Umudike Journal of Engineering and Technology (UJET); Vol. 8, No. 1, June 2022, pp. 37 – 48; Michael Okpara University of Agriculture, Umudike, Print ISSN: 2536-7404, Electronic ISSN:2545-5257; http://ujetmouau.net; doi: https://doi.org/10.33922/j.ujet_v8i1_5

MODEL DEVELOPMENT AND OPTIMIZATION FOR PREDICTING WHOLE KERNEL RECOVERY OF A PALM NUT CRACKING MACHINE USING MIXED VARIETY OF PALM NUTS

*[1]Sam, E. O., [2]Ndirika, V. I. O. and [2]Etoamaihe, U. J.

[1]Department of Agricultural and Environmental Engineering, Akwa Ibom State University, Ikot Akpaden, Nigeria.

[2]Department of Agricultural and Bio-Resource Engineering, Michael Okpara University of Agriculture, Umudike, Nigeria.

*Corresponding Author: emmoksamharvest@gmail.com

ABSTRACT

This work aimed at developing a mathematical model, validate and optimized for predicting whole kernel recovery as a performance parameter for a palm nut cracking machine, using mixed variety of palm nuts. The drying temperature of 105°C; five levels of cracking speed (1200, 1400, 1600, 1800 and 2000rpm); six levels of moisture content (12.4, 14.0, 16.2, 18.1, 20.0 and 27.8% w.b) and five levels of feed rate (360, 400, 450, 514.29, 600kg/h) were selected for the study. Full factorial design was used in the design of the experiment with three independent variables; cracking speed (rpm), moisture content (%) and feed rate (kg/hr)*, set at five, six, five level factorial respectively. Four hundred and fifty (450) samples of 1000g each of fresh palm nuts were used for the experiment. 150 samples were selected for each experimental run. Model to predict whole kernel recovery was developed using the concept of Buckingham Pi theorem. The developed models were verified and validated by fitting them into experimental data. Method of regression analysis as computed using Microsoft Excel programme of Microsoft package was used to describe the relationships, plot the graphs and compute the coefficients of determination* (R^2) *between the predicted and experimental values. The best combination for optimum whole kernel recovery for mixed varieties were obtained at feed rate of 580.41kg/hr, throughput capacity of 151.43kg/h, nut speed of 12.51m/s, peripheral velocity of 33.78m/s, cracking speed of 1935rpm, and moisture content of 16.69%w.b with optimum whole kernel recovery of 80.45%.*

***KEYWORDS**: Model, Optimization, Whole Kernel Recovery, Palm Nut, Cracking, Machine, Mixed Variety*

1. INTRODUCTION

The oil palm fruit (*Eleasis guineesis*) as one of the predominant agricultural products over the years, has gained much attention in the world due to its wide application as a major raw material in industries. It is one of the most essential cash crops grown in the tropics. Nigeria happens to be one of the leading producers of palm oil obtained from the oil palm fruit. The oil palm is a unique crop with two distinct types of oil namely; palm oil and palm kernel oil. Palm oil is extracted from the mesocarp of the fruits and palm kernel oil from the kernels of the palm nuts. The palm kernel is an edible seed and its oil can be fractionated into a liquid (olein), solid (stearin), and intermediate as shortening. Palm kernel oil can be used for making glycerin, candle, margarine, pomade, medicine, polish, oil paint and cheaper raw material for biodiesel when produced in abundant (Adebayo, 2004; Emeka and Olomu, 2007).

Palm nut shell has become an essential commodity in the oil palm industry. Many applications have been developed. Due to high calorific value of palm nut shell, this commodity has been considered one of the key biomass materials which may possibly replace fossil fuel for steam engines (Mohammad, 2005).

Basically, there are three distinct varieties of the oil palm fruit. These are the *Dura, Tenera* and *Pisifera*. *Dura* variety has a thin mesocarp, thick endocarp (shell) and the kernel tends to be large, comprising 7 - 20% of the fruit weight. The *Tenera* variety has a large mesocarp, thin endocarp (shell) and large to medium kernel. The *Pisifera* variety possesses thick mesocarp, small or no endocarp (shell) with small kernel where applicable. The endocarp (shell) of palm nut generally contains one or more kernels (Okokon *et al*., 2007).

The nuts are not useable until the kernels are sorted out from the shell (Hartmann *et al.,* 1993). The nut recovery is a unit operation that encompasses nut drying after separation from the pulps. This is followed by cracking, kernel separation from cracked nut mixture, kernel storage and kernel oil extraction. Therefore, cracking and sorting are two major operations that need serious development for drastic improvement in quantity and quality of palm kernel oil produced.

1.1. Statement of Problem.

There are heaps of palm nuts in virtually all processing mills and in local markets as a result of cracking problems. Considering the economic importance of palm kernels, this is a great loss to farmers. There is need to establish the moisture content that will increase the cracking efficiency, whole kernel recovery, reduce the percentage or possibly eliminate the broken kernels during cracking of fresh palm nuts. Drying temperature and drying time to get the expected moisture content must be ascertained.

Sorting out different varieties of palm nut also constitutes another major challenge in palm nut cracking. In most plantations, mixed varieties (Dura, Tenera and even Pisifera) of oil palm are planted, harvested and processed together in large quantities. To overcome the rigorous task of sorting and damages, the existing cracking machines needs to be improved for effective cracking of mixed varieties of palm nuts simultaneously.

The various factors affecting the performance of cracking machine as presented by Ndukwu (1998) and Shahbazi (2012) includes: the cracking time, nuts moisture content, feed rate, bulk density, throughput capacity, cracking speed and power. These factors if not properly controlled could reduce cracking machine performance. Therefore, modelling the performance parameters or contributing factors for cracking process of palm nut would provide better understanding of the fundamental relationship of these variables in order to identify the contribution of each variable. Also, optimization of the model will help to identify the best contribution of the variables that can be used to establish optimum conditions for palm nut cracking.

2. MATERIALS AND METHODS

The materials/equipment used for the study are: Mixed varieties of fresh oil palm nuts; Impeller Palm nut cracker; Friction Absorption Dynamometer; Digital Tachometer – Photo type; Model: DT-2234B; Digital Stop watch; Vernier Calliper; Electronic Weighing Balance (Model: EK5350; Max.: 5kg/11lb with 0.01g accuracy); Desiccators and Air Oven – Model: MINO/50; Serial No.: 13C280

2.1. Sample Acquisition and Preparation

Mixed varieties of fresh oil palm nuts were purchased from VIKA Farm, Uyo and NIFOR, Abak Station palm fruits processing mill. Cleaning of nuts was carried out manually to remove immature nuts and other unwanted materials from the bulk sample. The nuts were sorted out and graded into large, medium and small nuts as shown in Figure 1.

Figure 1: (a) Large nuts (b) Medium nuts (c) Small nuts

2.2. Description of the Experimental Machine

Palm nuts were cracked in a cracker (Figure 2) developed by Etuk Tech. Engineering Company based on the design consideration and analysis by Ismail *et al.* (2015) and Stephen and Lukman (2015). The machine was coupled together with a Friction Absorption Dynamometer, for determining torque during each run of cracking. It consists of five major units: the in-feed unit, the cracking unit, the discharge outlet, the driven unit and the dynamometer.

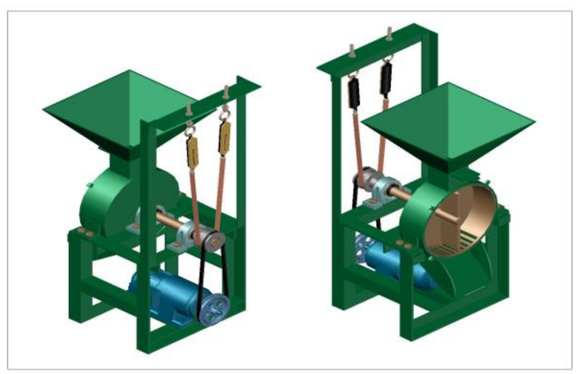


Figure 2: Isometric view of the palm nut cracker (Source: Sam, 2017)

2.3. Working Principles of the Machine

The machine was put into operation by starting the electric motor, which provides the required power to drive the pulley of the cracking machine thereby causing the impeller blades to rotate. The cracking speed was adjusted by adjusting the power supplied to the electric motor. The cracked mixture falls by gravity through discharge outlet situated directly below the cracking chamber.

2.4. Model Development

Model to predict the percentage of whole kernel recovery of a palm nut cracking machine was developed using the concept of Buckingham Pi theorem.

The variable influencing the percentage of whole kernel recovery WKR are:

- Volume of the nut before cracking - - - - V_n
- Moisture content of nuts - - - - - α_{mc}
- Diameter of cracking drum (mm) - - - - D_{cd}
- Feed rate (g/s) - - - - - - - F_r
- Peripheral velocity of impeller (m/s) - - - - P_v
- Nut dimension (mm) - - - - - - d_n
- Nut density (kg/m³) - - - - - - δ_n
- Cracking speed (rpm) - - - - - - S_c
- Speed of the nut (m/s) - - - - - - $\cap_s$
- Throughput (kg/h) - - - - - - T_p

The whole kernel recovery from the cracker is expressed in Equation (1) as:

$$WKR = f\left(V_n \, ; \alpha_{mc} \, ; \, D_{cd} \, ; \, F_r \, ; \, P_v \, ; \, d_n \, ; \, \delta_n \, ; \, S_c \, ; \cap_s \, ; \, T_p\right) \quad (1)$$

Adopting the $M\ L\ T$ system of dimension, the dimension of variables and the dimensional matrix are presented in Tables 1 and 2 respectively.

Table 1: Dimension of variables influencing whole kernel recovery of a palm nut cracking machine

S/N	Variables	Symbol	Unit	Dimension
1	Whole kernel recovery	WKR	%	$M^0 L^0 T^0$
2	Volume of the nut before cracking	V_n	m^3	$M^0 L^3 T^0$
3	Moisture content of nuts	α_{mc}	%w.b	$M^0 L^0 T^0$
4	Diameter of cracking drum	D_{cd}	mm	$M^0 L^1 T^0$
5	Feed rate	F_r	g/s	$M^1 L^0 T^{-1}$
6	Peripheral velocity of impeller	P_v	m/s	$M^0 L^1 T^{-1}$
7	Nut dimension	d_n	mm	$M^0 L^1 T^0$
8	Nut density	δ_n	kg/m^3	$M^1 L^{-3} T^0$
9	Cracking speed	S_c	Kgm^2/s	$M^1 L^2 T^{-1}$
10	Speed of the nut	$\cap_s$	m/s	$M^0 L^1 T^{-1}$
11	Throughput capacity	T_p	kg/h	$M^1 L^0 T^{-1}$

Table 2: Dimensional matrix of the variables influencing the whole kernel recovery of a palm nut cracking machine

S/N	Variables	Symbol	Dimension		
			M	L	T
1	Whole kernel recovery	WKR	0	0	0
2	Volume of the nut before cracking	V_n	0	3	0
3	Moisture content of nuts	α_{mc}	0	0	0
4	Diameter of cracking drum	D_{cd}	0	1	0
5	Feed rate	F_r	1	0	-1
6	Peripheral velocity of impeller	P_v	0	1	-1
7	Nut dimension	d_n	0	1	0
8	Nut density	δ_n	1	-3	0
9	Cracking speed	S_c	1	2	-1
10	Speed of the nut	$\cap_s$	0	1	-1
11	Throughput capacity	T_p	1	0	-1

Applying the Buckingham pi theorem to identify the dimensionless group to be formed, the following assertions were made:
The dependent variable = WKR
The repeating variables = V_n ; α_{mc} ; D_{cd} ; F_r ; P_v ; d_n ; δ_n ; S_c ; $\cap_s$; T_p
Total number of variables = 11
Number of fundamental dimensions = 3
Number of dimensionless groups to be formed = 11-3 = 8
So the required terms is expressed in Equation (2) as:

$$\pi_1 = f(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7) \quad (2)$$

The pi terms can be determined by considering the corresponding dimensional expression in Equation (3) as:

$$WKR ; V_n ; \alpha_{mc} ; D_{cd} ; F_r ; P_v ; d_n ; \delta_n ; S_c ; \cap_s ; T_p = 0 \quad (3)$$

From Table 2, α_{mc} is dimensionless and is therefore excluded from the dimensionless terms determination as shown in Equation (4); and is added when other dimensionless terms are determined (Simonyan *et al*., 2019).

$$WKR = f(V_n ; D_{cd} ; F_r ; P_v ; d_n ; \delta_n ; S_c ; \cap_s ; T_p) \quad (4)$$

The dimensionless equation is given in Equation (5) as:

$$f(V_n ; D_{cd} ; F_r ; P_v ; d_n ; \delta_n ; S_c ; \cap_s ; T_p) = 0 \quad (5)$$

Nut dimension (d_n), speed of nut ($\cap_s$) and throughput (T_p) were selected as recurring set of variables since their combination does not form a dimensionless group.

With $d_n, \cap_s$ and T_p selected, the exponent a, b and c attached to each recurring set respectively as $d_n{}^a \cap_s{}^b T_p{}^c$

The component of the exponential recurring set is divided by the remaining variables: V_n ; D_{cd} ; F_r ; P_v ; δ_n ; S_c . So the dimensionless group π_1, π_2, π_3, π_4, π_5, and π_6 were obtained as given in Equation (6) to (11) according to Ndirika (2005); Ndukwu and Asoegwu (2010). These expressions form the basis of the Buckingham Pi theorem of dimensionless groups.

$$\pi_1 = \frac{V_n}{d_n{}^a \cap_s{}^b T_p{}^c} \quad (6)$$

$$\pi_2 = \frac{D_{cd}}{d_n{}^a \cap_s{}^b T_p{}^c} \quad (7)$$

$$\pi_3 = \frac{F_r}{d_n{}^a \cap_s{}^b T_p{}^c} \quad (8)$$

$$\pi_4 = \frac{P_v}{d_n{}^a \cap_s{}^b T_p{}^c} \quad (9)$$

$$\pi_5 = \frac{\delta_n}{d_n{}^a \cap_s{}^b T_p{}^c} \quad (10)$$

$$\pi_6 = \frac{S_c}{d_n{}^a \cap_s{}^b T_p{}^c} \quad (11)$$

In order to obtain values for the exponents a, b and c, the principle of dimensional homogeneity is used to equate the dimension on each side of the equations of the π groups.
So Equation (6) becomes;

$$M^0L^0T^0 = \frac{M^0L^3T^0}{(M^0L^1T^0)^a(M^0L^1T^{-1})^b(M^1L^0T^{-1})^c} \quad (12)$$

From Equation (7);

$$M^0L^0T^0 = \frac{M^0L^1T^0}{(M^0L^1T^0)^a(M^0L^1T^{-1})^b(M^1L^0T^{-1})^c} \quad (13)$$

From Equation (8);

$$M^0L^0T^0 = \frac{M^1L^0T^{-1}}{(M^0L^1T^0)^a(M^0L^1T^{-1})^b(M^1L^0T^{-1})^c} \quad (14)$$

From Equation (9);

$$M^0L^0T^0 = \frac{M^0L^1T^{-1}}{(M^0L^1T^0)^a(M^0L^1T^{-1})^b(M^1L^0T^{-1})^c} \quad (15)$$

From Equation (10);

$$M^0L^0T^0 = \frac{M^1L^{-3}T^0}{(M^0L^1T^0)^a(M^0L^1T^{-1})^b(M^1L^0T^{-1})^c} \quad (16)$$

From Equation (11);

$$M^0L^0T^0 = \frac{M^1L^2T^{-1}}{(M^0L^1T^0)^a(M^0L^1T^{-1})^b(M^1L^0T^{-1})^c} \quad (17)$$

Employing dimensional homogeneity for M, L and T, the exponents a, b and c were evaluated. Substituting the values of the components a, b and c into Equations respectively;

$$\pi_1 = \frac{V_n}{d_n{}^3 \cap_s{}^0 T_p{}^0} = \frac{V_n}{d_n{}^3} \quad (18)$$

$$\pi_2 = \frac{D_{cd}}{d_n{}^1 \cap_s{}^0 T_p{}^0} = \frac{D_{cd}}{d_n} \quad (19)$$

$$\pi_3 = \frac{F_r}{d_n{}^0 \cap_s{}^0 T_p{}^1} = \frac{F_r}{T_p} \quad (20)$$

$$\pi_4 = \frac{P_v}{d_n{}^0 \cap_s{}^1 T_p{}^0} = \frac{P_v}{\cap_s} \quad (21)$$

$$\pi_5 = \frac{\delta_n}{d_n{}^{-2} \cap_s{}^{-1} T_p{}^1} = \frac{\delta_n d_n{}^2 \cap_s}{T_p} \quad (22)$$

$$\pi_6 = \frac{S_c}{d_n{}^2 \cap_s{}^0 T_p{}^1} = \frac{S_c}{d_n{}^2 T_p} \quad (23)$$

And $\pi_7 = \alpha_{mc}$ (24)

Combining the expressions for $\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6$ and π_7, Equation (2) is expressed in Equation (25) as:

$$\frac{V_n}{d_n{}^3} = f\left\{\frac{D_{cd}}{d_n}, \frac{F_r}{T_p}, \frac{P_v}{\cap_s}, \frac{\delta_n d_n{}^2 \cap_s}{T_p}, \frac{S_c}{d_n{}^2 T_p}, \alpha_{mc}\right\} \quad (25)$$

Combining the dimensionless terms to reduce the Equation to a manageable level. The dimensionless terms is expressed in Equation (26) to (29) as:

$$\pi_{12} = \frac{V_n}{{d_n}^2 D_{cd}} \quad (26)$$

$$\pi_{34} = \frac{F_r \cap_S}{T_p P_v} \quad (27)$$

$$\pi_{56} = \frac{\delta_n {d_n}^4 \cap_S}{S_c} \quad (28)$$

$$\pi_7 = \alpha_{mc} \quad (29)$$

The new dimensionless functional equation is expressed in Equation (30) as:

$$WKR = f(\pi_{12}; \pi_{34}; \pi_{56}; \pi_7) \quad (30)$$

$$WKR = f\left\{\frac{V_n}{{d_n}^2 D_{cd}}; \frac{F_r \cap_S}{T_p P_v}; \frac{\delta_n {d_n}^4 \cap_S}{S_c}; \alpha_{mc}\right\} \quad (31)$$

$$WKR \;=\; f(A; B; C; D) \quad (32)$$

Equation (31) gives the whole kernel recovery, WKR with all variables in Equation (1) as a function of four efficiency components which are presented as A, B, C and D respectively in Equation (32).

2.5. Model input parameters for whole kernel recovery

The average experimental results, machine input, crop and design parameters for mixed varieties of palm nut are presented in Tables 3

Table 3: Experimental results of the effects of different crop and cracking machine parameters on whole kernel recovery for Mixed variety of palm nut.

S/N	V_{nc}	α_{mc}	D_{cd}	F_r	P_v	d_n	δ_n	S_c	$\cap_s$	T_p	WKR_e
1	0.0016	12.4	0.385	360.00	20.73	0.0165	710.55	1200	7.54	277.78	58.37
2	0.0016	14.0	0.385	400.00	24.19	0.0165	710.55	1400	8.79	187.92	62.29
3	0.0016	16.2	0.385	450.00	27.65	0.0165	710.55	1600	10.05	177.84	86.00
4	0.0016	18.1	0.385	514.29	31.10	0.0165	710.55	1800	11.31	156.63	80.71
5	0.0016	20.0	0.385	600.00	34.56	0.0165	710.55	2000	12.57	141.36	70.61

2.6. Development of the prediction equation

The prediction equation was established by allowing one π-term to vary at a time while keeping the other constant and observing the resulting changes in the function. This was achieved by plotting the values of experimental whole kernel recovery against dimensionless constants shown in Tables 4. The values of experimental whole kernel recovery were plotted against dimensionless constant π_{12}, while keeping π_{34}, π_{56} and π_7 constant; π_{34}, while keeping π_{12}, π_{56} and π_7 constant; π_{56}, while keeping π_{12}, π_{34} and π_7 constant; and π_7, while keeping π_{12}, π_{34} and π_{56} constant as illustrated in Figures 3 to 6.

Table 4: Experimental whole kernel recovery values (WKR_e) and calculated values ($\pi_{12}, \pi_{34}, \pi_{56}, \pi_7$) of whole kernel recovery for Mixed variety of palm nut in an impeller-type nut cracker

S/N	WKR_e	$\pi_{12} = \frac{V_{nc}}{{d_n}^2 D_{cd}}$	$\pi_{34} = \frac{F_r \cap_s}{T_p P_v}$	$\pi_{56} = \frac{\delta_n {d_n}^4 \cap_s}{S_c}$	$\pi_7 = \alpha_{mc}$
1	58.37	15.26	0.4714	0.03309	12.4
2	62.29	15.27	0.7735	0.03313	14.0
3	86.00	15.32	0.9197	0.03327	16.2
4	80.71	15.33	1.1941	0.03329	18.1
5	70.61	15.34	1.5438	0.03330	20.0

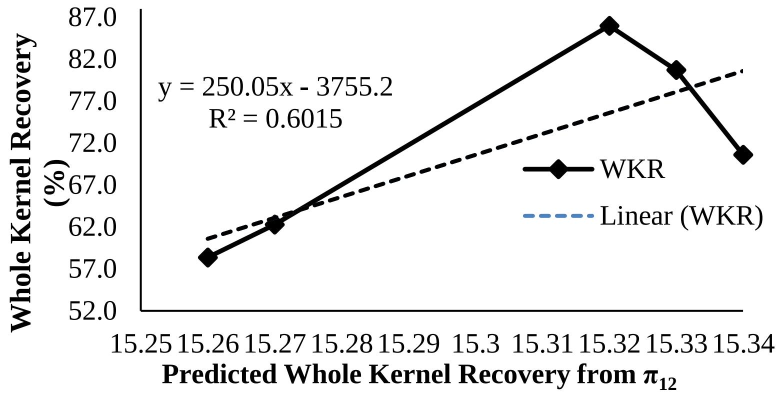


Figure 3: Variation of experimental whole kernel recovery against π_{12}, keeping π_{34}, π_{56} and π_7 constant

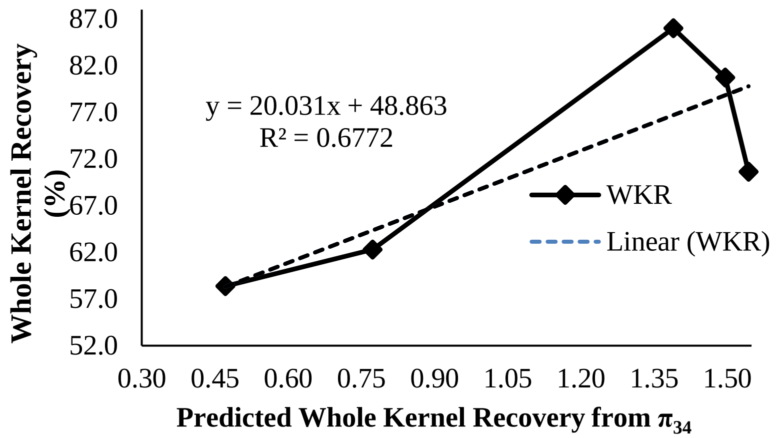


Figure 4: Variation of experimental whole kernel recovery against π_{34}, keeping π_{12}, π_{56} and π_7 constant

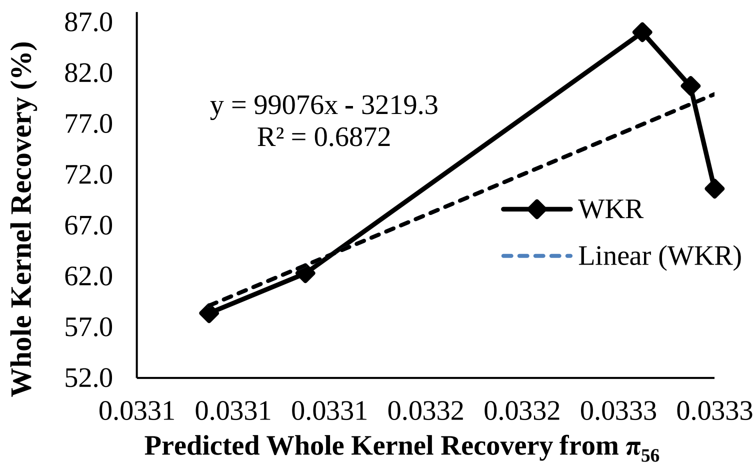


Figure 5: Variation of experimental whole kernel recovery against π_{56}, keeping π_{12}, π_{34} and π_7 constant

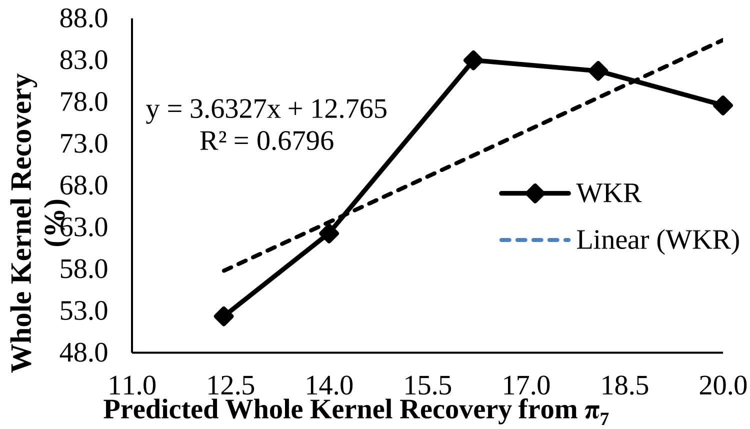


Figure 6: Variation of experimental whole kernel recovery against π_7 keeping π_{12}, π_{34} and π_{56} constant

The model equations obtained from the linear functions and R^2 values for mixed variety of palm nut are expressed in Equations 33 to 36 as:

$$WKR_{e/\pi_{12}-MIXED} = 250.05\pi_{12} - 3755.2 \quad R^2 = 0.6015 \tag{33}$$

$$WKR_{e/\pi_{34}-MIXED} = 20.031\pi_{34} + 48.86 \quad R^2 = 0.6772 \tag{34}$$

$$WKR_{e/\pi_{56}-MIXED} = 99076\pi_{56} - 3219.3 \quad R^2 = 0.6872 \tag{35}$$

$$WKR_{e/\pi_{7}-MIXED} = 3.633\pi_{7} + 12.77 \quad R^2 = 0.6796 \tag{36}$$

The plot of the π terms (Figures 3 – 6) forms a plane surface in linear space, and according to Ndukwu and Asoegwu (2010), it implies that their combination favours summation or subtraction. Therefore, the component equation was combined by summation. The component equation was formed by the combination of the values of Equations 33 – 36 and expressed in Equation (37) as:

$$WKR_p = f_1(\pi_{12}; \pi_{34}; \pi_{56}; \pi_7) + f_2(\pi_{12}; \pi_{34}; \pi_{56}; \pi_7) + f_3(\pi_{12}; \pi_{34}; \pi_{56}; \pi_7) + f_4(\pi_{12}; \pi_{34}; \pi_{56}; \pi_7) + K \tag{37}$$

Substituting Equations (33) to (36) into Equation (37), WKR_p for mixed varieties were obtained in Equation (38) as:

$$WKR_{p-MIXED} = 250.05\pi_{12} + 20.03\pi_{34} + 99076\pi_{56} + 3.633\pi_7 - 6912.87 \tag{38}$$

A further manipulation as permitted under the rules of the Burkingham pi theorem is manipulating with a constant factor. Therefore, Equation (38) was divided with a constant factor of 3.65, which yields the predicted model Equation expressed in Equation (39) with values close to the actual ones.

$$WKR_{p-MIXED} = 68.51\pi_{12} + 5.488\pi_{34} + 27144.11\pi_{56} + 0.995\pi_7 - 1893.94 \tag{39}$$

Substituting the values of dimensionless π terms $(\pi_{12}; \pi_{34}; \pi_{56}; \pi_7)$ into Equation (39), the predicted equation for whole kernel recovery was obtained as expressed in Equation (40) as:

$$WKR_{p-MIXED} = 68.51\left(\frac{V_{nc}}{{d_n}^2 D_{cd}}\right) + 5.488\left(\frac{F_r \cap_s}{T_p P_v}\right) + 27144.11\left(\frac{\delta_n {d_n}^4 \cap_s}{S_c}\right) + 0.995(\propto_{mc}) - 1893.94 \tag{40}$$

2.7. Model validation

The mathematical model was validated using the data generated from the impeller-typed palm nut cracker. The model validation was carried out at five levels of cracking speed (1200, 1400, 1600, 1800 and 2000 rpm), nut moisture content (12.4, 14.0, 16.2, 18.1 and 20.0 % w,b) and feed rate (360.00, 400.00, 450.00, 514.29 and 600.00 kg/h). The method of regression analysis as computed using Microsoft Excel programme of Microsoft package was used to describe the relationships, plot the graphs and compute the coefficients of determination (R^2) between the predicted and experimental values. Experimental values of parameters were substituted into Equation 40 to yield the predicted whole kernel recovery as presented in Table 5.

Table 5: Experimental (WKR_e) and calculated (WKR_p) values of whole kernel recovery for Mixed varieties of palm nut in an impeller-type nut cracker

S/N	Cracking Parameters			Whole Kernel Recovery	
	S_c	$\propto_{mc}$	F_r	$WKR_{e-Mixed}$	$WKR_{p-Mixed}$
1	1200	12.4	360.00	58.37	64.61
2	1400	14.0	400.00	62.29	68.03
3	1600	16.2	450.00	86.00	76.06
4	1800	18.1	514.29	80.71	78.80
5	2000	20.0	600.00	70.61	81.67

The predicted and experimental whole kernel recovery values were evaluated on a regression curve in order to obtain the coefficients of determination (R^2) and the Root Mean Square Error (RMSE). Figure 7 present the regression curves between the predicted and experimental whole kernel recovery, with their linear Equations and R^2 values.

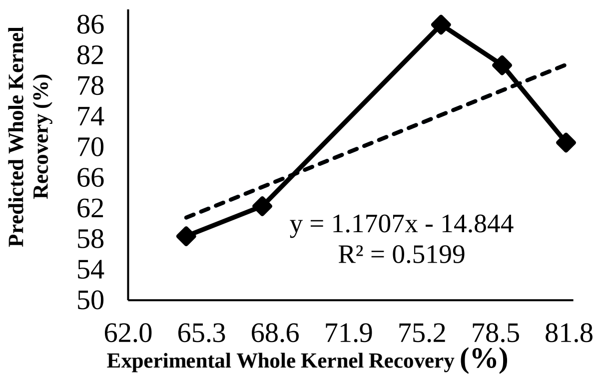


Figure 7: Graph of predicted (WKR_p) against experimental (WKR_e) whole kernel recovery for mixed variety of palm nut

From figures 7, it was observed that the predicted and experimental values have a very high correlation with R^2 values of 51.99% with a standard deviation of 11.76 and 13.77 as presented in Table 6.

The linear equations relating the predicted and experimental values of the whole kernel recovery is given in Equation (41) as:

$$WKR_{p-MIXED} = 1.17076WKR_{e-MIXED} - 14.844 \quad (41)$$

Equations 41 express the relationship between the predicted and experimental whole kernel recovery with R^2 values of 51.99%, with RMSE of 3.18 (Table 6) between the experimented and predicted whole kernel recovery values which is less than 5% of the average value of the experimental whole kernel recovery of palm nut using the impeller-type palm nut cracker. The validity of the models was examined by testing to know if the intercept and the slope were significantly different at 5% significance level.

Table 6: Experimental (WKR_e) and predicted (WKR_p) values of whole kernel recovery for mixed varieties of palm nut

S/N	Cracking Parameters			Whole Kernel Recovery	
	S_c	$\propto_{mc}$	F_r	$WKR_{e-Mixed}$	$WKR_{p-Mixed}$
1	1200	12.4	360.00	58.37	53.49
2	1400	14.0	400.00	62.29	58.08
3	1600	16.2	450.00	86.00	85.84
4	1800	18.1	514.29	80.71	79.64
5	2000	20.0	600.00	70.61	67.82
Standard deviation				11.76	13.77
RMSE				3.18	

2.8. Optimization of the Predictive Model

From the machine performance evaluation, the objective function considered is the maximization of the whole kernel recovery. That is, to determine the optimum levels of the whole kernel recovery model and the design variables under consideration that results to maximum whole kernel recovery for the three varieties of palm nut. The design variables used in the optimization are nut volume per unit time, dimension of nut, diameter of cracking drum, feed rate, throughput capacity, speed of the nut, peripheral velocity of impeller, nut bulk density, cracking speed and moisture content of the nut.

The lower and upper limits of the design variables which are incorporated as constraints for feed rate, throughput capacity, speed of the nut, peripheral velocity of impeller, cracking speed, and crop moisture content are presented in Table 7.

Table 7: Variables and values used for the simulation of whole kernel recovery during cracking of mixed varieties of palm nut

S/N	Variables	Symbol	Unit	Mixed variety
1	Nut volume per unit time	V_{nc}	m^3	0.0016
2	Dimension of nut	$\boldsymbol{d_n}$	m	0.0165
3	Diameter of cracking drum	$\boldsymbol{D_{cd}}$	m	0.385
4	Feed rate	F_r	kg/hr	$360 \leq F_r \leq 600$
5	Throughput capacity	T_p	kg/hr	$280 \leq T_p \leq 140$
6	Speed of the nut	$\cap_s$	m/s	$13 \leq \cap_s \leq 7$
7	Peripheral velocity of impeller	P_v	m/s	$20 \leq P_v \leq 35$
8	Nut bulk density	δ_n	kg/m^3	710.55
9	Cracking speed	S_c	Kgm^2/s	$1200 \leq S_c \leq 2000$
10	Moisture content	$\propto_{mc}$	$\% \, w.b$	$12 \leq \propto_{mc} \leq 28$

2.9. Model implementation and computer simulation

Figure 8 illustrates the flowchart of the developed simulation model for cracking of mixed varieties of palm nut in an impeller-type palm nut cracking machine. The mathematical models and simulation were solved with MATLAB program (version R2018b, MathWorks, Natick, Massachusetts, USA).

The MATLAB programming steps included: (i) creating system domain, (ii) defining the mathematical models, (iii) developing the functions and matrix, (iv) defining all boundary conditions and input variables, (v) numerical solution using MATLAB coding, (vi) coupling and integrating for maximum whole kernel recovery (vi) displaying data and graphs for different input variables and whole kernel recovery.

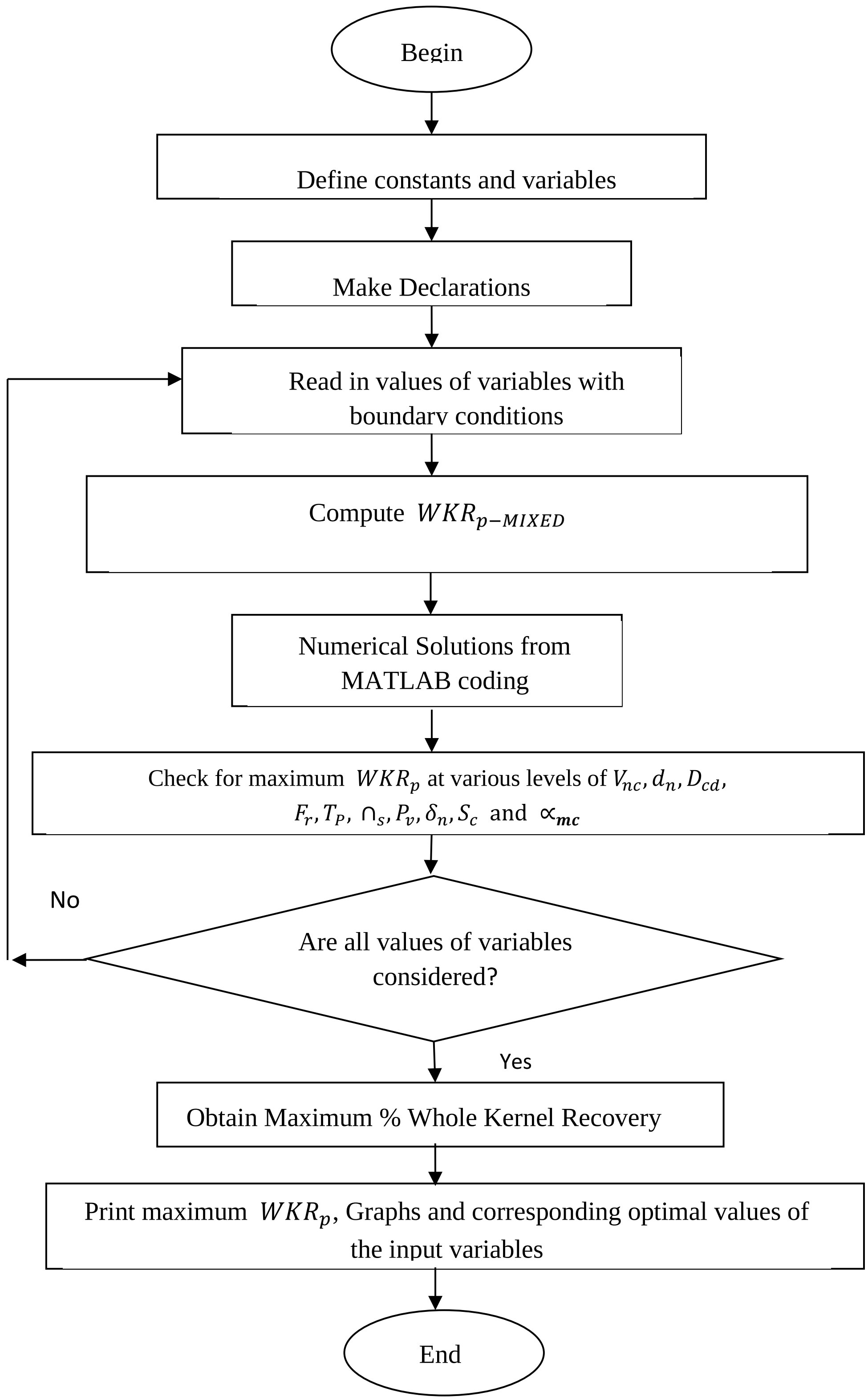
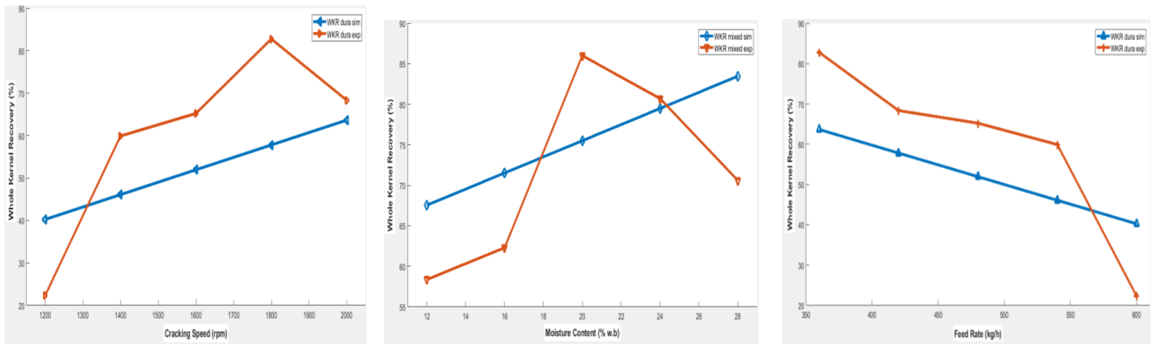


Figure 8: Flow chart for optimization simulation programme for whole kernel recovery (Algorithm)

The simulated and experimental whole kernel recovery results during the cracking process of palm nut are shown in Figures 9a, b and c. From the Figures, it can be seen that the whole kernel recovery are directly proportional to the cracking speed and moisture, whereas that of feed rate have inverse proportionality, but the simulated results of the throughput have a good proportionality index as compared to the experimental results. A similar result was obtained by Umani (2020). The developed model satisfactorily predicted the percentage whole kernel recovery of the palm nut during the cracking process with $R^2 > 0.98$ and < 5% relative error.



(a) (b) (c)

Figure 9: Graph of simulated and experimental whole kernel recovery versus (a) cracking speed (b) moisture content (c) feed rate

From the simulation results of the analysis, it was observed that the whole kernel recovery increases with increase in cracking speed and moisture content; and decreases with increase in feed rate. The best combination for optimum whole kernel recovery for mixed varieties were obtained at feed rate of 580.41kg/hr, throughput capacity of 151.43kg/h, nut speed of 12.51m/s, peripheral velocity of 33.78m/s, cracking speed of 1935rpm, and moisture content of 16.69%w.b with optimum whole kernel recovery of 80.45%.

3. CONCLUSION

Models to predict whole kernel recovery, mixed varieties of palm nut cracking machine were developed using the concept of Buckingham Pi theorem. The developed models were verified and validated by fitting them into experimental data. The method of regression analysis as computed using Microsoft Excel programme of Microsoft package was used to describe the relationships, plot the graphs and compute the coefficients of determination (R^2) between the predicted and experimental values. The simulated and experimental results during the cracking process and the best combination for optimum whole kernel recovery for mixed varieties was obtained

The developed model satisfactorily predicted the whole kernel recovery as performance parameters of the cracking machine during the cracking process with < 5% relative error.

REFERENCES

Adebayo, A. A. (2004). Development and Performance Evaluation of a motorized palm nut cracking machine. Proceedings of the Annual Conference of the Nigerian Institution of Agricultural Engineers. 26, 326-330.

Emeka, V, E. and Olumu, J. M. (2007). Nutritional Evaluation of Palm Kernel Meal Types 1. Proximate Composition and Metabolize Energy Values. *African Journal of Biotechnology, 6(21):2484-2486.*

Hartmann, T. H., Kester, D. E. and Davis, F. T. (1993). Plant Propagation Principles and Practice. (5th ed). New Delhi, pp. 105-210.

Ismail, S. O., Ojolo, S. J., Orisaleye, J. I., Adediran, A. A., and Fajuyitan, O. O. (2015). Design and Development of an Improved Palm Kernel Shelling and Sorting Machine. *European International Journal of Science and Technology*. 4(2): February, 2015

MATLAB program (version R2018b, MathWorks, Natick, Massachusetts, USA).

Mohammad, D. (2005). Palm Kernel Shell (PKS) is More Than Biomass for Alternative Fuel. Proceedings of the PIPOC 2007 International Palm Oil Congress (Chemistry & Technology).

Ndirika, V. I. O. (2005). A Mathematical Model for Predicting Output Capacity of Selected Stationary Grain Threshers. Agricultural Mechanization in Asia, Africa and Latin America. Vol.36(2) Pp 9-13.

Ndukwu, M. C. (1998). Performance Evaluation of a Vertical Shaft Centrifugal Palm Nut Cracker. B. Eng. Thesis, Owerri, Federal University of Technology.

Ndukwu, M .C. and Asoegwu, S. N. (2010). Functional Performance of a Vertical-Shaft Centrifugal Palm Nut Cracker: *Research in Agricultural Engineering*, 56 (2): 77-83.

Okokon, F. B., Udoh, M., Antia, O. and Ette, I. (2007). Investigation into the Grading of Large Scale Palm Nuts for Cracking. *World Journal of Biotechnology,* 8(2):1376-1384.

Sam, E. O. (2017). Construction of Dynamometer for the Determination of Power Requirement for Oil Palm Nut Cracking at Various Moisture Content level. M.Eng. Thesis, Unpublished, Department of Agricultural and Food Engineering, University of Uyo, Uyo, Nigeria.

Shahbazi, F. (2012). Effects of Moisture Content, Impact Direction and Impact Energy on the Cracking Characteristics of Apricot Pit. *World Applied Sciences Journal* 20(11): 1520-1528.

Stephen, A. I. and Lukman, A. A. (2015). Design and Construction of Palm Kernel Cracker and Separator. *International Journal of Engineering Trends and Technology (IJETT)*. 20(3) Feb 2015.

Umani, K. C., Olatunji, O. M., Ekop, I. E. and Akpan, G. E. (2020). Experimental Investigation of the effect of Rotor Speed of a Horizontal Shaft Centrifugal Palm Nut Cracker on Optimum Whole Kernel Production and Shell Particle Size. African Institute of Mathematical Sciences / Next Einstein Initiative. 7(2020)

