Modeling of cassava peeling performance using dimensional analysis

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Abstract: Cassava peeling constitutes global challenge despite increasing consumption of its end products. To provide scientific approach for mechanical peeling, the movement of tuber in the peeling chamber was analyzed and validated. Dimensional analysis was used to establish model equations for predicting the relationship between dimensionless functional properties, and crop and machine parameters. An improved cassava variety and 2014 model cassava peeler was used for the experiment. The effective machine speed varied from 100-140 r/min for smooth-edge and 140-160 r/min for serrated-edge cutting tool. The results showed that when using smooth-edge; peeling efficiency (μ) was ranged from 84.97%-94.60%, mechanical damage (λ) was ranged from 1.57%-11.19%, peel retention (P) was ranged from 5.41%-15.03% and throughput (η) was ranged from 387.10-1046.50 kg/h. When using serrated-edge, μ was ranged from 81.24%-91.36%, λ was ranged from 6.36%-8.41%, P was ranged from 8.64%-19.34% and η was ranged from 248.28-625.00 kg/h. A linear relationship was established between the machine speed versus ratio of velocity of conveyance and peeling time.

Keywords: cassava tuber, dimensionless parameters, peeling process, tool, variables

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1 Introduction

Cassava (*Manihot esculenta Crantz*) is a perennial woody shrub with an edible root, which has the ability to grow on marginal land where cereals and other crops do not grow well. Cassava was introduced into central Africa from South America in the sixteenth century. The plant is cultivated in many parts of the word, most especially in the tropical regions such as Brazil, India and several West Africa countries. It was thought to have made its entry into Nigeria in the late

17th century through the islands of Sao Tome. A critical evaluation of data on cassava production among leading countries has shown that Africa continent accounts for about 42% while Asia and South America contributes about 37% and 21% respectively. Nigeria is the world's largest producer of the crop with 34 million tons of fresh tuber annually followed by China. Statistic from FAO of the United Nations has however shown that Thailand is the largest exporting country of dried cassava with a total of 77% of world export in 2005 (Nassar and Ortiz, 2007). The second largest exporting country is Vietnam with 13.6%, followed by Indonesia with 5.8% and Costa Rica with 2.1%.

Many researchers have however revealed that the consumption spread across all classes of the economy ranging from the rich to the poor. The cassava potential is still being under-utilized because of its low level of prominence in the trade. This is a global challenge to agriculturists, food processors and engineers. Thus, the design of research initiatives in the quest for innovation, industrialization, and health and nutrition advancement must be driven to enhance knowledge-base through adequate public awareness activities to create a new social and economic order (Ogunmoyela, 2015). In many countries, significant research has begun to

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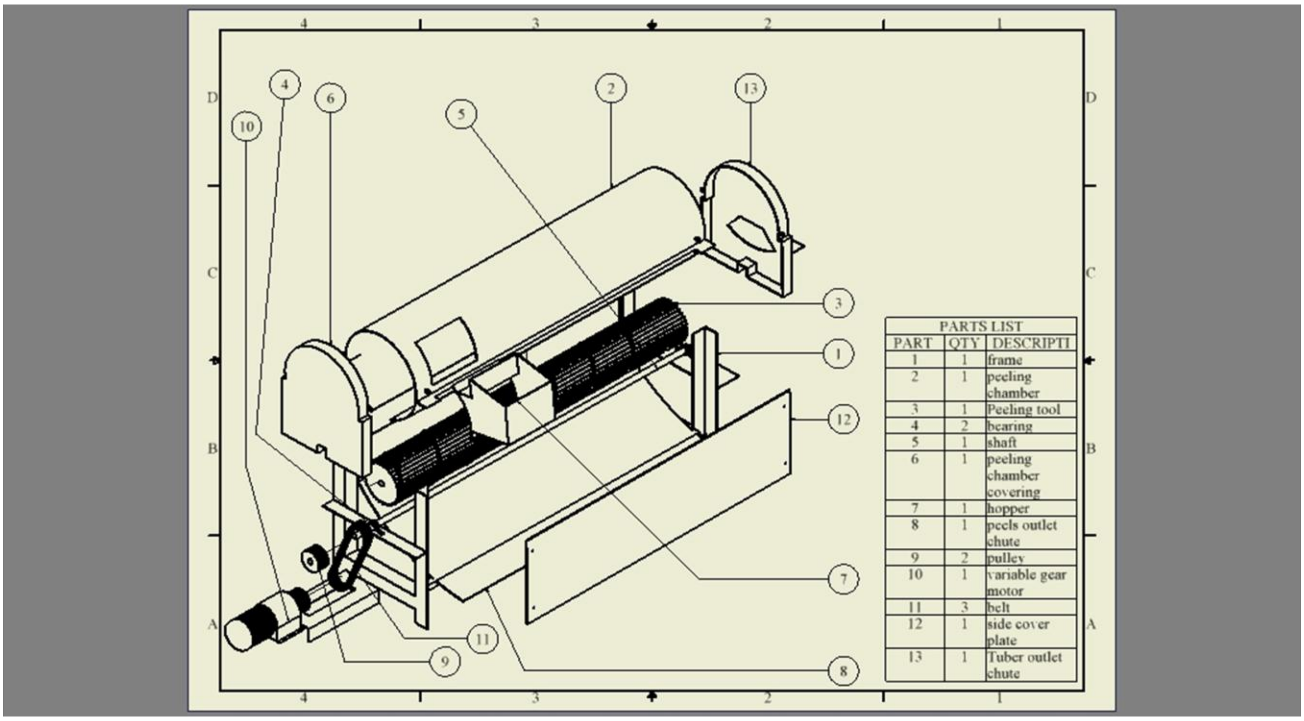
evaluate the use of cassava as an ethanol biofuel feedstock. Under the development for renewable energy in the eleventh five-year plan in the People's Republic of China, the target was to increase the application of ethanol fuel by non-grain feedstock to two million tons, and that of bio-diesel to 200 thousand tons by 2010. This will be equivalent to a substitute of 10 million tons of petroleum which was closely achieved (Fayose, 2013).

The shape of cassava tuber is the major difficulty imposing feature for the designing of cassava peeling machine. Most of the times, the proximal head tends to peel faster, leaving some peels retained in corner of the middle and distal end. Adetan et al. (2003) investigated the characterization of some properties of cassava root tuber. They reported that surface taper angle, peel thickness, proportion by weight of peel, peel penetration force, tuber shape and size were major properties that influence mechanical peeling performance of the tuber. Several peeling machines have been developed with different mechanism but with common goal "complete peeling". However, this unit operation has not gotten desired performance since peeling is still largely carried out manually.

The aim of this study is to use the dimensional analysis technique to develop the relationship between machine functional properties and some identified crop and machine variables during mechanical peeling process using an improved cassava variety.

2 Materials and methods

The automated cassava peeling machine used for this study was developed as part of step-B- project, Federal University of Technology, Akure, Nigeria as shown in Figure 1 (Jimoh, 2014). The machine was designed to remove the entire peel of tubers at different feed rate. The main feature of the machine includes: peeling chamber, peeling tool, supporting frame, peel outlet chute, shaft, hopper, tuber outlet chute and transmission system. The peeling chamber is designed in such a way that its curvature allowed displaced tubers to return and reposition it selves on the peeling tool, in the process; peeling is achieved in all orientation. This is repeated until it is completely peeled and delivered at the flesh tuber exit point for further processing. This is done to achieve regular contact period between tubers and peeling tool. The peel is collected and discharged through flat plate mounted under peeling chamber.



PARTS LIST		
PART	QTY	DESCRIPTI
1	1	frame
2	1	peeling chamber
3	1	Peeling tool
4	2	bearing
5	1	shaft
6	1	peeling chamber covering
7	1	hopper
8	1	peels outlet chute
9	2	pulley
10	1	variable gear motor
11	3	belt
12	1	side cover plate
13	1	Tuber outlet chute

Figure 1 Exploded view of the machine

2.1 Theoretical analysis

An improved cassava variety TMS 30572 used for this experiment was harvested in teaching and research farm, Federal University of Technology, Akure, Nigeria. The tubers were cut through along a transverse division mark at an interval of 50-100 mm from the proximal to distal end depending on the number of curvatures. This was done so as to reduce the effect of irregular shape of the tuber. Two cutting tool surfaces were engaged; smooth-edge and serrated-edge. The analysis of tuber movement in a mechanical system was accomplished by linear movement of tubers in the direction of auger and continuous impact between tubers and cutting tool. However, crop parameters, machine parameters and operational parameters were closely related and alteration of one parameter will definitely affect others. Similarly, a close examination shows that operational parameters can be expressed as the function of some independent variables as follows:

Dependent variables are:

Peeling efficiency, μ; mechanical damage, λ; peel retention, P; and throughput capacity, η.

Independent variables are:

Mass of tuber, t_w; length of tuber, t_l; proportion by peel, w_p; peel thickness, t_p; peel penetration force, f; peel shear stress, τ; moisture content, ϕ; machine speed, s; velocity of conveyance, v; thickness of cutting blade, t_{cb}; and peeling time, t.

Considering circular motion of the auger, the tubers has net force exerted on it toward the center of the circle with magnitude v^2/R, where v is the velocity of conveyance and R is the radius of the tuber.

$$/\sum F^1/=\frac{t_w v^2}{R}\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

The net force is horizontal. The static frictional force F_s provides the centripetal force because the tubers do not slide on the surface of the cutting tool (Jimoh, 2014).

$$F_s=t_w a\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Frictional force, F_s is a function of velocity of conveyance. By combining Equations (1) and (2), we have:

$$F_s=\frac{t_w v^2}{R}\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

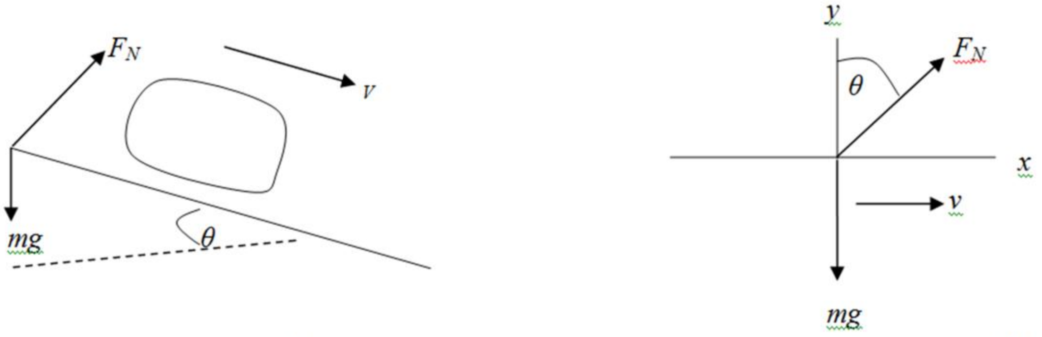
Thus F_s increase as v increases, the maximum frictional force corresponds to maximum velocity of conveyance; v_m is $F_{s.max}$

$$\frac{t_w {v_m}^2}{R}=F_{s.\max}=\mu_s F_N=\mu_s t_w g\ldots\ldots\ldots(4)$$

Solving for v_m

$$v_m=\sqrt{\mu_s gR}\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Where μ_s is the coefficient of static friction between the cutting tool edge and tuber surfaces and F_N is the vertical force acting normally (Thompson, 1999) as is shown in Figure 2.



(a) (b)

Figure 2 Movement of tuber in the peeling chamber (a) sketch of the peeling system (b) free body diagram of the tuber

2.2 Theoretical model

The dimensions and performance of the prototype machine are deduced from crop and machine parameters by using dimensional analysis and similarity criteria which require that variables be similar dynamically. Relationships between dependent and independent variables are established with view to determine which parameters affect the performance of the machine. *Buckingham* Π Theorem proves the conclusion that if a functional relationship contains m variables with a total of n basic dimensions, on the application of dimensional analysis, the relationship will contain m-n groups of dimensionless groups.

Let a functional relationship consist of variables x_1, x_2, ..., x_m regardless of which is the dependent variable among them. We can express the functional relationship as:

$$f\left(x_1, x_2, ..., x_m\right) = 0.................(6)$$

If the variables together have *n* basic dimensions, then the dimensional analysis procedure will transform the functional relationship to

$$f_1\left(\Pi_1, \Pi_2, ..., \Pi_{m-n}\right) = 0..............(7)$$

In determining the Π's, *n* of the variables are selected as repeating variables. They must jointly contain the *n* basic dimensions. Thus;

$$\Pi_1 = \left(x_1^{a11} x_2^{a12} ....x_n^{a1n}\right)x_{n+1}.................(8)$$

$$\Pi_2 = \left(x_1^{a21} x_2^{a22} ....x_n^{a2n}\right)x_{n+2}.................(9)$$

$$\Pi_{m-n} = \left(x_1^{a(m-n)1} x_2^{a(m-n)2} ....x_n^{a(m-n)n}\right)x_m.........(10)$$

For each equation, the variables are expressed in terms of the basic dimensions; the Π is similarly expressed but each basic dimension is raised to power zero (Ogboja, 2005). The equations are then solved for the exponents by equating the exponent of each basic dimension to zero.

Modeling of machine efficiency using principle of dimensional homogeneity,

$$\mu = f\left(w_p, t_p, F, \tau, \phi, v, s, t_{cb}, t\right)...................(11)$$

$$f_1\left(\mu, w_p, t_p, F, \tau, \phi, v, s, t_{cb}, t\right) = 0....................(12)$$

There are ten variables and three basic dimensions *M, L* and *T*. Therefore, the solution will yield seven Π terms. In selecting the repeating variables, it will be helpful to select one to reflect the conveyance of the tubers, another to reflect mass of moving tuber and the last one to reflect the characteristic dimension of the peel. Consequently, let us select *v*, *F* and t_p. Thus;

$$f_2\left(\mu, \frac{v^2 w_p}{F t_p}, \frac{\tau}{F}, \phi, \frac{s}{v}, \frac{t_{cb}}{t_p}, \frac{vt}{t_p}\right) = 0....................(13)$$

Modeling of mechanical damage,

$$\lambda = f\left(t_w, l, t_p, F, \tau, \phi, v, s, t_{cb}, t\right)........................(14)$$

$$f_1\left(\lambda, t_w, l, t_p, F, \tau, \phi, v, s, t_{cb}, t\right) = 0....................(15)$$

There are eleven variables and three basic dimensions *M*, *L* and *T*. Therefore, the solution will yield eight Π terms. Thus;

$$f_2\left(\lambda, \frac{t_w v^2}{F t_p}, \frac{l}{t_p}, \frac{\tau}{F}, \phi, \frac{s}{v}, \frac{t_{cb}}{t_p}, \frac{vt}{t_p}\right) = 0...........(16)$$

Modeling of peel retention,

$$P = f\left(l, w_p, t_p, F, \tau, \phi, v, s, t\right)..............(17)$$

$$f_1\left(P, l, w_p, t_p, F, \tau, \phi, v, s, t\right) = 0................(18)$$

There are ten variables and three basic dimensions *M*, *L* and *T*. Therefore, the solution will yield seven Π terms. Thus;

$$f_2\left(P, \frac{l}{t_p}, \frac{w_p v^2}{F t_p}, \frac{\tau}{F}, \phi, \frac{s}{v}, \frac{vt}{t_p}\right) = 0..........(19)$$

Modeling of throughput capacity,

$$\eta = f\left(t_w, v, s, t\right)..............................(20)$$

$$\eta = f_1\left(\frac{v}{t_w}, \frac{s}{t_w}, \frac{t}{t_w}\right)......................(21)$$

The variables of the functional relationship are rendering dimensionless to obtain:

$$\eta = f_2\left(\frac{v}{t}, \frac{s}{t}\right)............................(22)$$

2.3 Test procedures

In the course of the peeling process, it was observed that an accurate length and diameter classification cannot be achieved, therefore, the weight of tubers was chosen as the constant variable for tuber classification. The machine was evaluated on the basis of weight classification using variable gear motor at speed; 100, 110, 120, 130, 140 r/min for smooth-edge cutting tool and 140, 145, 150, 155, 160 r/min for serrated-edge cutting tool. Unit feeding of cassava in to the hopper was carried out and this peeling was considered to be a preliminary test. Mass peeling process at different feed rates 10, 20, 30, 40, 50 kg for each of the machine speed were also carried out. The tuber flesh is collected at tuber outlet while tuber peel is collected at peel outlet. The machine functional parameters such as peeling efficiency, μ %; mechanical damage, λ,%; peel retention, P %; and throughput capacity, η kg/h, were obtained using Equations 23-26 as stated in (Jimoh et al. 2014).

$$\mu = \frac{w_{pr}}{w_{pr} + w_{prh}} \qquad (23)$$

$$\lambda = \frac{w_{trp}}{w_{trp} + w_{tc}} \qquad (24)$$

$$P = \frac{w_{prh}}{w_{prh} + w_{pr}} \qquad (25)$$

$$\eta = \frac{w_{pr} + w_{prh} + w_{trp} + w_{tc}}{t} \qquad (26)$$

Where W_{pr} is weight of peel removed by machine, W_{prh} is weight of peel removed by hand after machine peeling, W_{trp} is weight of tuber flesh removed along with peel, W_{tc} is weight of tuber flesh completely peeled and t is peeling time.

3 Results and discussions

Using Equations (4) and (5), it was observed from theoretical analysis that the coefficient of static friction, μ_s was 0.614 for smooth-edge and 0.671 for serrated-edge. Maximum velocity of conveyance, v_m was 1.16 m/s (140 r/min) for smooth-edge and 1.32 m/s (160 r/min) for serrated edge as is shown in Tables 1 and 2. If these are exceeded during mechanical peeling, more damages are expected to be done to tuber flesh.

1 Dimensionless machine functional parameters using smooth-edge cutting tool during peeling of TMS 30572 cassava tuber

Speed, r/min	Feed rate, Kg	Peeling efficiency, %	Mechanical damage, %	Peel retention, %	Throughput capacity, kg/h
100	10	84.97	1.57	15.03	387.10
	20	86.06	2.36	13.94	685.71
	30	86.80	3.89	13.20	857.14
	40	86.96	8.06	13.04	947.37
	50	87.19	10.57	12.82	972.97
110	10	88.37	1.81	11.63	395.60
	20	88.39	2.54	11.61	705.88
	30	88.73	4.06	11.27	878.05
	40	88.86	8.24	11.15	972.97
	50	88.90	10.76	11.10	994.48
120	10	90.91	1.94	9.09	404.49
	20	91.10	2.73	9.09	720.00
	30	91.34	4.25	8.90	900.00
	40	91.48	8.41	8.66	993.10
	50	91.91	10.92	8.52	1011.20
130	10	94.60	2.45	5.41	413.79
	20	94.37	3.04	5.63	734.69
	30	93.95	4.45	6.05	923.08
	40	93.22	8.57	6.78	1014.10
	50	92.68	11.05	7.32	1022.70
140	10	93.18	3.03	6.82	423.52
	20	92.88	4.25	7.12	757.89
	30	92.42	4.61	7.58	947.37
	40	91.92	8.71	8.09	1043.50
	50	91.71	11.19	8.29	1046.50

Table 2 Dimensionless machine functional parameters using serrated-edge cutting tool during peeling of TMS 30572 cassava tuber

Speed, r/min	Feed rate, kg	Peeling efficiency, %	Mechanical damage, %	Peel retention, %	Throughput capacity, kg/h
140	10	82.72	8.41	17.28	248.28
	20	83.66	7.57	16.34	354.68
	30	84.64	7.42	15.36	450.00
	40	81.24	7.32	18.76	489.80
	50	80.66	6.95	19.34	545.45
145	10	82.90	8.18	17.10	253.52
	20	84.02	7.45	15.98	360.00
	30	85.22	7.26	14.78	459.57
	40	81.78	7.21	18.22	500.00
	50	81.45	6.81	18.55	559.01
150	10	83.51	8.07	16.49	257.14
	20	84.62	7.34	15.38	367.35
	30	85.79	7.14	14.21	469.57
	40	82.43	7.09	17.57	512.46
	50	82.33	6.70	17.67	573.25
155	10	87.18	7.82	12.82	262.77
	20	88.15	7.03	11.85	375.00
	30	90.84	6.82	9.16	484.30
	40	84.51	6.75	15.49	529.41
	50	83.33	6.36	15.67	596.03
160	10	87.63	7.70	12.37	272.73
	20	88.83	7.13	11.17	387.10
	30	91.36	6.92	8.64	502.33
	40	84.98	6.85	15.02	553.85
	50	85.27	6.58	14.73	625.00

Table 1 shows the dimensionless functional properties of the machine using smooth-edge cutting tool during peeling of TMS 30572 cassava tuber. As feed rate increased from 10-50 kg, peeling efficiency slightly increased and peel retention slightly decreased particularly at low speed (100-120 r/min). This was as a result of prolongs interaction between the tubers and cutting tool. As the tubers spin, it collides with one another, and this could have contributed to low velocity of conveyance at high feed rate. However, at high speed (130-140 r/min) as feed rate increased from 10-50 kg, peeling efficiency decreased and peel retention increased. This could have been as a result of low interaction between tubers and cutting tool. At high speed, the interaction is much higher between tubers than between tubers and cutting tool. In order words, less contact was made with the cutting tool at high feed rate. Mechanical damage increased as feed rate increased and also increased as the speed of the machine increased. This could be as a result of low adhesion between peel and tuber flesh and elastic properties of the tuber because of high moisture since it was freshly harvested. It is evident from Equation 26 that throughput capacity is the resultant effect of tuber weight with respect to time. Thus, it increased as weight of tuber increased and equally increases as machine speed increased since at high speed, delivery time will be shorter.

The dimensionless functional properties of the machine using serrated-edge cutting tool as shown in Table 2 revealed that; as the speed increased from 140-160 r/min, machine efficiency increased with the increase in feed rate up to 30 kg while peel retention decreased. As the feed rate further increased, efficiency decreased and peel retention increased. This was because of high surface traction between cutting tool and tubers as a result of two rough surfaces in contact. The contact area is much smaller especially at high feed rate. Mechanical damage decreased as feed rate increased and slightly decreased with the increase in speed. This could be as a result of limited contact. Throughput equally increased as speed and feed rate increased in the same trend with smooth-edge cutting tool. The magnitude of throughput in serrated-edge is lower than that of smooth-edge because the cutting of the blade opposes tuber motion which invariably increased the delivery time.

The common crop and machine parameters that determine dimensionless functional properties include machine speed, velocity of conveyance of the tuber and its delivery time. Graph of machine speed versus ratio of velocity of conveyance and peeling time during preliminary test using smooth-edge cutting tool as is shown in Figure 3 demonstrated linear relationship. As the speed increased from 100-140 r/min, *v/t* increased from 0.011-0.014. Similarly Figure 4 also had shown linear relationship while using serrated-edge. As the speed of the machine increased from 140-160 r/min, *v/t* equally increased from 0.005-0.007.

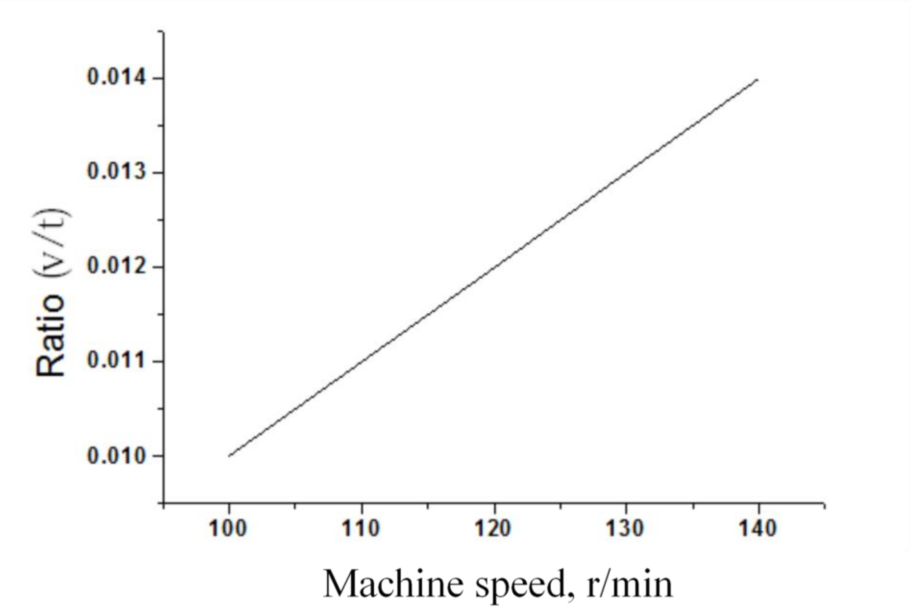


Figure 3 Machine speed, r/min versus ratio of velocity of conveyance and peeling time, *v/t* using smooth-edge cutting tool during preliminary test

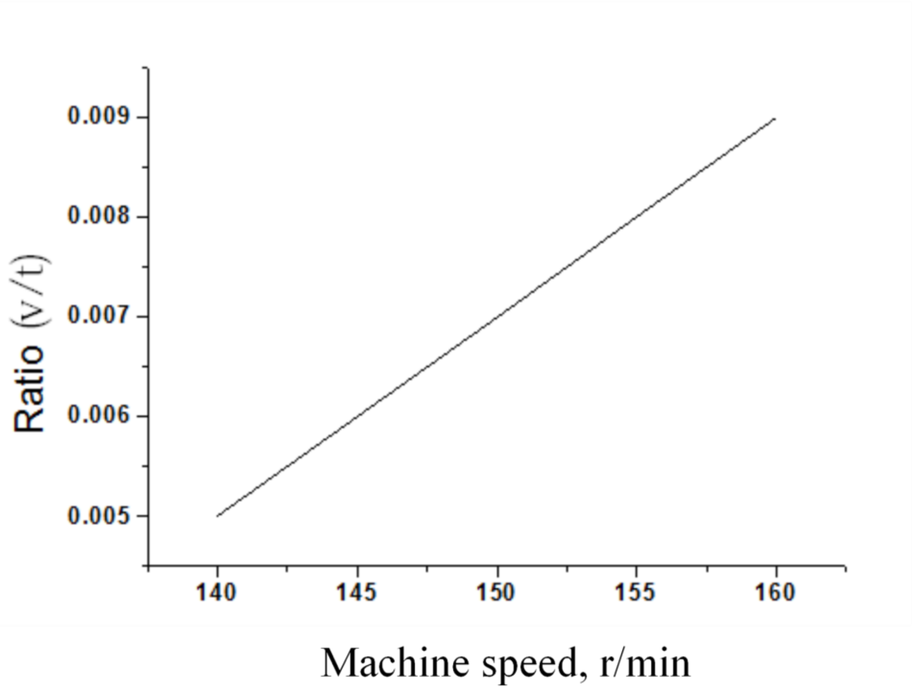


Figure 4 Machine speed, r/min versus ratio of velocity of conveyance and peeling time, *v/t* using serrated-edge cutting tool during preliminary test

4 Conclusions

(1) The dimensionless machine functional parameters is said to be optimum when machine speed and feed rate is about 130 r/min and 10-20 kg respectively using smooth-edge peeling tool. When serrated-edge tool is engaged, the optimum performance is achieved when the speed and feed rate is about 160 r/min and 30 kg respectively. This information is important in cassava peeling mechanization.

(2) The adhesion between peel and tuber flesh is low when freshly harvested and it is therefore economical to peel cassava tuber as soon as possible to reduce mechanical damage. The broken tuber flesh could be considered as animal feed.

(3) It may however be essential to carry out other studies to determine upper and lower control limits of the dimensionless machine functional $\bar{\bar{X}}$operties at different farm locations under different soil parameters using control chart.

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