of palm nut was drawn from large tonnage, which had been sun-dried for commercial kernel and shell extraction. The sample was classified into four groups of sizes and varied during experimentations. This was done to relate the overall performance of the machine to nut sizes.

All weight measurements of samples were taken on weighing balance and replicated, to determine the proportion of nut constituent being fed into the experimental machine.

2.4.1 Determination of kernel recovery

Kernel recovery (K_r) assessed the percentage of the kernels which were recovered from the mixture. It is mathematically expressed as:

$$K_r = \frac{m_{sk}}{m_{sk} + m_{lk}} \times 100 \tag{26}$$

where, m_{sk} is mass of separated kernels (kg); m_{lk} is mass of kernels apparently lost (discharged) with shells (kg).

2.4.2 Determination of shell recovery

Similar to kernel recovery, shell recovery (S_r) evaluated the percentage of the shells which were recovered from the mixture, and is given by:

$$S_r = \frac{m_{ss}}{m_{ss} + m_{ls}} \times 100 \tag{27}$$

where, m_{ss} is mass of separated shells (kg); m_{ls} is mass of shells apparently lost (discharged) with kernels (kg).

2.4.3 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:

$$M_d = \frac{M_b}{M_b + M_u} \times 100 \tag{28}$$

where, M_d is mechanical damage (%); M_b is mass of broken kernel (kg); M_u is mass of unbroken kernels (kg).

2.4.4 Determination of cracking efficiency

Cracking efficiency (C_E) was defined as the ratio of the mass of completely cracked nut to the total mass of the nut fed into the hopper, expressed in percentage. It was calculated as:

$$C_E = \frac{M_T - M_{PC}}{M_T} \times 100 \tag{29}$$

where, M_T is total mass of the palm nut sample fed into the hopper (kg); M_{PC} is mass of partially cracked and uncracked palm-nut (kg);

2.4.5 Determination of separation efficiency

The separation efficiency (S_E) of the machine in percentage was computed as:

$$S_E = \frac{K_r S_r}{100} \tag{30}$$

2.4.6 Determination of performance efficiency

The overall performance efficiency (P_E) of the machine in percentage was computed as:

$$P_E = \frac{C_E S_E}{100} \tag{31}$$

3 Results and discussions

3.1 Prediction results of performance model

The response of the performance efficiency to the speed variation in terms of cracking and separation efficiencies are graphically shown in Figures 1-3 (a, b, c and d) and 4(a, b, c and d) respectively. The output curves in terms a, b, c and d correspond to the prediction variables of particles sizes 10, 14, 20 and 25 mm respectively. For the cracking process, the prediction curves show that the efficiency reduces in the order of 85, 90 and 95 kg h^{-1} levels of feed rates, as well as the increasing trend of the iteration speeds (Equation (13)). This indicates that the cracking performance efficiency of the modified machine will be inversely influenced by the feed rates and its operational speed. More so, for separation process, increase in speed also implies reduction in its output efficiency (Equation (23)). It can therefore be understood from the trend that the development of integrated palm-nut cracker and kernel-shell separator would be better off at reasonably low speed and feed rates when product qualities are expected. This observation compares well with the findings of Koya and Faborode (2006).

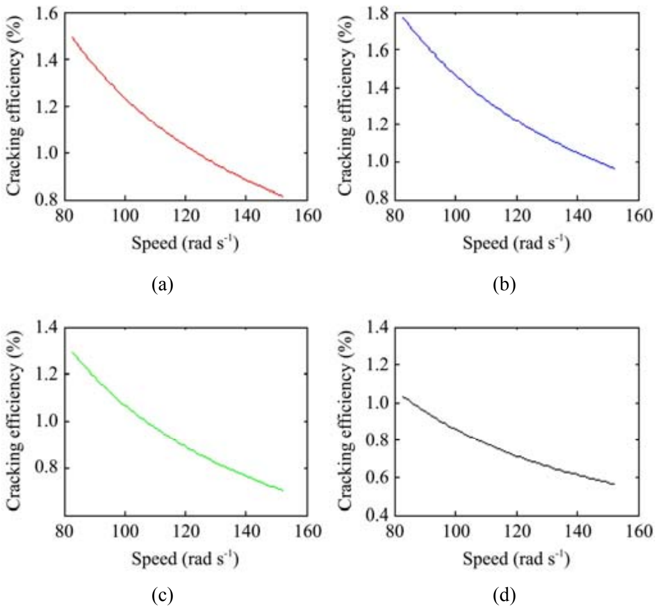

Figure 1 Graphical output of cracking efficiency model at feed rate 85 kg h^{-1}

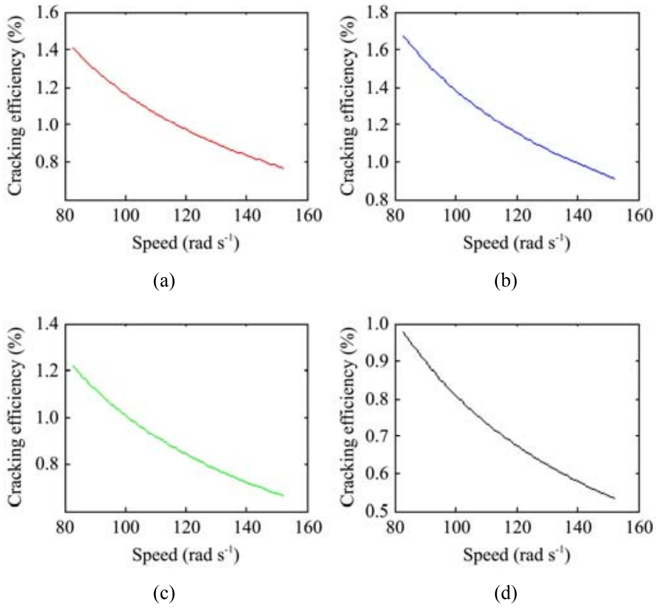

Figure 2 Graphical output of cracking efficiency model at feed rate 90 kg h^{-1}

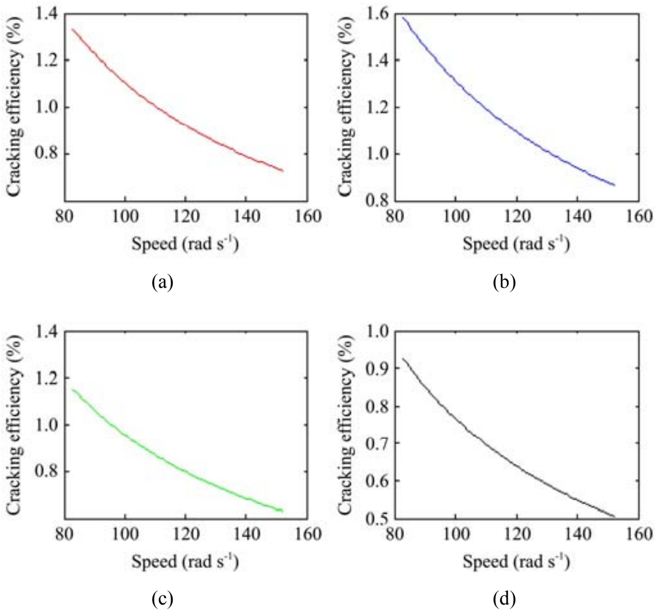

Figure 3 Graphical output of cracking efficiency model at feed rate 95kg h^{-1}

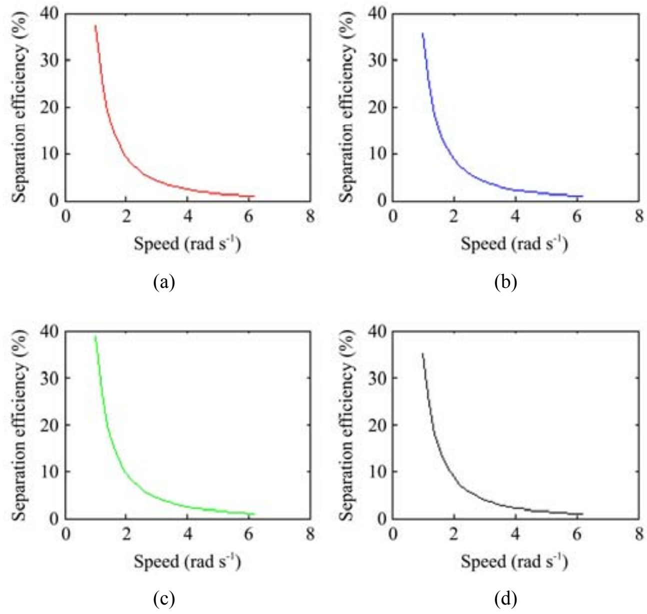

Figure 4 Graphical output of separation efficiency model

3.2 Model validation

Table 3 shows the overall predicted and the experimental performance efficiencies. Equations (13) and 23 were used for computing the predicted cracking and separation efficiencies before using Equation (25) to compute the overall performance efficiency.

Figure 5 showed the graphical analysis of the numerical data comparing the predicted and experimental values of performance efficiency. The trend from the curves shows significant numerical correlation between the performance efficiencies of model and experimental values. It was demonstrated that predicted performance efficiency increased as its corresponding experimental values increased. The results also showed that the developed performance model of the machine is in agreement with the experiment with a set of high R^2

values.

Table 3 Experimental and predicted performance efficiencies

Sieve size (mm)	Feed rate (kg h^{-1})	Performance efficiencies (%)	
		Predicted	**Experimental
10	85	99.63	83.53
	90	94.10	67.64
	95	89.14	56.16
	Mean	94.29	69.11
	Standard deviation	5.25	13.74
14	85	99.03	84.51
	90	93.53	69.81
	95	88.60	60.22
	Mean	93.72	71.51
	Standard deviation	5.22	12.23
20	85	99.98	88.56
	90	94.43	71.86
	95	89.46	61.58
	Mean	94.62	74.00
	Standard deviation	5.26	13.61
25	85	97.80	96.57
	90	93.17	76.94
	95	88.26	63.35
	Mean	93.07	78.95
	Standard deviation	4.77	16.70

Note: **Computed as adjusted experimental performance.

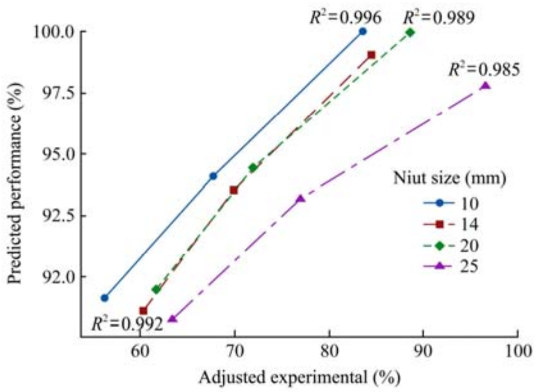

Figure 5 Validation of predicted and adjusted experimental performance efficiencies

This implies that the theoretical model developed is valid for the performance efficiency prediction of the modified integrated palm nut cracker and kernel-shell separator. The equations relating the predicted and experimental performance efficiency obtained by the least square method are respectively presented below as:

$$\text{Pred}=67.95+0.3811\times\text{Adj\_Exp}\ [R^2=99.6\%,\ \text{size}=10\ \text{mm}] \quad (31)$$

$$\text{Pred}=63.34+0.4248\times\text{Adj\_Exp}\ [R^2=99.2\%,\ \text{size}=14\ \text{mm}] \quad (32)$$

$$\text{Pred}=66.18+0.3844\times\text{Adj\_Exp}\ [R^2=98.9\%,\ \text{size}=20\ \text{mm}] \quad (33)$$

$$\text{Pred}=70.69+0.2835\times\text{Adj\_Exp}\ [R^2=98.5\%,\ \text{size}=25\ \text{mm}] \quad (34)$$

where, Pred - Predicted performance efficiency; Adj_Exp - Adjusted experimental performance efficiency.

These set of predicting equations are comparable to the equation obtained by Ndukwu and Asoegwu (2011), for predicting the cracking efficiency of a vertical-shaft palm nut cracker.

4 Conclusion

The developed performance efficiency model of the modified system, based on Buckingham's π theorem, showed adeptness in predicting the performance of the integrated machine in terms of its modelling parameters, which varied jointly and directly with cracking force, moisture content, coefficient of friction, shape of the particle and gravitational acceleration, and inversely with feed rate, shaft speed of cracker, speed of rotating incline drum and length of the slide. The overall predicted performance ranged between 88.26%-99.98%, based on the particle sizes. The results of correlation between numerical values of predicted performance efficiency and experimental results showed that there was a significant relationship (at optimum R^2 value of 0.996), implying that the theoretical model developed is valid for performance efficiency prediction of the fabricated palm nut cracker integrated with kernel-shell separator.

References

Degrimencioglu, A., and A.K. Srivastava. 1996. Development of screw conveyor performance models using dimensional analysis. *Transactions of the American Society of Agricultural and Biological Engineers*, 39(5): 1757–1763.

Delaplace, G., P. Coppenolle, J. Cheio, and F. Ducept. 2012. Influence of whip speed ratios on the inclusion of air into a bakery foam produced with a planetary mixer device. *Journal of Food Engineering*, 108(4): 532–540.

Douglas, J. F., J. M. Gasorek, and J. A. Swaffield. 1995. *Fluid Mechanics*.3rd ed. Singapore: Longman Publishers.

Hartley, C.W.S. 1987. *The Project of Oil Palm and the Extraction in the Oil Palm*. London: Longman Publishers.

Hassan, R., K. Loubière, J. Legrand, and G. Delaplace. 2012. A consistent dimensional analysis of gas-liquid mass transfer in a volume aerated stirred tank containing purely viscous fluids with shear-thinning properties. *Chemical Engineering Journal*, 184: 42–56.

Idowu, D.O., and O. K. Owolarafe. 2017. Mathematical modelling of the performance of an impact gourd (*Trichosanthes cucumerina*. L) seed sheller. *Agricultural Engineering International*: *CIGR Journal*, 19(1): 142–149.

Ituen, E. U. U., and I. V. O. Modo. 2000. The effect of fermentation period on palm oil production in eastern Nigeria using traditional methods. *Indigenous Knowledge and Development Monitor*, 8(1): 7–12.

Koya, O. A., A. Idowu, and M. O. Faborode. 2004. Some physical properties of palm kernel and shell relevant in nut cracking and product separation. *Journal of Agricultural Engineering and Technology*, 12: 33–45.

Koya, O. A., and M. O. Faborode. 2006. Separation theory for palm kernel and shell mixture on a spinning disc. *Biosystems Engineering*, 95(3): 405–412.

Mohammed, U. S. 2002. Performance modelling of the cutting process in sorghum harvesting. Unpublished Ph.D. diss., Ahmadu Bello University., Zaria.

Ndirika, V. I. O. 2006. A mathematical model for predicting output capacity of selected stationary grain threshers. *Agricultural Mechanization in Asia, Africa and Latin America*, 36(2): 9–13.

Ndukwu, M. C., and S. N. Asoegwu. 2010. Functional performance of a vertical-shaft centrifugal palm nut cracker. *Research in Agricultural Engineering*, 56(2): 77–83.

Ndukwu, M. C., and S. N. Asoegwu. 2011. A mathematical model for predicting the cracking efficiency of vertical-shaft centrifugal palm nut cracker. *Research in Agricultural Engineering*, 57(3): 110–115.

Ojolo, S. J., O. Damisa, J. I. Orisaleye, and C. Ogbonaya. 2010. Design and Development of cashew nut shelling machine. *Journal of Engineering Design and Technology*, 8(2): 146–157.

Okafor, V. C., P. K. Ejesu, D. C. Chinweuba, and R. N. Nwakuba. 2016. A mathematical model for predicting the extrusion efficiency of a vertical column shaft palm oil extrusion machine using dimensional analysis. *Greener Journal of Science Engineering and Technological Research*, 6(1): 1–8.

Oke, P. K. 2007. Development and performance evaluation of indigenous palm kernel dual processing machine. *Journal of Engineering and Applied Sciences*, 2(4): 701–705.

Petit, J., T. Six, A. Moreau, G. Ronse, and G. Delaplace. 2013. β-lactoglobulin denaturation, aggregation, and fouling in a plate heat-exchanger: pilot-scale experiments and dimensional analysis. *Chemical Engineering Science*, 101: 432–450.

Shefii, S., S. K. Upadhyaya, and R. E. Garrett. 1996. The importance of experimental design to the development of empirical prediction equations: A case study. *Transaction of American Society of Agricultural and Biological Engineers*, 39(2): 377–384.

Simonyan, K. J., Y. D. Yiljep, and O. J. Mudiare. 2006. Modeling the grain cleaning process of a stationary sorghum thresher. *Agricultural Engineering International*: *CIGR Journal*, 3: manuscript PM06012.

Singh, J., and P. C. Bargale. 2004. Development of a small capacity double stage compression screw press for oil expression. *Journal of Food Engineering*, 43(2): 75–82.