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A Mathematical Model for Predicting Power Requirement of A Cocoyam Chipper

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Abstract
A mathematical expression for predicting the power requirement for the chipping process of a mechanically operated cocoyam chipper is presented. The chipper power requirement model was developed by dimensional analysis using the concept of Buckingham's *Pi* Theorem. The model was verified and validated by fitting it into experimental data from the developed mechanical cocoyam chipper. The results obtained revealed that the predicted model correlated well with the experimental data with an R-square value of 0.998. Also, the difference between the predicted and the measured power requirement means was not statistically significant at 5 % level.

Keywords: Modeling, Predicting, Power, Cocoyam, Chipper

Introduction

Cocoyam corms when harvested are prone to deterioration if not properly stored. Therefore, the cocoyam corms must be dried to ensure safe storage over a much more extended period without the risk of losses from rotting (Kay, 1987). Chipping operation is one of the most important post harvest processes for root and tuber crops which help to achieve the required size reduction for easy crop drying. However, manual chipping operation is laborious and time-consuming. Therefore, it is essential to mechanize the chipping process of cocoyam to overcome the difficulty of handling large scale processing with traditional method. The existing chipping machines developed by Bolaji *et al*. (2008), Raji and Igbeka (1994), Adejumo *et al*. (2011), Ogundipe *et al*. (2011) and others were all designed specifically for cassava roots. Ikejiofor *et al*. (2016) developed and evaluated a cocoyam chipping machine. The various factors affecting the performance of chipping machine as presented by Adejumo *et al.* (2011), Bolaji *et al*. (2008), Ogundipe *et al*. (2011), and others include machine factors such as cutting velocity, feed rate, chipping slot size, weight of chipping disc, chipping force, radius of chipping plate, feeding chute clearance and also crop factors such as crop moisture content, bulk density, length and weight of tubers. If not properly controlled, these factors could reduce the performance of the chipping machine. Power requirement is an important criterion in evaluating the chipping performance (Ogundipe *et al*., 2011). Modeling the performance parameters or contributing factors for chipping process of cocoyam would provide a better understanding of the fundamental relationship of these machine and crop variables in order to identify each variable's contribution. Ikejiofor (2017) developed mathematical models for predicting the performance of cocoyam chipping processes. Also, Ikejiofor *et al*. (2016) developed a mathematical model for predicting the cocoyam chipper's throughput capacity. Ndirika *et al*. (1996) developed a mathematical model to predict the power requirement of selected stationary grain thresher. The model was validated with experimental results from stationary grain thresher. Ndirika *et al*. (2001) optimized the power requirement model developed to obtain optimum values of the independent variables at minimum grain loss for millet and sorghum threshers. The result obtained from the simulation revealed that a minimum grain loss of 0.09 % was obtained for millet thresher and 0.35 % for the sorghum thresher at 9 % grain moisture content, cylinder speed of 5m/s and feed rate of 0.03 kg/s. Also, the power requirements obtained at these levels are 2.5 KW and 4.6 KW for millet and sorghum threshers, respectively. These compare favourably with a minimum grain loss of 0.10 % and 0.46 %, respectively for millet and sorghum threshers with 2.45 KW and 4.5 KW power requirement for millet and sorghum threshers respectively obtained from actual measurement at the same values of the parameters. This study aimed to develop and verify a mathematical model for predicting the power requirement of the developed cocoyam chipper.

Materials and Methods

Instrumentation and measurement

The data generated from the developed cocoyam chipper used to verify of the power requirement model were evaluated by the following methods: An electronic balance of sensitivity 0.01 g and with a range of 0.01 g to 500 g was used for weight measurement. Time was measured using a stopwatch. Moisture contents of the sliced cocoyam corms were determined by oven drying the cocoyam samples at a temperature of 75 °C for 24 hours. The moisture contents on a wet basis for the various oven-dried samples were calculated using the formula provided by Kajuna *et al.* (2001). The bulk density was determined as the ratio between the mass of the cocoyam corms in a container to its volume (Kaleemullah and Kailappan, 2003). The wattmeter whose wattage values ranged between 0 and 4800 watts was used to measure power requirements. Finally, the cutting velocity was determined using the equation.

Cutting velocity (V_c) = $\frac{\pi DN}{60}$……… (1)

Where, V_c = cutting velocity (m/s), D = diameter of machine pulley (m), N = speed of rotation of machine pulley (rpm)

Theoretical development

The cocoyam chipper power requirement model was developed by dimensional analysis using the concept of Buckingham's *Pi* theorem (Ndirika, 1997; Walter, 1985).

The total power required for the chipping process was expressed by Ogundipe *et al*. (2011) as:

Total power requirement $P = P_C + P_R$ ……. (2)

P_C = Power needed to chip tuber (W)

P_R = Power required to rotate plate (W)

The use of dimensional analysis can determine the power needed to chip tuber.

Assuming that the variables of importance include: cutting velocity (V_c), chipping force (F), weight of chipping disc (W_c), feed rate (F_r) and bulk density (β).

Power to chip, $P_c = f(V_c, F, W_c, F_r)$ ……… (3)

Using the [M], [L], [T] system of dimension (Ndirika, 1997; Babashani, 2008), the dimensions of the variables identified in this study are presented in Table 1, while the dimensional matrix is presented in Tables 2. The procedure for applying Buckingham's Pi Theorem to identify the dimensionless group to be formed is as follows:

The total number of variables = 6
Number of fundamental dimension = 3
Number of the dimensionless group to be formed = 3

Table 1: Dimensions of the variables influencing (P_c)

Variable	Symbol	Unit	Dimension [M], [L], [T]
Power to chip	P_c	kgm^2/s^3	ML^2T^{-3}
Cutting velocity	V_c	m/s	LT^{-1}
Chipping force	F	kgm/s^2	MLT^{-2}
Weight of disc	W_c	kg	M
Feed rate	F_r	kg/s	MT^{-1}
Crop bulk density	β	kg/m^3	ML^{-3}

Table 2: Dimensional matrix of the variables

Parameters Dimensions	P_c	V_c	F	W_c	F_r	β
M	1	0	1	1	1	1
L	2	1	1	0	0	-3
T	-3	-1	-2	0	-1	0

The required solution will be:

$$\pi_1 = k_p f[\pi_2, \pi_3] \quad ……. (4)$$

Where, K_p = Power constant, π_1, π_2 and π_3 =First, second and third pi terms respectively.
Using the Buckingham's Pi theorem, π_1, π_2 and π_3 were found to be:

$$\pi_1 = \frac{P_c W_c^{4/3} \beta^{2/3}}{F_r^{3}}, \quad \pi_2 = \frac{V_c W_c^{2/3} \beta^{1/3}}{F_r}$$

$$\pi_3 = \frac{F W_c^{2/3} \beta^{1/3}}{F_r^{2}}$$

$$\therefore \frac{P_c W_c^{4/3} \beta^{2/3}}{F_r^{3}} = K_p \left[\frac{V_c F W_c^{4/3} \beta^{2/3}}{F_r^{3}}\right] \quad ….. (5)$$

Rearranging equation 5, then

$$P_c = K_p V_c F \quad ……… (6)$$

The power required to rotate plate, P_R is expressed by Ogundipe *et al*. (2011) as:

$$P_R = (W_p r_p) W_s \ldots\ldots.. (7)$$

Where, W_p = weight of plate (N), r_p = radius of chipping plate (m), W_s = speed of plate (rad/sec)
According to Ogundipe *et al*. (2011), the speed of plate in (rad/sec) is given as:

$$W_s = \frac{2\pi N}{60} \ldots\ldots\ldots (8)$$

Where, N = revolutions per minute. Therefore, the total power requirement (P) as given by the equation 2, can be predicted as:

$$P = K_p V_c F + (W_p r_p) \frac{2\pi N}{60} \ldots\ldots.. (9)$$

Where, K_p = power constant, F = chipping force (kgm/s2), V_c = cutting velocity (m/s), W_p= weight of plate (N), r_p= radius of chipping plate (m), N = revolutions per minute.

Value of constant

The power constant (Kp) in the equation was determined by linearizing π1 and π4, which are

$\frac{P_c W_c^{4/3} \beta^{2/3}}{F_r^{\ 3}}$ and $\frac{V_c F W_c^{4/3} \beta^{2/3}}{F_r^{\ 3}}$ respectively from the developed model by the method of least squares using data from available literature (Bolaji et al., 2008; Ogundipe et al., 2011; Oladeji, 2014; Aji et al., 2013). The slope of the line of best fit gives the value of the power constant, K_p which was 0.99, as presented in Figure 1. The regression coefficient, R, obtained was 0.95. The linear regression result obtained shows that the intercept was significant at 5 % since t_{cal} value of 8.605 > t_{tab} value of 2.306. This also indicates that the equation used is justified and that the regression line does not pass through the origin.

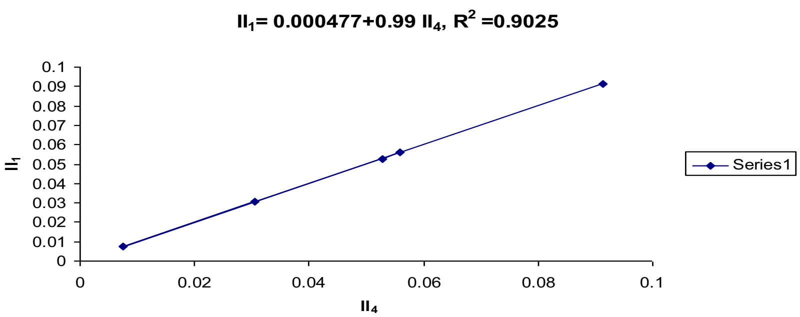

Figure 1: Determination of power constant, K_p

Verification and Validation of the Model

The power requirement model was verified in order to confirm its consistency with established experimental results from a cocoyam chipper. The study was conducted using data from the developed cocoyam chipper, and the predicted model was compared with the experimental result. The crop and operating conditions for the cocoyam chipper used are presented in Table 3.

Table 3: Crop and operating conditions for the chipper

S/No	Parameters	Values / Levels		
		1	2	3
1	Cutting speed, N (rpm)	300	350	375
2	Cutting Velocity, V_c (m/s)	3.93	4.58	4.91
3	Chipping force, F (Kgm/s^2)	137.44	193.68	249.92
4	Feed Rate, Fr (kg/s)	0.056	0.058	0.06
5	Chipping Slot Area, Ss (m^2)	0.0014	0.0016	0.0018
6	Moisture Content, M_c (%)	57.81	52.39	46.92
7	Bulk density, β_d dry basis (kg/m^3)	200.03	231.28	263.78
8	Weight of Chipping Plate, W_p (kg)	1.78	2.67	3.56
9	Radius of Chipping Plate, r_p (m)	0.19	0.19	0.19
10	Initial Weight of Tubers, W_1 (kg)	5.6	5.8	6.0

A model will have greater confidence if a good fit and a high significance level is attained. However, the method developed by Gregory and Fedler (1986) for calculating the coefficient of determination, R^2 statistically for non-linear and linear function and with one or more independent variables was adopted. Thus,

$$R^2 = \frac{1 - V_o}{V_t} \ldots\ldots\ldots (10)$$

Where, R^2= coefficient of determination, V_o = estimated variance about the mean from the measured data, V_t = estimated variance about the mean from the predicted model

Since the R^2 value from equation 10 must have a level of significance before the model is considered verified, the statistical significance test was done to ascertain how adequately the sample data test used to develop the model represents the whole population. The significance level for a given R^2 can be obtained by computing't' as presented by (Snedecor and Cochron, 1980) in equation 11. Then, the significance level can be determined in a table of't' values.

$$t = \frac{R(Df)^{\frac{1}{2}}}{(1 - R^2)^{\frac{1}{2}}} \quad \ldots\ldots (11)$$

Where, t = student's t – value, R = coefficient of regression, *Df*= degrees of freedom (number of data points minus the number of constants as defined in the model)

Results and Discussion

Model validation

The power requirement model (equation 9) was validated with measured data from the developed cocoyam chipper. The result established that the model described well with the measured data obtained from the developed chipper with R^2 value of 0.998. The data used for comparison between the values of power requirement obtained from the experimental result and that obtained using the formulated performance models are presented in Figure 2. When the means of the computed and measured power requirement were compared statistically, it was revealed that there was no significant difference between the means at 0.05 level of significance, since the calculated't' value (1.068) is less than the table 't' value (2.776). However, the result revealed a higher model correlation with data from the developed cocoyam chipper. Therefore, the model is considered valid for describing the total power requirement of the cocoyam chipper.

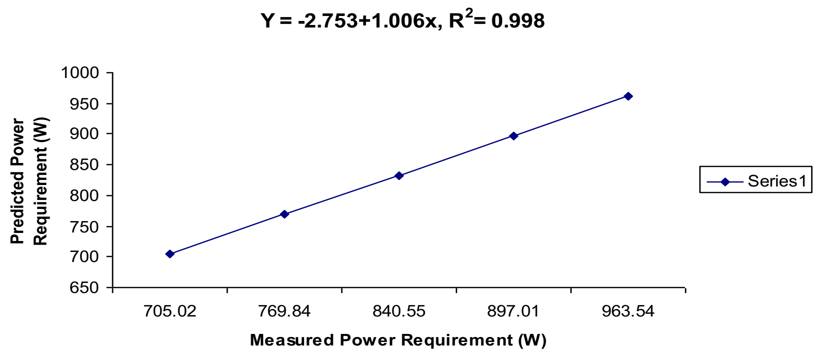

Figure 2: Computed versus measured power requirement (Watt)

Conclusion

The study revealed that the power requirement of cocoyam chipper could be described using the mathematical model, including variables such as cutting velocity, chipping force, weight of chipping disc, feed rate and crop bulk density. The difference between the predicted and measured power requirement means was not statistically significant at 5 % level. The predicted power requirement model described well with experimental results from the developed cocoyam chipper.

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