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A study on the mathematical model for predicting the peel removal efficiency of a cassava peeler

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Abstract: A mathematical model for predicting the peeling efficiency of a cassava peeler was developed using a dimensional analysis based on Buckingham' s pi theorem. The model was validated using data from experimental studies which revealed a maximum coefficient of determination of R^2 = 0.8366 between the measured and predicted values. The developed model proved appropriate in estimating the peel removal efficiency for a cassava peeler by up to 83.66%. There was no significance difference between the experimental and predicted values at a 0.05 significance level.

Keywords: Buckingham's pi; dimensional analysis; independent variable; model; tuber size

Adequate mechanised processing helps in reducing the intensive manual labour that is associated with post-harvesting operations. The processing of cassava tubers for human or industrial utilisation involves various operations in which peeling is vital (Oyedele et al. 2019). The peel removal efficiency influences the product quality the most importantly as regards unwanted materials as a result of the peeling process. Peeling remains a challenge in all the subsequent operations in cassava processing (Olukunle and Jimoh 2012). Olukunle (2007) affirmed that due to technological advancements, the production of cassavas was necessary in various areas so as to increase its usage in the oil and gas sector, enhance food security, to provide an instrument for quick industrialisation and foreign exchange. The capacity of a peeler could be quickly and easily evaluated with a good theoretical model that predicts the carrying capacity of a machine.

Modelling can be defined as the representation, in theoretical terms, of the behaviour of real objects and devices, or a system of postulates, information and inferences presented as a function of the state of affairs or entities. The modelling could be illustrative, predictive or even descriptive. For predictive modelling, it can be viewed as a system of possible models conceived to give insight on experiments that are not conducted. Some sets of observations follow these predictions which serve as a means of validating the model and suggest reasons for the model inadequacies (Dym and Ivey 1980; Dym 1994; Cha et al. 2000). Different mathematical modelling methods that are adopted are: dimensional homogeneity and analysis, conservation and balance principles, abstraction and scaling and effects of linearity. In view of the different techniques, a dimensional analysis has become a promising and compelling method that is often employed in modelling systems. This is because of its ease of presentation, planning and experimental data interpretation, giving an organised means of planning and executing experiments, and it also assists in scaling up a model to prototype (Bahrami et al. 2006; Asonye et al. 2018). A dimensional analysis is a mathe-

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matical method employed in determining the effects of physical phenomena and their functional relationship. It provides a means of minimising complex physical problems to a minimal level prior to getting a quantitative result (Andrzej 2015).

Theoretical modelling in various aspects of agricultural engineering include harvesting (Baruah and Panesar 2005a; Baruah and Panesar 2005b), sprayers (Teske et al. 1991), tillage operations (Fielke 1999), crop handling systems (Gorial and O'Callaghan 1991) and other important areas of post-harvest technologies which include; modelling the egusi melon (*Colocynthis citrullus*) flowrate through a circular orifice hopper (Asoegwu et al. 2010); ultrasound assisted oil extraction from canola seed optimisation (Jalili et al. 2017); development of a model for describing infrared radiation and drying characteristics of onion slices for optimum management of operational variables (Jain and Pathare 2004); modelling the process of cleaning grains for a sorghum thresher (Simonyan et al. 2006); and modelling the process of drying a hybrid convective vegetable crop (Nwakuba 2018). A few works have modelled cutting processes such as impact of cutting on the behaviour of forage crops (McRandal and McNulty 1978); modelling of cutting process in harvesting sorghum (Mohammed 2002); laser based modelling of potato cutting and peeling efficiency (Somsen et al. 2004; Ferraz et al. 2007); lycopene extraction modelling from tomato pulp (Dolatabadi et al. 2016); numerical and experimental study of cutting energy of okra (Asonye et al. 2018); mathematical modelling to estimate the cutting energy of the cocoa yam (Asonye et al. 2019); a mathematical model for predicting the throughput capacity of a cassava chipper (Ikejiofor et al. 2016); and cassava peeling performance modelling using a dimensional analysis (Jimoh et al. 2016), there is still a dearth of data on modelling the peeling efficiency of cassava tubers.

Researchers have utilised dimensional analyses based on Buckingham's pi theorem as a vital tool in developing the predicted equation for different systems which include developing a model for a screw-conveyor using a dimensional analysis (Degrimencioglu and Srivastava 1996); a mathematical model for predicting the capacity of a grain threshers (Ndirika 2006); microwave assisted extraction (MAE) modelling for total monomeric anthocyanins (TMA) (Farzaneh and Carvalho 2017); a model for predicting the cracking efficiency of a centrifugal palm nut cracker (Ndukwu and Asoegwu 2011); and the thermal deterioration of tomato paste (Ganje et al. 2018). Despite other techniques for determining the dimensional analysis, notably the indicial technique, based on Buckingham's pi theorems, proves appropriate for obtaining results (Asonye et al. 2018).

Hence, the current study is undertaken to establish a mathematical model for predicting the peel removal efficiency of a cassava peeler using a dimensional analysis.

MATERIAL AND METHODS

Theoretical model. The cassava peel removal efficiency of the system was developed by a dimensional analysis based on Buckingham's pi theorem (Meyer 1985; Ndirika 1997). Considering the peeling process, the variables that were considered as being dominant include: the speed of the tuber rotation (ω), peel shear stress (τ), peeling tool speed (λ), cutting tool thickness (t_{ct}), coefficient of friction between the tool and the peel (μ), shape of the tuber (γ), peel penetration force (F), thickness of the peel (t_p) and the moisture content of the tuber (φ). The general relationship for the peeling efficiency is expressed as Equation (1):

$$\eta = f\left(\mu,\gamma,\lambda,t_p,F,\tau,\varphi,\omega,t_{ct}\right) \quad (1)$$

where: η – the peeling efficiency.

Using the [M], [L], [T] system of dimensions (Ndirika 1997; Babashani 2008), the variable dimensions are presented in Table 1 and the dimensional matrix is shown in Table 2. From Buckingham's pi theorem (Fox and McDonald 1992), the number of dimensionless groups (n) to be formed is given as in Equation (2):

$$n = N - x \quad (2)$$

where: N – number of variables involved in the study = 10; x – number of fundamental dimensions = 3.

Hence, $n = 10 - 3 = 7$.

Therefore, seven dimensionless groups were formed, indicating the need to form: π_1; π_2; π_3; π_4; π_5; π_6; and π_7.

From Table 2, it was observed that η, γ, μ and φ are dimensionless and, hence, were removed from the dimensionless terms' determination for addition later (Simonyan et al. 2006), while the other parameters were combined to form the π groups. The tuber rotational speed (ω), peel penetration force (F) and peel-

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Table 1. Modeling parameters for the peeling cassava tuber

No.	Variable	Symbol	Unit	Dimensions
1	Efficiency	η	%	$M^0L^0T^0$
2	Coefficient of friction	μ	μ	$M^0L^0T^0$
3	Peel tool speed	λ	$m \cdot s^{-1}$	LT^{-1}
4	Peel thickness	t_p	m	L
5	Peel penetration force	F	$kg \cdot s^{-2}$	MT^{-2}
6	Peel shear stress	τ	$kg \cdot s^{-2} \cdot m^{-2}$	$ML^{-1}T^{-2}$
7	Moisture content	ϕ	ϕ	$M^0L^0T^0$
8	Angular speed	ω	rpm	T^{-1}
9	Cutting tool thickness	t_{ct}	m	L
10	Shape of the tuber	γ	γ	$M^0L^0T^0$

ing tool speed (λ) were selected as the recurring set of parameters because they contained all the primary dimensions involved in the problem as their combination does not result in a dimensionless group.

Having selected (ω), (F) and (λ) as the recurring sets, the exponents a, b and c are placed on them, respectively, so that when their product $\omega^a F^b \lambda^c$ is divided by the remaining parameters t_p, τ and t_{ct}, the dimensionless group(s) π_1, π_2 and π_3 are obtained as shown in Equations (3–5) (Ndirika 2006; Simonyan et al. 2006; Asoegwu et al. 2010; Ndukwu and Asoegwu 2011).

Hence,

$$\pi_1 = \frac{t_p}{\omega\lambda} \tag{3}$$

$$\pi_2 = \frac{\tau\lambda}{F} \tag{4}$$

$$\pi_3 = \frac{t_{ct}}{\omega\lambda} \tag{5}$$

Table 2. Variable dimensional matrix

No.	Variable	Symbol	M	L	T
1	Efficiency	η	0	0	0
2	Coefficient of friction	μ	0	0	0
3	Peel tool speed	λ	0	1	–1
4	Peel thickness	t_p	0	1	0
5	Peel penetration force	F	1	0	–2
6	Peel shear stress	τ	1	–1	–2
7	Moisture content	ϕ	0	0	0
8	Angular speed	ω	0	0	–1
9	Cutting tool thickness	t_{ct}	0	1	0
10	Shape of the tuber	γ	0	0	0

M, L, T – dimensions

$$\pi_4 = \eta \tag{6}$$

$$\pi_5 = \mu \tag{7}$$

$$\pi_6 = \varphi \tag{8}$$

$$\pi_7 = \gamma \tag{9}$$

Combining the above equations to generate Equation (10), whose components are dimensionless, is given below.

$$\pi_1 = f\left(\pi_2;\pi_3;\pi_4;\pi_5;\pi_6;\pi_7\right)$$

$$\therefore \frac{t_p}{\omega\lambda} = f\left(\frac{\tau\lambda}{F}, \frac{t_{ct}}{\omega\lambda}, \eta, \mu, \varphi, \gamma\right) \tag{10}$$

By combining the dimensionless terms to minimise it to a reasonable level (Shafii et al. 1996) either by multiplication and/or division, we obtain Equations (11–14), which are dimensionless.

$$\pi_{1,2} = \frac{\pi_1}{\pi_2} = \frac{t_p}{\omega\lambda} \times \frac{F}{\tau\lambda} = \frac{F\,t_p}{\omega\tau\lambda^2} \tag{11}$$

$$\pi_{3,4} = \frac{\pi_3}{\pi_4} = \frac{t_{ct}}{\eta\omega\lambda} \tag{12}$$

$$\pi_{5,6} = \frac{\pi_5}{\pi_6} = \frac{\mu}{\varphi} \tag{13}$$

$$\pi_7 = \gamma \tag{14}$$

The new dimensionless functional relationships become Equations (15–17):

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$$\pi_{3,4} = f\left(\pi_{1,2};\pi_{5,6};\pi_7\right) \tag{15}$$

$$\frac{t_{ct}}{\eta\omega\lambda} = f\left(\frac{Ft_p}{\omega\tau\lambda^2};\frac{\mu}{\varphi};\gamma\right) \tag{16}$$

$$\therefore \frac{1}{\eta} = f\left(\frac{Ft_p}{\tau t_{ct}\lambda};\frac{\mu\omega\lambda}{\varphi t_{ct}};\frac{\gamma\omega\lambda}{t_{ct}}\right) \tag{17}$$

Hence, Equation (18) describes the expression for the peeling efficiency (η) with the parameters as a function of three functional components:

$$\eta = f\left(\frac{\tau\lambda t_{ct}}{Ft_p};\frac{\varphi t_{ct}}{\mu\omega\lambda};\frac{t_{ct}}{\gamma\omega\lambda}\right) \tag{18}$$

Functional components are represented as X, Y and Z, respectively, in Equation (19):

$$\eta = f\left(X;Y;Z\right) \tag{19}$$

Input parameters for the model and validation. The validation parameters were determined by holding the other parameters, as listed in Table 3, constant while varying the tuber size. Applying the experimental results as obtained by Adetan et al. (2003); Kolawole et al. (2007); Nwagugu and Okonkwo (2009); and Aji et al. (2016), Table 3 shows the values of the parameters for predicting the peel removal efficiency of the peeler.

Table 3. Evaluation parameters for predicting the peeling efficiency

No.	Variables	Value
1	Coefficient of friction	0.38–0.54
2	Tool feed rate (mm·s^{-1})	0.35–0.41
3	Peel thickness (mm)	2.12–2.94
4	Peel penetration force (N·mm^{-1})	0.88–1.21
5	Peel shear stress (N·mm^{-2})	1.35–6.05
6	Moisture content (%wb)	63.00–70.00
7	Cutting tool thickness (mm)	1.00–2.00
8	Shape of the tuber	0.62–0.84
9	Speed of tuber (rev·s^{-1})	3.18–4.71

The predicted peeling efficiency equation was established by making one of the efficiency components X, Y or Z vary at a time while holding the others constant and observing the resulting functional change (Shafii et al. 1996). This was obtained when the experimental values of η were plotted against X while keeping Y and Z constant. X was determined by substituting the measured values (as listed in Table 3) for the peel shear stress (τ), speed of the cutting tool (λ), thickness of the peel (t_p), thickness of the cutting tool (t_{ct}) and peel penetration force (F) into X. Also, η against Y was plotted keeping X and Z constant while the same was undertaken for Z keeping X and Y constant. In evaluating the efficiency of the peeling for X, Y and Z, the speed of cutting tool was varied while the other factors were kept constant (Shafii et al. 1996; Simonyan et al. 2006). The obtained values for the predicted peeling efficiency were plotted against the measured (experimental) values on a regression curve using the statistical package in MS Excel 2010 and the coefficient of determination (R^2). A multivariate analysis of variance (MANOVA) was carried out using the Statistical Package for Social Sciences (SPSS) to determine the relationship between the predicted and experimental values. The validity or suitability (goodness of fit) of the developed model was tested by comparing it with the experimental data. The obtained coefficients of determination (R^2) were indicators of the suitability of the developed model.

Experimental procedure. Twenty samples of cassava tubers (*Manihot esculenta* Crantz) brought from Obafemi Awolowo University, Ile-Ife, Nigeria, Teaching and Research Farm were thoroughly cleaned of all impurities and sorted to ten samples. Some physical properties of the selected tubers were determined. An automated cassava peeling process at a pre-set speed of 0.33 mm·s^{-1} moves the peeling knife through a distance of 200 mm, peeling the sample tuber which rotates against a stationary peeling knife. Figure 1 show the experimental set-up of the peeling mechanism. The data generated from the physical model utilised in verifying the peel removal efficiency were evaluated below.

Peeling efficiency measurement. The peel removal efficiency was measured by weighing the peels removed in the course of the peeling, thereafter, the total weight of the peel of the tuber was determined, expressed as a percentage (%).

Weight measurement. An electronic balance with a sensitivity 0.01 g and a range of 0.01 g to 5 000 g was used for the weighing.

Moisture content determination. The moisture content of the cassava tuber were obtained using the American Society of Agricultural and Biological Engineers (ASABE) standard and the percentage of the moisture content was calculated on a wet basis.

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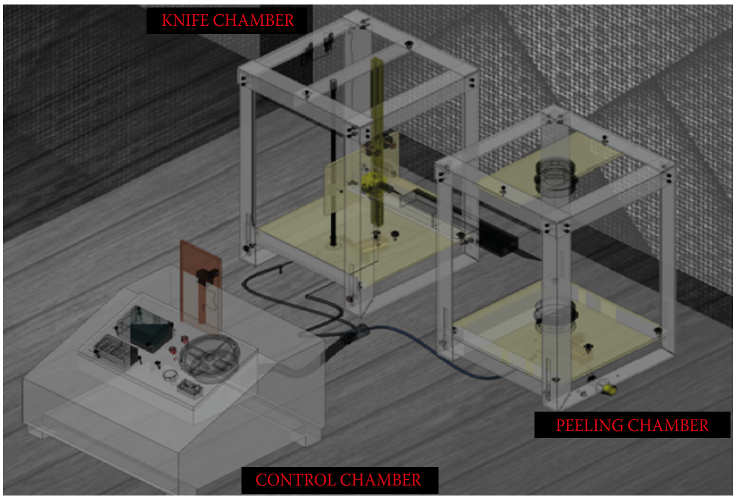

Figure 1. Experimental setup of the peeling mechanism

RESULTS AND DISCUSSION

Model testing. Table 4 shows the experimental values of the peeling efficiency obtained from the automated cassava peeler. The predicted peeling efficiency was obtained by substituting the values of the peeling variables into the peeling efficiency equation expressed as a function of:

$$X = \left(\frac{\tau\lambda t_{ct}}{F t_p}\right)$$

$$Y = \left(\frac{\varphi t_{ct}}{\mu\omega\lambda}\right)$$

$$Z = \left(\frac{t_{ct}}{\gamma\omega\lambda}\right)$$

The Table 4 shows a direct relationship between the $\eta_{measured}$ and the predicted values (X, Y, Z).

The obtained results showed a significant effect of the cutting tool speed on the peeling efficiency requirement for the cassava peeler which authenticates the effect on the peeling efficiency of cassava peeler being studied. This is as reported by Fadeyibi and Olusola (2020), who observed that the peeling efficiency increased with an increase in the shaft speed for peeled tubers. The plots showing the $\eta_{measured}$ against X, Y and Z are shown in Figure 2–4, respectively, with their linear equations and R^2 values expressed in Equations (20–22), respectively.

Hence,

$$\eta_{measured} = 13.553X + 48.141 \quad R^2 = 0.8397 \tag{20}$$

$$\eta_{measured} = -9.5488Y + 84.584 \quad R^2 = 0.8336 \tag{21}$$

$$\eta_{measured} = -12.479Z + 84.584 \quad R^2 = 0.8336 \tag{22}$$

Table 4. Experimental values $\eta_{measured}$ and predicted values (X, Y, Z) of the peeling efficiency for the cassava tubers

No.	Cutting tool speed (mm·s^{-1})	Measured (η)	$X = \left(\frac{\tau\lambda t_{ct}}{F t_p}\right)$	$Y = \left(\frac{\varphi t_{ct}}{\mu\omega\lambda}\right)$	$Z = \left(\frac{t_{ct}}{\gamma\omega\lambda}\right)$
1	0.31	64.22	1.1969	2.1294	1.6296
2	0.33	66.10	1.2740	2.0003	1.5309
3	0.35	65.38	1.3514	1.8860	1.4434
4	0.37	68.15	1.4286	1.7841	1.3654
5	0.39	68.43	1.5058	1.6926	1.2954

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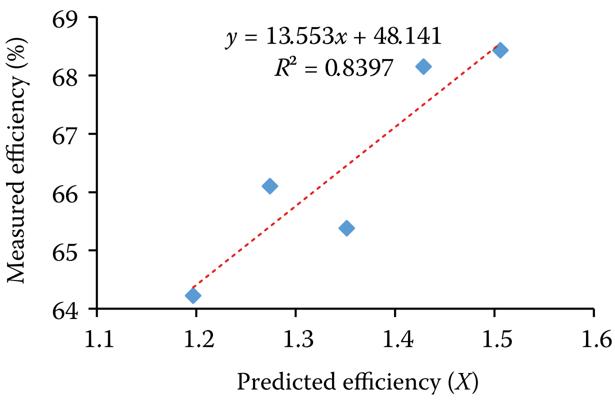

Figure 2. Variation of the measured peeling efficiency against X keeping Y and Z constant

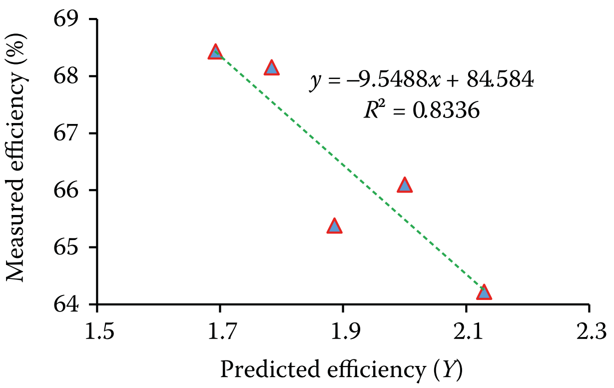

Figure 3. Variation of the measured peeling efficiency against Y keeping X and Z constant

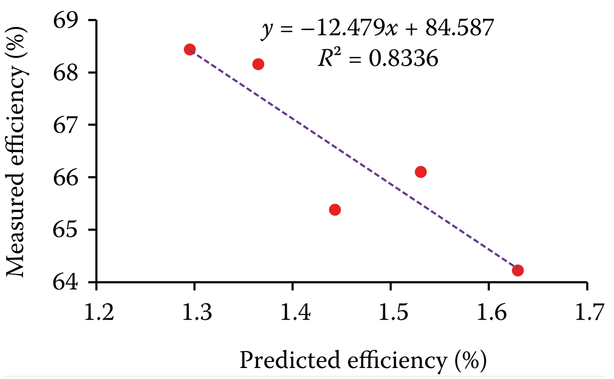

Figure 4. Variation of measured peeling efficiency against Z keeping X and Y constant

The plot of X, Y and Z terms in Figure 1–3 forms a plane surface in linear space and, according to Mohammed (2002), this shows that their combinations favour summation or subtraction. Hence, the component equations formed by the summation and subtraction of Equation (20–22), respectively.

$$\therefore \eta = f_1(X,Y,Z) - f_2(X,Y,Z) - f_3(X,Y,Z) + K \quad (23)$$

$$\therefore \eta_{measured} = f_1(X,Y,Z) + f_2(X,Y,Z) + f_3(X,Y,Z) + K \quad (24)$$

It must be noted that:

At f_1, Y and Z was kept constant while X varies; at f_2, X and Z was kept constant while Y varies; at f_3, X and Y was kept constant while Z varies substituting Equation (20–22) into Equation (23) and performing some algebraic manipulations yields into Equation (25):

$$\eta = 13.553X + 9.5488Y + 12.479Z - 121.027 \quad (25)$$

Substituting the same equations into Equation (24) gives Equation (26):

$$\eta = 13.55X - 9.5488Y - 12.479Z + 217.309 \quad (26)$$

Substituting the variables for X, Y and Z into Equation (25–26) above yields Equation (27–28):

$$\eta = 13.553\left(\frac{\tau\lambda t_{ct}}{F t_p}\right) + 9.5488\left(\frac{\varphi t_{ct}}{\mu\omega\lambda}\right) + 12.479\left(\frac{t_{ct}}{\gamma\omega\lambda}\right) - 121.027 \quad (27)$$

$$\eta = 13.55\left(\frac{\tau\lambda t_{ct}}{F t_p}\right) - 9.5488\left(\frac{\varphi t_{ct}}{\mu\omega\lambda}\right) - 12.479\left(\frac{t_{ct}}{\gamma\omega\lambda}\right) + 217.309 \quad (28)$$

Applying further manipulations under the rule of Buckingham's pi theorem (Shafii et al. 1996), which are manipulated with a constant factor of –1 and 0.35 for Equation (27–28), respectively, then yields the predicted model equations expressed in Equation (29–30), as given below.

$$\eta = -13.553\left(\frac{\tau\lambda t_{ct}}{F t_p}\right) - 9.5488\left(\frac{\varphi t_{ct}}{\mu\omega\lambda}\right) - 12.479\left(\frac{t_{ct}}{\gamma\omega\lambda}\right) + 121.027 \quad (29)$$

$$\eta = 4.7425\left(\frac{\tau\lambda t_{ct}}{F t_p}\right) - 3.3421\left(\frac{\varphi t_{ct}}{\mu\omega\lambda}\right) - 4.3677\left(\frac{t_{ct}}{\gamma\omega\lambda}\right) + 76.058 \quad (30)$$

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Hence, the final predicted model equation will be either of the two equations which gives better statistical inference.

Model validation. The theoretical model was validated using data obtained from the peeling machine. The validation of the model was conducted at five cutting tool speeds. A regression analysis method as obtained using the Microsoft Excel was utilised in describing the functional relationship, to plot the graphs and determine the coefficient of determination (R^2). More so, a general linear model (GLM) under the SPSS was used to determine the relationship between the predicted and experimental values.

The experimental values of the variables were substituted into Equation (29–30) to generate the predicted peel removal efficiency values as plotted against the experimental results on a regression curve in order to obtain the coefficients of determination as given in Figure 5 and 6, respectively. Both equations define the relationship between the experimental and the predicted efficiency of the peeling values with high correlation R^2 values of 0.8199 and 0.8361, respectively. When the mean of experimental and predicted values are compared using a multivariate analysis of variance (MANOVA) at a 5% level of significance, there was no statistical difference since the calculated value is less than the P–value. The obtained results are similar to that reported by Ndukwu and Asoegwu (2011), who observed no significance difference in the mean of the predicted and experimental values as compared using the least significance difference (LSD) at a 1% and 5% level of significance.

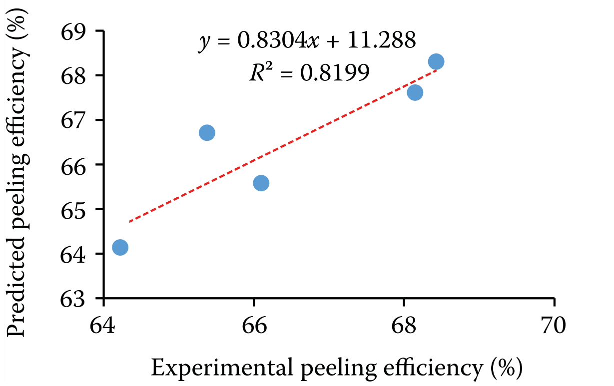

Figure 5. Graph of the relationship between experimental and predicted peeling efficiency for summation of components parameters

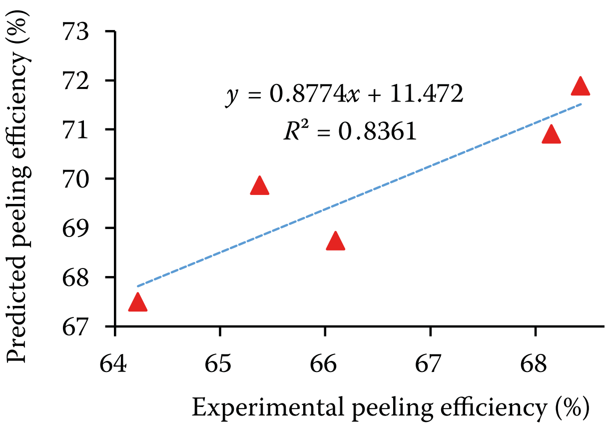

Figure 6. Graph of the relationship between experimental and predicted peeling efficiency for subtraction of components parameters

Having high R^2 values for the individual predicted equations is an indication that the method adopted in developing the mathematical model is acceptable and can be deployed in the development of other tubers.

From the statistical inference conducted, the predictive model equation derived from the subtraction of the components' parameters gave a higher coefficient of determination (R^2) value of 0.8361 when compared to 0.8199 obtained from the summation of the components' parameters.

Hence, the predicted model equation, which yields the better statistical inference of a higher R^2 value of 0.8361, was chosen as the predicted model equation for the peel removal efficiency requirement for the cassava peeler.

Hence,

$$\eta = 4.7425\left(\frac{\tau\lambda t_{ct}}{F t_p}\right) - 3.3421\left(\frac{\varphi t_{ct}}{\mu\omega\lambda}\right) - 4.3677\left(\frac{t_{ct}}{\gamma\omega\lambda}\right) + 76.058 \tag{31}$$

CONCLUSION

A mathematical model for predicting the peeling efficiency of a cassava peeler was presented using the principle of a dimensional analysis based on Buckingham's pi theorem. The model was validated using data from an automated cassava peeler. The obtained results indicate a high coefficient of determination (R^2 = 0.8361) between the predicted and the experimental η values. There was no significance difference between the predicted and experimental peeling efficiency at a 0.05 significance level. This is an indication that the adopted technique is ap-

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propriate and acceptable in developing theoretical model. Also, the expression will guide designers in cassava peeler designs to avoid any rigours of experimentation thereby obtaining an efficient peeling set-up. Hence, the developed model could be used to predict the peeling efficiency of a cassava peeler by up to 83.61% certainty.

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