Prediction of Tuber Peeling Rate Based on Classical Particle Removal Theories

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Abstract

Classical particulate modeling is a mathematical approach that is suitable for describing the behavior of a processing machine because of its ability to accommodate varying degrees of technical parameters. This research was carried out to predict the peeling rate of an existing multi-tuber peeling machine using classical particle removal theories. The machine was designed to peel fresh cassava, sweet potatoes, and cocoyam tubers at a speed range of 350-750 rpm using a selection gear system. The tuber peeling rate were determined over 1-h of machine operation at intervals of 5 min. The classical Weibull and Jennings models, formulated for removing impurities from the outer surface of solids, were used to constitute the models for predicting the peeling rate and the amount of tuber peels removed. The machine was rerun for another 30 min, and the values of the peeling rates and the amount of peels removed were computed and used for the independent validation of the resulting models. Results show a log increase in the peeling rate of the machine with an increase in the residence time and the speed of the machine operation ($p< 0.05$). Also, the Weibull model parameters were better estimator of the peeling rate with $R^2 > 95\%$ and Mean Square Error less than 10%, irrespective of the speed and the residence time of machine operation. Therefore, the models can be used for predicting the peeling rate of the machine within its operating speed limits.

Keywords: classical particle removal theory; multi-tuber peeling machine; peeling rate; Weibull model; Jennings model
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1. Introduction

Root and tuber crops are essential commodities of human diet all over the world. Almost all the food we eat daily is made of tubers, perhaps because they provide the energy needed for our work. Just like other crops grown in the tropics, the production of root and tuber crops is seasonal [1]. Therefore, the demand and supply of the crops are critical to their availability for processing. But this is usually limited due probably to the limitations in production systems. The general pattern of the supply of root crops from the surpluses of subsistence farming may eventually lead to high

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marketing costs for the product. Therefore, the processing of the crops is essential to meet the market availability challenges.

Processing of root and tuber crops can be done either manually or mechanically. Unlike manual processing, the latter is more important because it enhances productivity both in terms of yield and performance. Although the mechanical operations have been successfully applied to the processing of root and tuber crops [2-8], a major issue that remains is the unusually low peeling rate of the technology as depreciation sets in with age [9-11]. Most of these technologies have now become obsolete and unreliable for their intended use. The way to address this is not to design a new working machine, but in modeling the existing machine operations to predict defects and processes for routine maintenance. The mechanism of the mechanical cassava tuber peeling technology has been described by Adetan *et al.* [12], Seth [13] and Olukunle and Akinnuli [14]. The authors developed mathematical models for predicting the peeling efficiency of the cassava peeling machine; and recommended the peeling concept as a reliable tool for studying the behavior of the peeling technology. However, their research was limited in application since the model was specifically developed for the understanding of the concept of the peeling operation of the cassava tuber. Also, their tool was not general and might not be suitable for the understanding of the concept of a multi-tuber peeling machine operation. Asonye *et al.* [15] and Mohammed *et al.* [16] also explained the relationship between the peeling rate and geometry of the peeling operation by developing models. But the peeling behavior predicted was largely empirical and thus not easily scaled-up for industrial applications. There is therefore the need to develop a mathematical model for predicting the peeling rate of tubers in processing. This makes research and validation experiments more straight forward since food products are complex systems that undergo various changes and reactions when processed. The objective of this research was to develop mathematical models for predicting the peeling rate of an existing machine operating at different speeds.

2. Materials and Methods

2.1 Materials and samples preparation

A 30 kg each of the freshly harvested cassava, sweet potato and cocoyam tubers were purchased from the central market in Omuaran Market, Kwara State Nigeria. The produce samples were transported to the Landmark University, Omuaran for experimentation. Initially, the tubers were manually clean with running water to remove mud and clay, and thereafter spread under the sun to dry for 1 h. The tubers were sorted into various categories of different sizes ranging from small, medium, and large to facilitate machine processing.

2.2 Description of existing tuber peeling machine

An existing multi-tuber peeling machine was used to carry out the peeling operation, as shown in Figure 1. A detailed design of the machine has been reported by Fadeyibi and Ajao [2]. The machine consists of a rotating drum, eccentrically placed on a shaft, and powered with a 5 HP electric motor. With the help of a gear system arrangement, the machine was operated at speeds of 350, 550 and 750 rpm. Tubers are fed via the inlet, and the operation began by engaging the gear to the predetermined speed. The peeling force was applied to the tubers by the scraping and scratching action of the rotating perforated wire gauze drum. The peels were discharged through the perforations and collected underneath the machine via a chaff collector bowl. The peeled tubers were then collected via the same inlet opening used for feeding.

Figure 1. Multi-tuber peeling machine [2]

2.3 Evaluation of peeling rate

The peeling rate of the machine can be defined as the mass of the peels obtained divided by the residence time of the machine operation. By engaging the gear to 350 rpm, 20 kg of each of the tubers was fed gently through the opening for inlet made on the peeling drum. The existing peeling machine was operated for a period of 1 h, and the peeling rate was evaluated at intervals al of 5 min. The peeling rate was determined using the expression in equation (1). The procedure was repeated at 550 rpm and 750 rpm, and the peeled products are shown in Figure 2. A total of ten samples of peels each from the cassava, potato and cocoyam tubers were used to constitute the models for predicting the rate of tuber peeling.

$$\dot{m} = \frac{\Delta m}{t} \tag{1}$$

where;
$\dot{m}$ = peeling rate (kg/min)
Δ m = mass change in tuber peels (kg)
t = Time taken to peel the required quantity (min)

(a) Sweet potatoes (b) cassava (c) cocoyam

Figure 2. Peeled tubers

2.4 Classical particle removal theory

2.4.1 Modeling based on Weibull model

The removal of peels from tubers is a multiplex procedure that requires adequate details for real practice. To improve the practical peeling procedure, a mathematical model would be helpful [16]. We used the Weibull probability distribution to analyze the data since the data are classified field data with significant variabilities resulting from the influence of the environment and some uncontrolled variables associated with the machine operation [17]. Based on this and according to Calabria and Pulcini [18], we viewed the machine data as a set of random variables, which are independent statistically. A univariate probability distribution function was used to model the random variables according to equation (2) [19-21].

$$\mathrm{F}\ (\mathrm{t}, \emptyset) = \mathrm{p}\ (\mathrm{T} \leq \mathrm{t}) \qquad -\infty < \mathrm{t} < \infty \tag{2}$$

where; $\emptyset$ = set of parameters for the distribution,
T = lifetime of the peeling machine (min),
t = time of machine operation (min)

Thus, the Weibull model was developed based on equation (2), by expressing a 2-parameter special case of the model as shown in equation (3).

$$\begin{aligned} \mathrm{F}\ (t, \emptyset) &= 1 - \exp\left[-\left(\frac{\mathrm{t}}{\alpha}\right)^{\beta}\right] \qquad \mathrm{t} \geq 0 \\ \mathrm{F}\ (t, \emptyset) &= 1 - \exp\left[-(\lambda \mathrm{t})^{\beta}\right] \qquad \mathrm{t} \geq 0 \end{aligned} \tag{3}$$

where $\lambda = 1/\alpha$, α (scale parameter) > 0 and β (shape parameter) > 0

We later mimic this approach to describe the amount of peels remaining after processing of the tubers by further modifying the 2-parameter special case Weibull model as in equation (4) [16, 22].

$$\mathrm{r} = \mathrm{e}^{-\mathrm{k_R t}} \tag{4}$$

where; r = remaining peels (kg)
k_R = peeling constant

However, the peeling variables in equation (4) were adjusted to reflect the peeling removal characteristics of the machine as shown in equation (5) [23].

$$\mathrm{r} = \mathrm{e}^{-(\frac{\mathrm{t}}{\mathrm{T}})\mathrm{R}} \tag{5}$$

where; T = theoretical peeling time constant to reach 100% of the peels removal rate
t = peeling or residence time (min)
R = slope of the peeling characteristics

According to the procedure reported by Dürr and Graßhoff [24], we can express the peeling removal characteristics of the machine as a percentage of the amount of peels removed based on the scale, shape, and location constraints of a general Weibull model (Figure 3). Apparently, the amount of the tuber peels removed varies with the peeling time and the peeling resistance for each of three

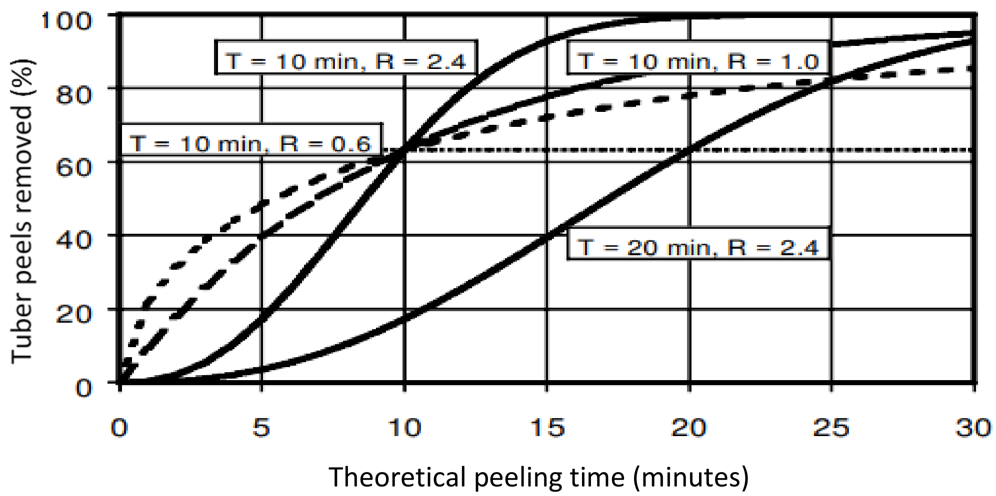

Figure 3. A typical Weibull model showing the relationships between peeling time and the amount of peels removed [24]

curves, which represent the parameters of the Weibull model. The fourth curve or broken line represents the effective peeling resistance between 10 to 20 min of the theoretical peeling time. The general formula for the time co-ordinates of the point of inflection of the curves in the model is represented in equation (6) [24].

$$t_i = T\left(\frac{R-1}{R}\right)^{1/R} \tag{6}$$

Therefore, the peeling rate is the time derivative of the mass of peels removed. Combining equations (4) and (5), a relationship for the peeling rate is apparent in equation (7).

$$\dot{m} = \frac{ds}{dt} = -\frac{dr}{dt} = \left(\frac{R}{T}\right)\left(\frac{t}{T}\right)^{R-1} e^{-(t/T)^R} \tag{7}$$

The relative peeling rate, which is defined as the ratio of the peeling rate to the amount of peels remaining, was therefore

$$\dot{m} = \frac{v}{r} = \left(\frac{R}{T}\right)\left(\frac{t}{T}\right)^{R-1}$$
$$\ln \dot{m} = \ln\left(\frac{R}{T}\right) + (R-1)\ln\left(\frac{t}{T}\right)$$

where, r_p = relative peeling rate (kg/s).

Interesting features of the peeling process becomes apparent by plotting the relative peeling rate versus the amount of peels removed. Thus, we computed the relative peeling rate as a function of the amount of peels removed.

2.4.2 Modeling based on Jennings model

A new mathematical model is presented here, initially developed by Jennings for describing the cleaning rate of soil on contact surfaces. Accordingly, Jennings model was proposed for describing the mechanism of particle removal from the tubers during the peeling operation as expressed in equation (8) [25, 26].

$$\frac{dm}{dt} = -K_R . m \tag{8}$$

$$\int_0^m \frac{dm}{m} = -K_R . \int_0^t dt$$

$$\ln\ m = -K_r . t + c$$

where, K_r and c are Jennings model parameters, m = mass of peels removed (kg), t = peeling time (min).

2.4.3 Parameter estimation

The peeling rate and the relative amount peels obtained from the performance analysis were used to constitute the models based on the Weibull and Jennings models. A linear relationship was established, and the values of the parameters were obtained experimentally. The values of the parameters, K_r and c were estimated from the Jennings models, while the values of R-1 and R/T were estimated from the Weibull models for the cassava, sweet potatoes, and cocoyam tubers.

2.4.4 Verification of the models

An independent validation was used to verify the degree fitness of the models using experimental data. In this approach, the tuber peeling machine was operated again for 30 min, and the peeling rate and the relate amount of peels were computed, as presented in Table 1. The data obtained were analyzed independently for the model verification, based on the mean square error (MSE) and the coefficients of determination (R^2), using equations (9) and (10).

$$MSE = \frac{1}{a}\sum_{i=1}^{k}(M - M_i)^2 \tag{9}$$

$$R^2 = \frac{\sum_{i=1}^{k}(\hat{M} - M)^2}{\sum_{i=1}^{k}(M - \bar{M})^2} \tag{10}$$

where, M = tuber peeling rate and amount of peels removed, $\hat{M}$ = model estimated response, $\bar{M}$ = mean response, k = sample size, a = number of runs for each tuber peeling (6).

3. Results and Discussion

3.1 Effect of residence time and speed on peeling rate and amount of tuber peels

The tuber peeling rate was obtained by differentiating the peeling efficiency with respect to time. The effects of the residence time of the machine operation on the relative amount of tuber peels obtained from the 750, 550 and 350 rpm speed of the rotating shaft are presented in Figures 4-6. The relative weight of the tuber peels increases with an increase in the residence time irrespective of the speed of operation of the peeling machine. There was a log increase in the peeling rate of tuber peels with an increase in the residence time and speed of the machine operation based on the

Weibull particle removal theory. Also, an increase in the relative amount of peels with an increase in the residence time and speed operation was observed based on the Jennings particle removal theory. This behavior may be due to increasing load intensity on the peeling drum at high speeds. According to the theories, multiple particles of tuber peels may inadvertently affect the flow of air effecting peeling [25, 27]. Similarly, Rothaug *et al.* [28] and Ferraz *et al.* [29] also suggested that larger amount tuber particles may decrease the performance of the peeling unit and hence the throughput capacity of the machine. The performance will be enhanced with an increase in the inertia of the speed of the machine and a decrease in the residence time. Although the peeling rate was lower at 750 rpm, the machine performance was observed to increase with decreasing speed up to 350 rpm. Thus, the peeling rate and the relative amount of peels were high at the beginning of the machine operation.

Table 1. Experimental data for independent validation

Tuber		**750 rpm**		**550 rpm**		**350 rpm**	
	t	**m**	**ṁ**	**m**	**ṁ**	**m**	**ṁ**
Cassava	5	11.63	0.074	18.87	6.130	18.98	6.020
	10	10.77	0.123	17.01	7.990	17.11	7.890
	15	10.11	0.126	16.00	9.000	16.01	8.990
	20	9.830	0.109	13.89	11.11	15.00	10.00
	25	8.820	0.127	12.57	12.43	13.98	11.02
	30	8.150	0.128	11.18	13.82	12.33	12.67
Sweet potato	5	14.23	0.770	13.78	1.220	13.16	1.840
	10	13.15	1.850	12.45	2.550	12.44	2.560
	15	12.22	2.780	11.84	3.160	11.63	3.370
	20	11.78	3.220	10.11	4.890	10.18	4.820
	25	10.13	4.870	9.670	5.330	9.460	5.540
	30	9.670	5.330	8.190	6.810	8.190	6.810
Cocoyam	5	11.63	0.370	11.06	0.940	10.44	1.560
	10	10.77	1.230	10.79	1.210	10.04	1.960
	15	10.11	1.890	10.14	1.860	9.760	2.240
	20	9.830	2.170	9.580	2.420	8.440	3.560
	25	8.820	3.180	8.880	3.120	8.160	3.840
	30	8.150	3.850	8.010	3.990	7.770	4.230

m = amount of tuber peels (kg); ṁ = tuber peeling rate (kg/min), t = residence time (min)

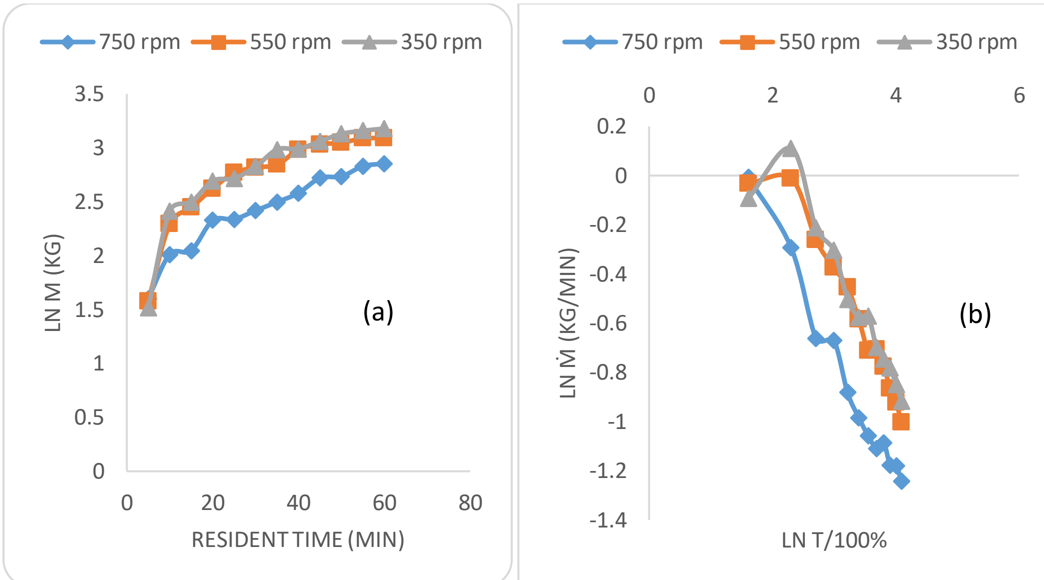

Figure 4. Jennings model prediction for cassava tuber peeling based on (a) effect of residence time on relative weight and (b) effect of theoretical peeling time constant on the peeling rate

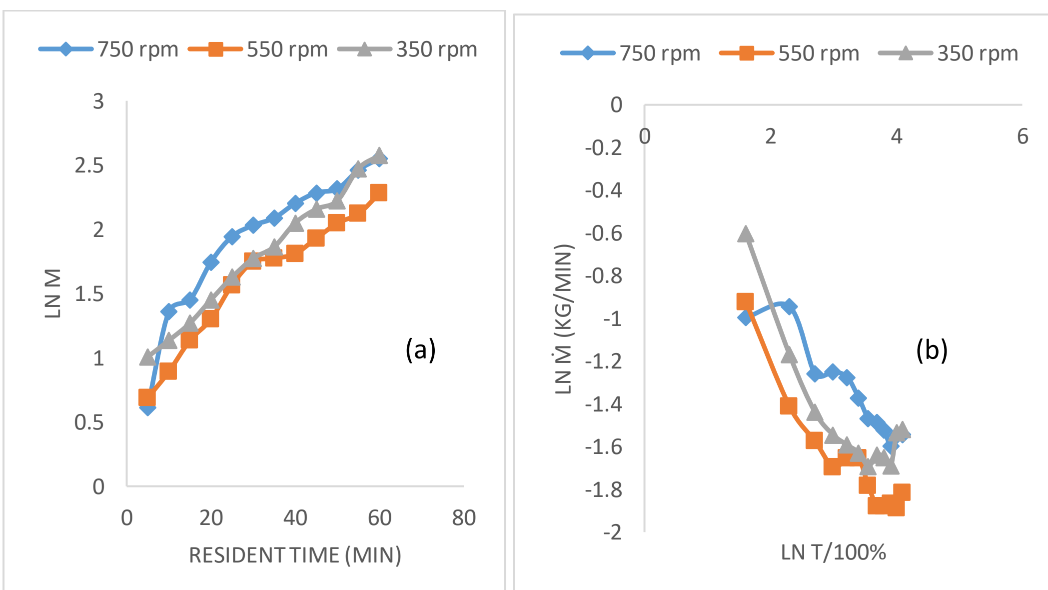

Figure 5. Jennings model prediction for sweet potato peeling based on (a) effect of residence time on relative weight and (b) effect of theoretical peeling time constant on the peeling rate

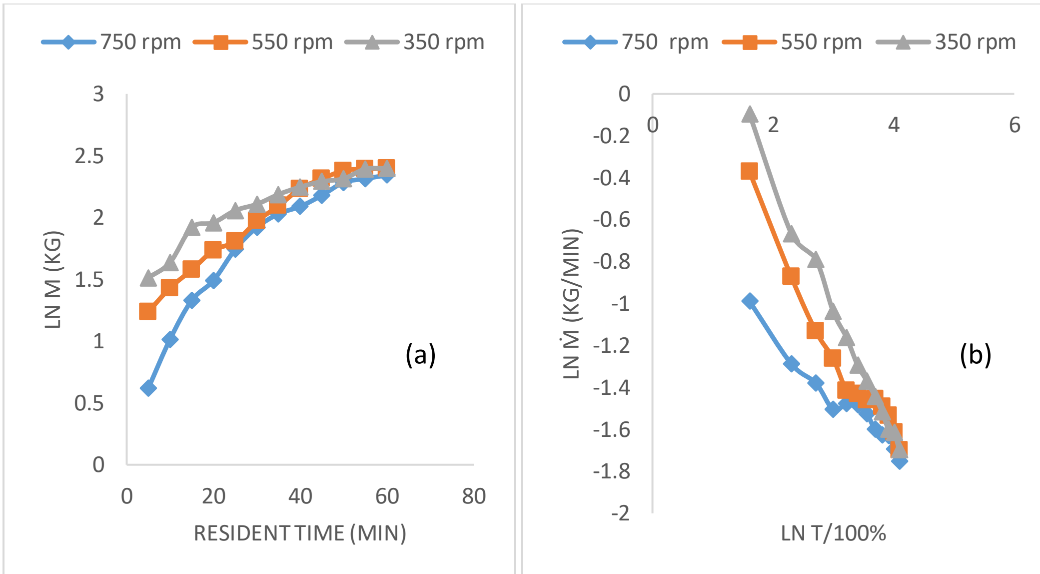

Figure 6. Jennings model prediction for cocoyam peeling based on (a) effect of residence time on relative weight and (b) effect of theoretical peeling time constant on the peeling rate

3.2 Prediction of peeling rate

The parameters for predicting the peeling rates of the cassava, sweet potatoes and cocoyam tubers are shown in Tables 2 and 3. The Weibull model parameters appears to be a better estimator of the tuber peeling rate than the Jennings model because of the higher values of the determination coefficient and lower mean square error. Simonyan and Yiljep [30] reported similar results in their study on the grain separation and cleaning efficiency of conventional sorghum thresher. Also, Peng *et al.* [31] corroborated our findings in their work on the peeling behavior of a viscoelastic thin film. The authors agreed that there is a close relationship between the peel-off force and the tuber peeling rate. The peeling rate is also theoretically related with the peeling efficiency of the machine, the higher the peeling rate, the higher the peeling efficiency. This means that the amount of the peels obtained from the cassava, cocoyam and potatoes tubers will decrease significantly with an increase in the residence time of machine operation. A similar result was reported by Liu *et al.* [32] in their work on the effect of particles on the surface cleaning of dry ice. The authors opined that theoretical analysis of the moments of forces caused by particle impact and aerodynamic drag showed that particle impact is primarily responsible for the peeling.

3.3 Independent model validation

The results of the independent validation of the models for predicting the cassava, sweet potatoes, and cocoyam tubers, from the Weibull and Jennings theories are shown in Figures 7-9, respectively. The values obtained from the models were very close to the actual data obtained from an independent experiment, with mean square error generally less than 10% as shown in Tables 2 and 3. Irrespective of the speed and the residence time differences, the models were able to predict the peeling rate and the amount of peels well within acceptable limits. Previous studies have shown that most models used for describing the peeling rate and the amount of peels are influenced by various

Table 2. Weibull model parameters for tuber peeling

Product	-(R-1)	ln (R/T)	R^2	MSE	Speed (rpm)
Cassava	0.5060	0.7946	0.9802	0.014039	750
	0.4269	0.8398	0.9336	0.020462	550
	0.3996	0.7969	0.8759	0.058424	350
Sweet potato	0.2726	-0.4615	0.9086	0.339939	750
	0.3459	-0.5346	0.8925	0.033261	350
	0.3509	-0.3253	0.7329	0.019684	550
Cocoyam	0.2658	-0.6249	0.9529	0.820625	750
	0.4770	0.2560	0.9505	0.991292	550
	0.6254	0.8583	0.9942	0.794371	350

Table 3. Jennings model parameters for tuber peeling

Product	$-K_R$	c	R^2	MSE	Speed (rpm)
Cassava	0.0201	1.7600	0.9203	0.047496	750
	0.0215	2.0183	0.7694	0.024448	550
	0.0225	2.0309	0.7539	0.047385	350
Sweet potato	0.0285	0.9930	0.8636	0.458236	750
	0.0272	0.7241	0.9505	0.126436	550
	0.0286	0.8724	0.9953	0.713663	350
Cocoyam	0.0213	0.8273	0.9005	0.967158	750
	0.0219	1.2518	0.9558	0.993578	550
	0.0151	1.5943	0.9100	0.805114	350

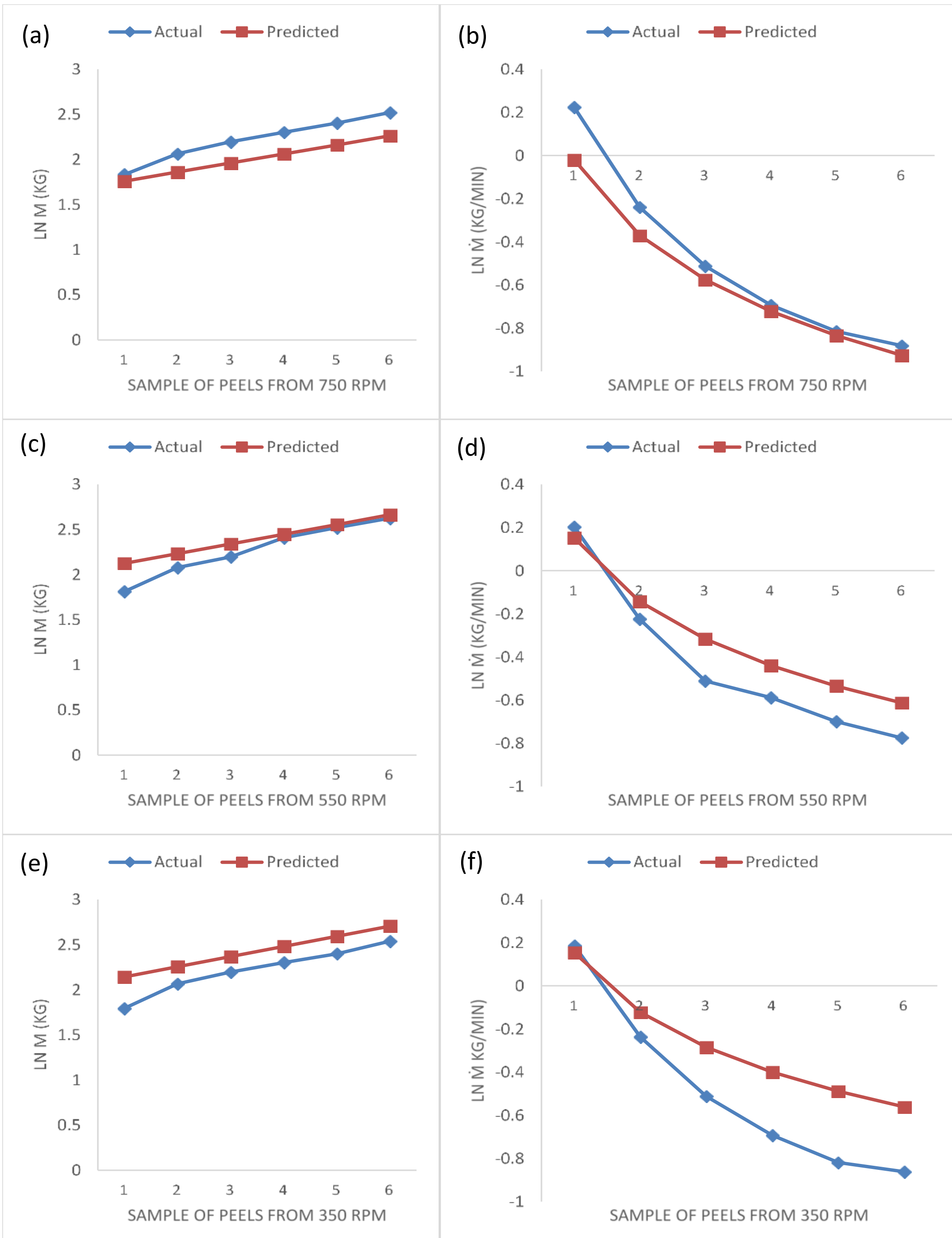

Figure 7. Independent validation of models for predicting cassava peeling rate using (a) Weibull model at 750 rpm, (b) Jennings model at 750 rpm, (c) Weibull model at 550 rpm, (d) Jennings model at 550 rpm, (e) Weibull model at 350 rpm, and (f) Jennings model at 350 rpm

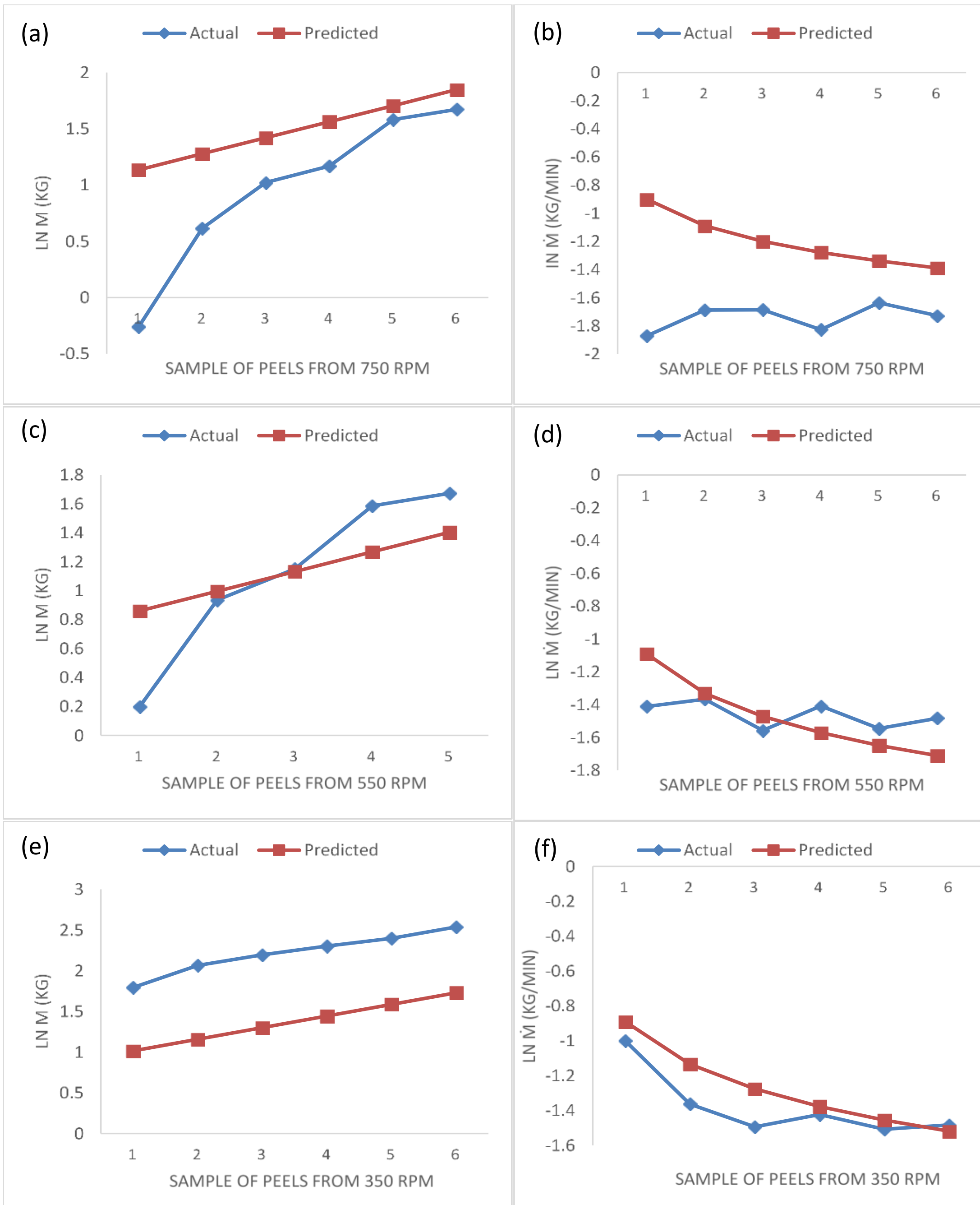

Figure 8. Independent validation of models for predicting sweet potatoes peeling rate using (a) Weibull model at 750 rpm, (b) Jennings model at 750 rpm, (c) Weibull model at 550 rpm, (d) Jennings model at 550 rpm, (e) Weibull model at 350 rpm, and (f) Jennings model at 350 rpm

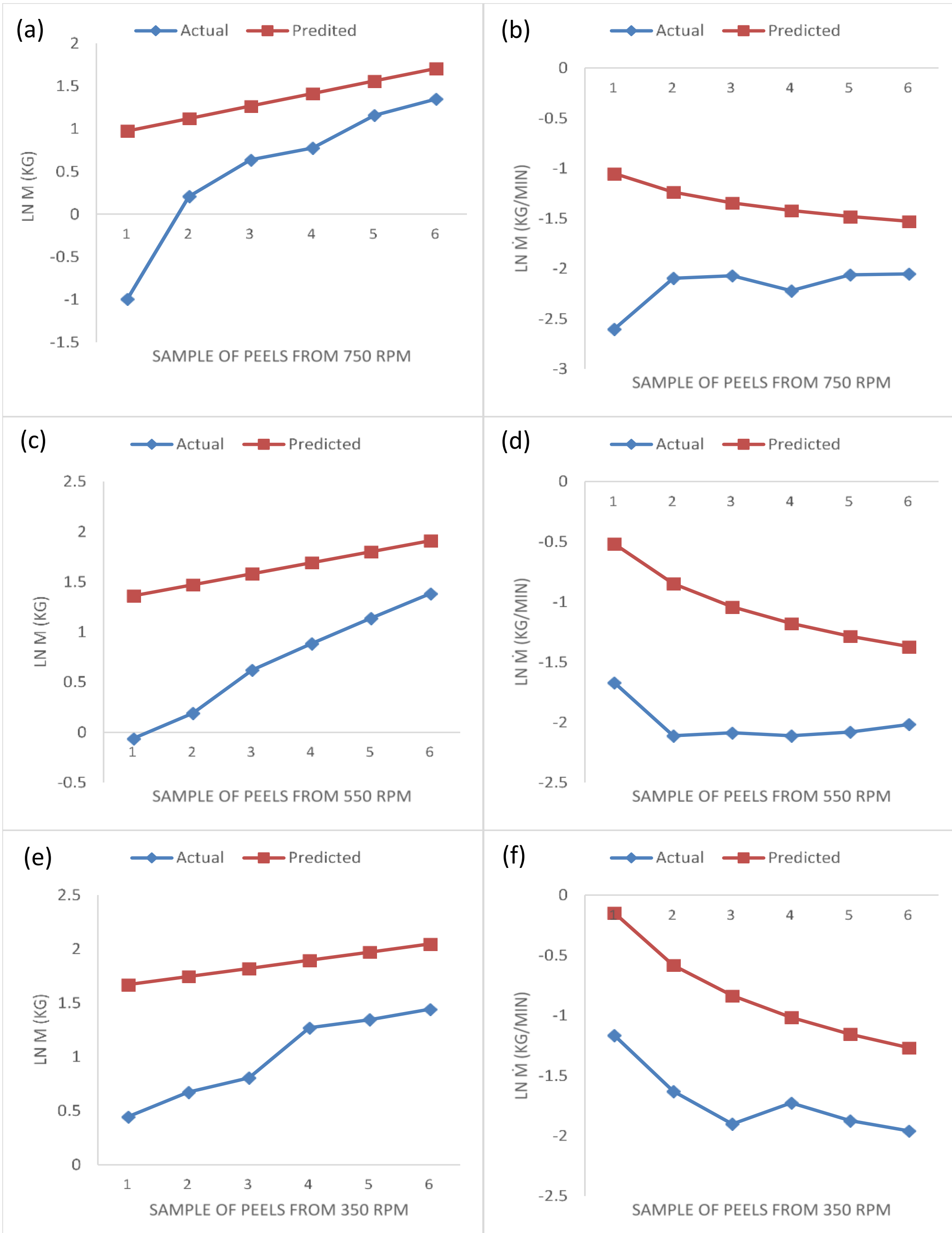

Figure 9. Independent validation of models for predicting cocoyam peeling rate using (a) Weibull model at 750 rpm, (b) Jennings model at 750 rpm, (c) Weibull model at 550 rpm, (d) Jennings model at 550 rpm, (e) Weibull model at 350 rpm, and (f) Jennings model at 350 rpm

model parameters, including the peeling angle, thickness, and other intrinsic property [33-37]. Also, Kutzbach [38] shows similar results in his work on the mathematical modelling of grain separation. Thus, in this investigation, the model parameters can be used for predicting the response variables with very close margin of errors.

4. Conclusions

This research predicted the peeling rate of an existing multi-tuber peeling machine using classical particle removal theories. The machine was designed to peel fresh cassava, sweet potatoes, and cocoyam tubers at a speed range of 350-750 rpm. The tuber peeling rate were determined for 1 h at intervals of 5 min. The models were developed based on the Weibull and Jennings theories. The peeling rate of the machine increases with an increase in the residence time and the speed of the machine operation ($p< 0.05$). Also, the relative weight of the tuber peels increases with an increase in the residence time irrespective of the speed of operation of the peeling machine. The values obtained from the models were very close to the actual data obtained from an independent experiment, with mean square error generally less than 10%. The Weibull model parameters were better estimators of the peeling rate with $R^2 > 95\%$ and mean square error (MSE) < 10%, irrespective of the speed and residence time of machine operation.

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