Theory of a mechanical method of peeling cassava tubers with knives

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A b s t r a c t. A new but highly promising mechanical cassava peeling concept was investigated. The concept is based on the principle of peel-flesh separation through compression and peel removal with knives. The mechanism of this principle was described and mathematically modelled. Preliminary experiments were carried out on root slices of 100 mm length using a peeling machine developed earlier on the basis of this principle. The data collected were used to validate the model. The model developed predicts the performance index (peel removal efficiency) with a certainty level of 95.46%. Thus, the model adequately explains the peeling concept and it is, therefore, an invaluable and reliable tool for further development and improvement of mechanical cassava peeling machines.

K e y w o r d s: cassava tubers, mechanical peeling, compression peeling, modelling peeling efficiency

INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is grown mainly in the tropical parts of Africa, Brazil, Malagasy, Indonesia, South India, Philippines, Malaya, Thailand and China (Ajibola, 2000). In the tropical part of Africa, it has become the most important crop in terms of both the total land area devoted to its production and the proportion it contributes to the human diet. Jeon and Halos (1992) reported that 60% of root crop consumption in Africa is accounted for by cassava.

The cassava root tuber is the main economically useful part of the cassava plant. Apart from the importance of the cassava tuber as a constituent of human food, it has many non-food uses and it has become a foreign exchange earner for the producing countries. China, the second largest producer of cassava in the world, earns over 2 billion dollars per year from the crop. This commercial potential of cassava is currently being under-utilized in Nigeria which is the largest producer of the crop in the world with over 34 million tonnes of fresh tubers being produced annually (Ajibola, 2000).

Before the cassava tuber is processed into any of its food and some of its non-food products, it must be peeled. Ideally, and especially in the food industry, the peel must be completely removed without removing the useful tuber flesh. The major cassava peeling problem arises from the fact that cassava roots exhibit appreciable differences in weight, size and shape. There are also differences in the properties of the cassava peel which varies in thickness, texture and strength of adhesion to the root flesh. Thus, it is difficult to design a cassava peeling machine that is capable of efficiently peeling all roots due to the wide differences in the properties of roots from various sources. Indeed, the development of a technically and economically acceptable cassava peeling machine is still a challenge.

For most processes, attempts at designing machines that will replace human labour usually focus on simulating the motion of the human hand during such processes. However, manual peeling of cassava by shearing with a knife has been shown not only to be inefficient but also wasteful (Anekwe, 1984). Consequently, a need arises to examine the possibility of using methods other than one that simulates manual peeling by shearing with a knife.

Chemical peeling (using a hot solution of sodium hydroxide to loosen and soften the skin of roots), which is well developed for peeling sweet potatoes in processing industries, has been considered. A major reason why this method will not be suitable for cassava peeling is that a higher temperature and more root immersion time will be required for cassava roots because they have peels that are tougher than those of potatoes. This will result in the formation of an objectionable heat ring (dark colour) on the surface of the useful root flesh and the gelatinisation of starch in the cassava root (Igbeka, 1985). Such roots are obviously unsuitable for *gari* or industrial starch production. For similar reasons, steam peeling is also ruled out for the peeling of cassava roots.

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Abrasion has been tried by many researchers but success has been limited. Many of the abrasive action batch peeling machines tend to reduce tubers to thin uniform cylinders before all peel is removed (Ezekwe, 1976). Besides, at the time when the big roots in the batch are yet to be adequately peeled by the abrasive peeler, many of the small roots would already have been completely grated.

Ohwovoriole *et al.* (1988) reported on a simple manual rig that works on the principle of peel-flesh separation through compression followed by peel removal with knives. With freshly harvested tubers, they reported no loss of useful flesh. Adetan (2002) developed a mechanical peeling machine based on the peeling concept reported by Ohwovoriole *et al.* (1988).

This paper discusses the theory of this new cassava peeling concept and models it mathematically. The model was validated using the peeling machine developed by Adetan (2002) on the basis of this principle.

PEELING CONCEPT

A transverse section of the tuber (Fig. 1) shows that it consists of a central core called the pith. This is surrounded by the starchy flesh which forms the bulk of the tuber and the main storage region. Covering the cambium layer is the tuber peel which consists of a corky periderm on the outside and cortex on the inside. The cortical region is usually white in colour and varies in thickness between 1.2 and 4.15 mm (Adetan *et al.*, 2003). Unlike other root crops, the peel of fresh cassava roots is quite distinct from, and adheres relatively loosely to, the root flesh because of the thin cambium layer separating them. This peel breaks loose from the flesh when the tuber is subjected to sufficient compression.
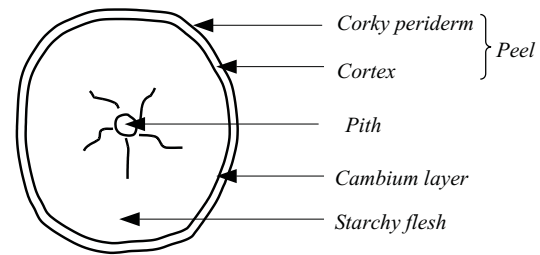

Fig. 1. Transverse section of typical root tuber.

The mechanism of peel-flesh separation is illustrated in Fig. 2. In this Figure, the broken lines represent boundaries of rings (circular strands) of flesh in the root (including the peel) before compression pressure is applied. Consider the transverse section of the portion of the root bounded by abcdefgh. When compressed, this portion flattens out into ABCDEFGH. The originally circular strands of flesh straighten out and all strands within the zone of compression tend to assume the same length. Therefore, within this zone, the straightened strands are subjected to varying strains (compression/tension) because the outer ones were originally longer than the inner ones before compression (the outer ones being located at greater radial distances from the root centre than the inner ones). In turn, the strands of flesh in the compression zone are subjected to varying stresses (compression/tension). Some relative strand-strand shear stresses are thus built up throughout the zone of compression. The higher the compression pressure applied to the root, the higher are these relative strand-strand shear
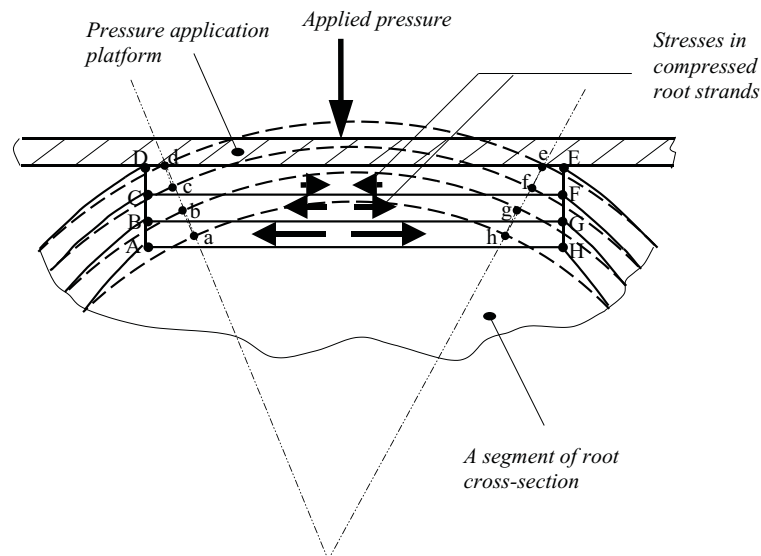

Fig. 2. Mechanism of peel-flesh separation; a, b, c, d, e, f, g, h – before compression; A, B, C, D, E, F, G, H – after compression.

stresses. If the compression pressure applied is high enough, the shear stress developed at the peel-flesh interface becomes high enough to cause the peel to break loose from the flesh. Therefore, if a tuber piece is sufficiently compressed, a slit of the peel deep into the cambium followed by a careful unwrapping of the peel will separate the peel from the rest of the root. This unwrapping is very smooth when the root is freshly harvested and is still succulent. This is the property that is being exploited in peeling with the principle of peel-flesh separation through compression and peel removal with knives. This principle appears to be quite promising in the solution of the seemingly intractable cassava peeling problem because it results in virtually 100% useful flesh recovery (Adetan, 2002). To make use of it in the peeling of cassava tubers, Adetan (2002) suggested a system in which root slices will roll between a spring-loaded bed of knives below it and a pressure application platform above it (or vice versa), as shown in Fig. 3.

bed of spring-loaded knives is located above the belt-conveyed moving root. The belt moves over a rigid table of aluminium sheet that forms the pressure application platform. The machine has facilities for varying the average size h of the aperture between the knives and the belt, the angle of inclination of the bed of knives to the belt surface, α, the velocity of the belt, V, and the force in the springs (which determines the force in play between the pressure application platform and the root, F_p). It is assumed that even the roots that have surface taper angles α_r higher than α will pass through the peeling zone resting on the pressure application platform as shown in Fig. 5.

From experimental observations reported by Adetan (2002), the peeling process features the following process stages.
a) Separation of the tuber peel from the flesh by compression.
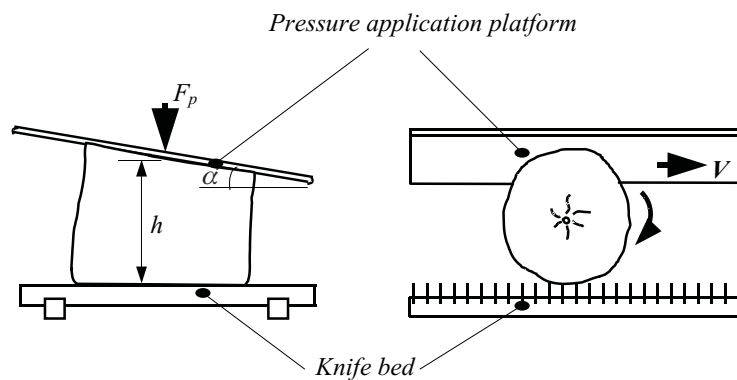b) Penetration and removal of tuber peel with knives.

Fig. 3. Root slice rolling between moving pressure application platform and bed of knives: F_p – force in play between pressure application platform and root; α – angle of inclination of the knife bed to the pressure application platform; h – average clearance between knife bed and pressure application platform; V – linear speed of conveyance of root slices between the bed of knives and the pressure application platform.

THEORETICAL ANALYSIS OF CASSAVA PEELING

To analyse the peeling concept described above, the whole or sliced root to be peeled is considered as an approximate frustum of a cone. The two performance indices of primary importance in the operation of peeling machines are the useful flesh recovery index, R, and the peel removal efficiency, C. As pointed out earlier, an important feature of the present peeling concept is that the useful flesh recovery is always 100%. Consequently, the machine performance index that needs to be maximized is the peel removal efficiency, C. The operating principle of the peeling machine developed by Adetan (2002), which utilizes the present peeling concept, forms the basis for the following theoretical analyses. In this machine, shown in Fig. 4, the

Peel-flesh separation by compression

This stage of the peeling process is analysed using Hertz theory. As the root is pressurised by the application of the force, F_p, (Fig. 6), it experiences a radial deformation, δ. According to Hertz theory as reported by Mohsenin (1970), this radial deformation is given by:

$$\delta = k_c \left(\frac{F_p^{\,2}}{d_a} \right)^{1/3},$$ (1)

where: k_c – constant, d_a – average root diameter.

Referring to Fig. 6, it can be seen that for a unit length of root, the width, q, of the resulting flat area of contact between the root and the pressure platform is given by:
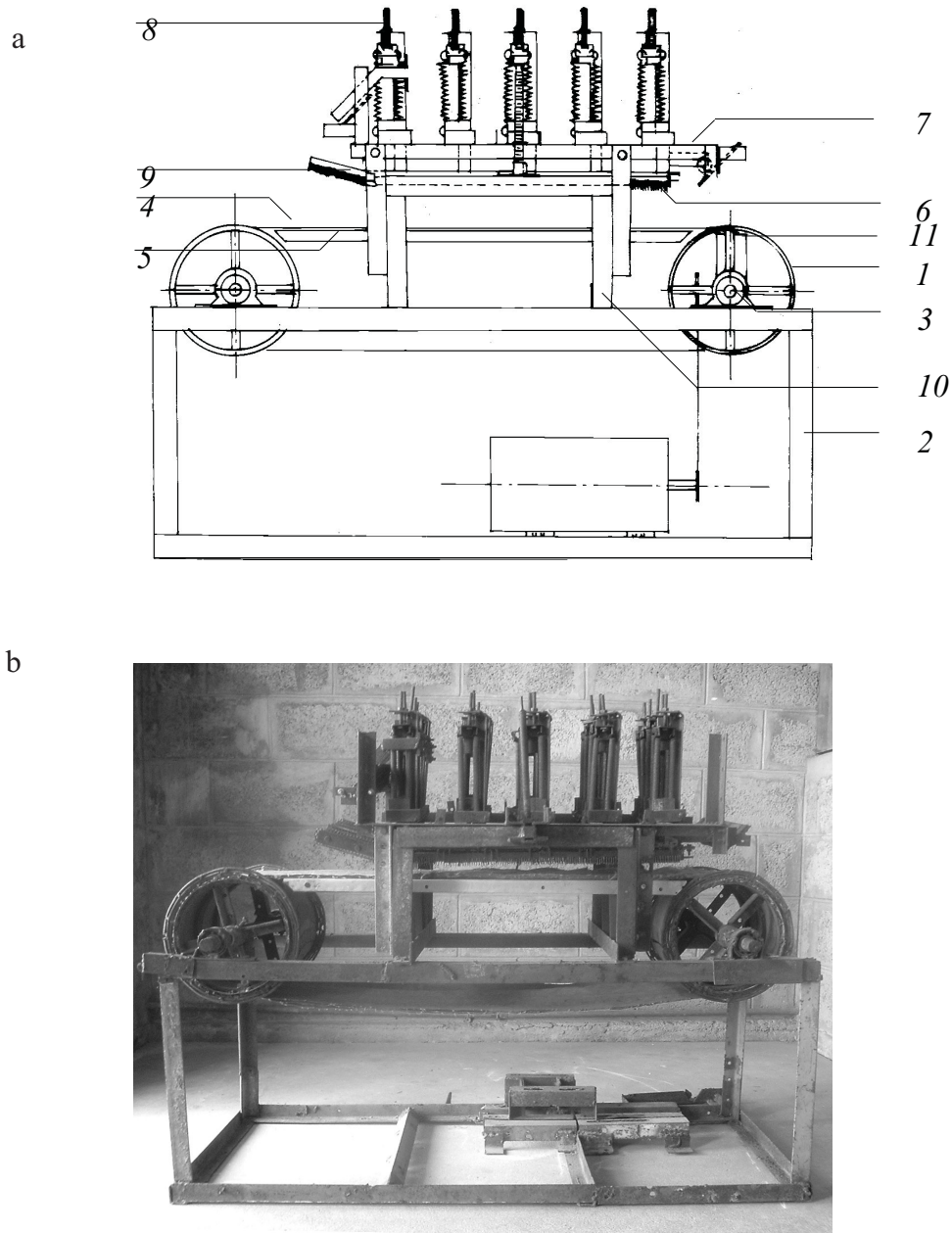
Fig. 4. Side views of the cassava tuber peeling machine: a) schematic illustration, b) photograph; 1 – conveyor drum; 2 – main frame; 3 – bearing; 4 – conveyor belt; 5 – conveyor belt platform; 6 – peeling blades; 7 – knife assembly bearing frame; 8 – spring load adjuster nut; 9 – root pick-up; 10 – main frame link arm; 11 – speed reduction gear box.

$$q = 2\sqrt{d_a{}^2/4 - \left(\frac{d_a}{2} - \delta\right)^2},$$

which simplifies to:

$$q = 2\sqrt{\delta d_a - \delta^2} = 2\sqrt{\delta(d_a - \delta)}. \qquad (2)$$

Usually, δ would be very small compared to d_a. Therefore, we can re-write Eq. (2) as:

$$q = 2\sqrt{\delta d_a}. \qquad (3)$$

Thus, q can be written as a function of δ and d_a as follows:

$$q = f_1(\delta d_a)^{\frac{1}{2}}, \qquad (4)$$

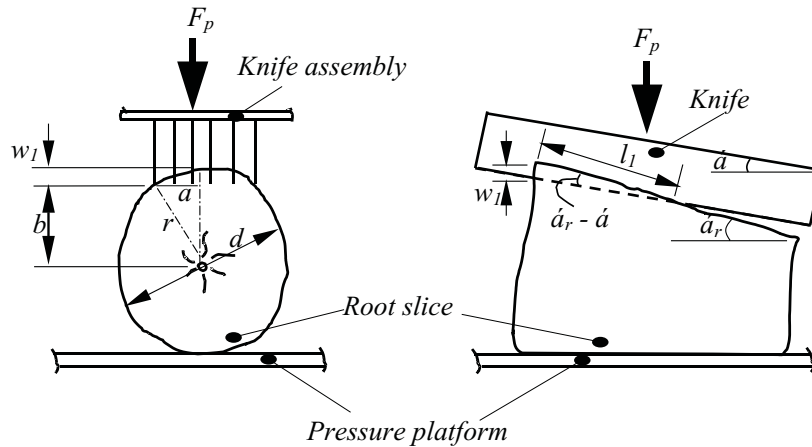where f_1 is a functional notation.

Fig. 5. Typical placement of root in relation to knife bed and pressure platform: w_1 – depth of penetration of knife into the body of the root, b – vertical height of knife edges above the centre of the root rolling under the knife bed.
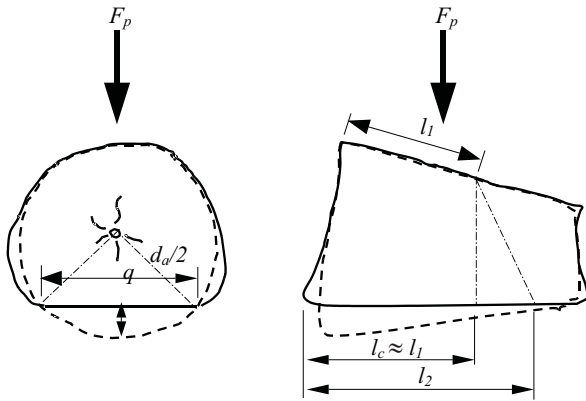

Fig. 6. Compressed shape of root slice: --- tuber profile before compression, — profile of compressed tuber; l_1 – length of line of contact of a knife with the root, l_2 – total length of root surface being compressed by the pressure platform, l_c – horizontal length of root assumed subject to uniform maximum compression.

Substituting Eq. (1) into Eq. (3) and writing the result as a functional expression, q may be written as a function of F_p and d_a as:

$$q = f_2 \left\{ \left[\left(\frac{F_p^2}{d_a} \right)^{1/3} d_a \right]^{1/2} \right\}, \tag{5}$$

which simplifies to:

$$q = f_2 \{ [F_p d_a]^{1/3} \}. \tag{6}$$

For a root of unit length, q is a measure of the width of the root surface over which peel–flesh separation is being effected.

Referring to Fig. 6 where l_2 is the length of root surface being compressed by the pressure application platform, we can deduce that the area of contact of the root with the platform is approximately loaded as shown in Fig. 7. The

average cassava root surface taper angle, α_r, is typically very small. It is about 5.3° (Adetan *et al*., 2003). Thus, while root surface compression covers length l_2 of the root, the area around this length that is affected by the compression may be taken as being approximately rectangular.

For a root length other than unity, we may define a modified q as q_m. Observing that for a given F_p, the value of q_m would decrease as l_2 increases, we may write:

$$q_m = f_3 \left(\left[F_p d_a \right]^{1/3} / l_2 \right). \tag{7}$$

Denoting the proportion of the rectangular area lq_m which is affected by compression by A_r, then, the measure of the amount of peel separated from the tuber flesh by compression is $A_r l q_m$. Consequently, the measure of the percentage of the total area of peel covering a root of length, l, that is separated from the flesh by compression is $A_r l q_m / \pi d_a l$. Thus, the contribution of the compression stage of the
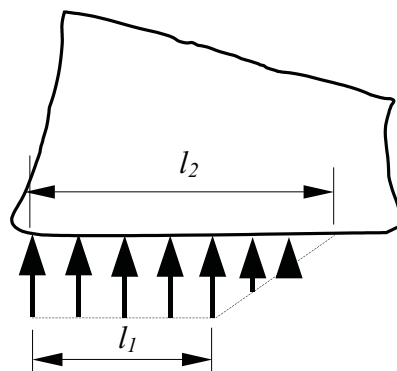

Fig. 7. Compression load distribution on a root slice at the root-platform contact surface.

peeling process to C is denoted by C_1 and written as a function of A_r, q_m and d_a as follows:

$$C_1 = f_4\left(A_r q_m / d_a\right). \tag{8}$$

Substituting Eq. (7) into Eq. (8), we obtain:

$$C_1 = f_5\left\{A_r\left[F_p d_a\right]^{1/3} / l_2 d_a\right\}. \tag{9}$$

If we re-examine Fig. 6, it would be observed that l_2 can be expressed as a function of l_1 so that Eq. (9) becomes:

$$C_1 = f_6\left\{A_r\left[F_p d_a\right]^{1/3} / l_1 d_a\right\}. \tag{10}$$

To obtain A_r for a root of length l having a compressed length l_2, we have, as stated earlier, assumed that the compressed area is approximately rectangular. Thus,

$$A_r = l_2 q_m / l q_m \approx l_1 q_m / l q_m = l_1 / l . \tag{11}$$

Substituting this into Eq. (10), we obtain:

$$C_1 = f_7\left\{\left[F_p d_a\right]^{1/3} / d_a l\right\}. \tag{12}$$

Peel penetration and removal with knives

A close examination of Fig. 5 shows that w_1, the depth of penetration of peeling knives into the body of the root, can be expressed as a function of some independent variables as follows:

$$w_1 = f_8\left(\frac{wF_p}{Fl_1}\right), \tag{13}$$

where: w – difference between the maximum diameter of a root and the average height of knife bed above the pressure application platform, h, F_p – force in play between pressure application platform and root, F – force required to penetrate root peel by a unit length of knife, l_1 – length of line of contact of a knife with the root.
Assuming that f_8 is a linear function:

$$w_1 = k_s\left(\frac{wF_p}{Fl_1}\right), \tag{14}$$

where k_s = constant of proportionality.
Consider an enlarged root penetration position extracted from Fig. 5 and shown in Fig. 8. From Fig. 8, an expression can be written for w_1 as follows:

$$w_1 = l_1 \sin\left[\alpha_r - \alpha\right], \tag{15}$$

where α_r – average angle of taper of root surface along its length, α – angle of inclination of knife bed to the pressure application platform.

Equating Eqs (14) and (15), we have:

$$l_1 \sin\left[\alpha_r - \alpha\right] = \frac{k_s wF_p}{Fl_1}$$

$$\Rightarrow Fl_1^2 \sin\left[\alpha_r - \alpha\right] = k_s wF_p$$

$$l_1 = \left(\frac{k_s wF_p}{F \sin\left[\alpha_r - \alpha\right]}\right). \tag{16}$$

From practical experience during experimentation with the peeling machine developed by Adetan (2002), it was observed that it is reasonable to assume that $w_1 \approx 3.5$ mm when $w = 10$ mm, $F_p = 240$ N for a typical root having radius at its highest diameter end, $r = 25$ mm, length of root, $l = 100$ mm and $\alpha_r \approx \alpha$ ie $l_1 \approx l = 100$ mm.
Putting these values into Eq. (14), we obtain:

$$k_s = \frac{350F}{2400}. \tag{17}$$

Adetan *et al.* (2003) reported a linear relationship between the force per unit length of knife edge, F (N mm^{-1}), that is required to penetrate into the body of a cassava root, and the average diameter of the root, d (mm). This relationship is given by (Adetan *et al.*, 2003):

$$F = 0.977 + 0.008803\, d . \tag{18}$$

Using Eq. (18), for $d = 2r = 50$ mm, we obtain $F = 1.417$ N mm^{-1}. Putting this into Eq. (17), we have:

$$k_s \approx 0.207.$$

Substituting this value of k_s into Eq. (16), we have:

$$l_1 = \left(\frac{0.207\, wF_p}{F \sin\left[\alpha_r - \alpha\right]}\right)^{1/2}. \tag{19}$$

Let us define C_2 as the effect of the peel penetration and removal stage on C, the peel removal efficiency. C_2 is a function of l_1 because the latter is a measure of the extent of interaction between the root and the knife. A logarithmic relationship between C_2 and l_1 has been suggested (Adetan, 2002) as follows:
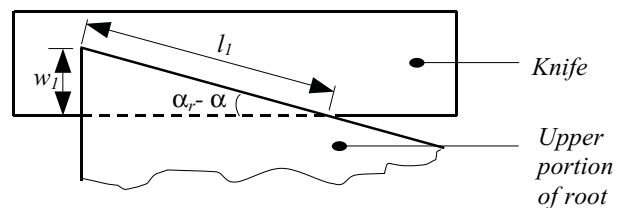
$$C_2 = f_9 \left(\ln l_1\right). \tag{20}$$

Fig. 8. Portion of root penetrated by knife.

Effect of velocity on peel removal efficiency

The velocity of conveyance of roots within the peeling zone, V, is expected to affect the value of C. If we denote the contribution of the velocity effect by C_3, it is expected that the lower the value of V is, the higher will C_3 be. This is not difficult to understand if it is realized that a low conveyance velocity implies that the root would be retained between the pressure application platform and the knives for a longer period of time. Thus, there would be more time for the system to pressurize the root well enough for the purpose of separating the peel from the flesh; there would also be more time for the knives to penetrate the root peel for better peel removal. The effect of V on C may be evaluated experimentally for a given peeling system that is designed based on the principle described in this work.

Combined effect of root compression, peel penetration and velocity on peel removal efficiency

Theoretically, C_2 depends on C_1 and it is zero if C_1 is zero. Also, both C_1 and C_2 will depend on velocity and, therefore, C_3. Thus, it is likely that it is the interaction of C_1, C_2, and C_3 that makes up the resultant C rather than the sum of their individual effects. We may therefore write:

$$C = f_{10} (C_1 C_2 C_3).\qquad(21)$$

Substituting Eqs (12) and (20) into Eq. (21), we obtain:

$$C = f_{10}\left\{\frac{\ln l_1}{l d_a}\left[F_p d_a\right]^{\frac{1}{3}} C_3\right\}.\qquad(22)$$

Assuming that f_{10} is a linear function, we can re-write Eq. (22) as:

$$C = k_0 + k_1\left\{\frac{\ln l_1}{l d_a}\left[F_p d_a\right]^{\frac{1}{3}} C_3\right\},\qquad(23)$$

where k_0 and k_1 are constants.

Equation (23) may yet be re-written as:

$$C = k_0 + k_1 E,\qquad(24)$$

where:

$$E = \left\{\frac{\ln l_1}{l d_a}\left[F_p d_a\right]^{\frac{1}{3}} C_3\right\}.\qquad(25)$$

EXPERIMENTAL VALIDATION OF THEORY

To determine the function C_3 and the values of k_0 and k_1, root slices of length $l = 100$ mm were run in the peeling machine developed by Adetan (2002) at 7 different levels of linear velocity of the root-conveying belt (V), 4 levels of spring load (which is a measure of F_p), 5 levels of height of knife bed above conveyor belt (h), and an angle of inclination of knife bed to belt surface, α equal to 5.3°. In all, there were 140 data points. The data taken included mass measurements (for the calculation of C) and root diameter measurements (for the calculation of d_a, α_r and w).

The average of the values of peel removal efficiency at each level of the linear velocity of belt was calculated from the experimental data. Table 1 shows the resulting values for all levels of velocity. A regression analysis of the values of C_3 on the values of V gave the best fitting relationship as a linear one of the form:

$$C_3 = 0.8 - 0.12\ V.\qquad(26)$$

There is a high negative correlation of 96.33% (coefficient of determination, 92.79%) between C_3 and V implying that 92.79% of the variation of C with V is explained by the linear model of Eq. (26) and that the higher V is, the lower is the peel removal efficiency, C. A test of the significance of correlation confirms that there exists a linear relationship between C and V at 0.01 significance level.

The values of k_0 and k_1 were determined from the experimental data by linear regression analysis. The value of E was computed for each data point using Eq. (25). The data points were then arranged in ascending order of the value of measured C and divided into seven groups according to these values of C. The averages of C and E for each group were computed.

A regression analysis gives the relationship between C and E as:

$$C = -0.5122 + 109.32\ E.\qquad(27)$$

The correlation coefficient between C and E is 0.9770 while the coefficient of determination is 0.9546. A test of the significance of correlation confirms that there exists a linear relationship between C and E at 0.01 significance level. Thus, Eq. (27) is about 95.46% accurate in predicting C. Substituting Eq. (26) into Eq. (25), we obtain:

$$E = \left\{\frac{\ln l_1}{l d_a}\left[F_p d_a\right]^{\frac{1}{3}} (0.8 - 0.12\ V)\right\}.\qquad(28)$$

T a b l e 1. Variation of peel removal efficiency (C_3) with velocity (V) of conveyance of roots

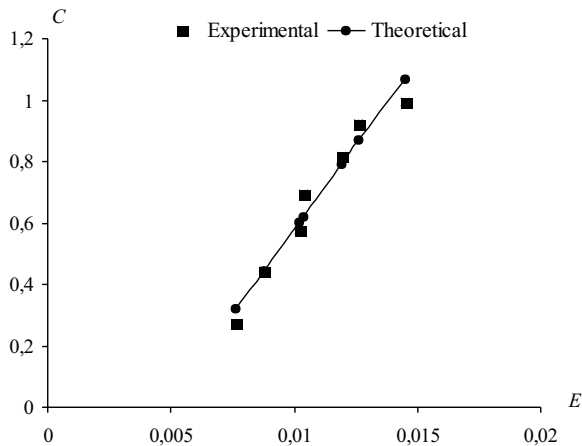| V (m s^{-1})	0.20	0.39	0.98	1.31	1.63	1.96	2.29
C_3	0.758	0.738	0.693	0.686	0.582	0.527	0.524

Fig. 9. Graph of peel removal efficiency (*C*) against the lumped modelling parameter (*E*).

Substituting Eq. (28) into Eq. (27), we have:

$$C = -0.5122 + 109.32 \left\{ \frac{\ln l_1}{l d_a} \left[F_p d_a \right]^{\frac{1}{3}} (0.8 - 0.12\,\mathrm{V}) \right\}, \quad (29)$$

where: l_1 is determined using Eq. (19).
Using Eq. (27), theoretical values of *C* corresponding to the values of *E* were computed. For the purpose of easy comparison, graphical plots of the experimental and theoretical values of *C* against *E* are shown in Fig. 9. These plots further illustrate the accuracy of the model represented by Eq. (29) in predicting the value of *C* given values for *l*, d_a, F_p and *V*.

Thus, Eqs (29) and (19) adequately model the theory of mechanical cassava peeling by the principle of peel-flesh separation through compression and peel removal with knives described in this paper with 95.46% accuracy.

REASUMPTION

This paper explains the theory of a new cassava peeling concept. It also models it mathematically using intuition and Hertz theory. This concept works by compressing the roots to separate the peel from the flesh and cutting into the peel and unwrapping it to remove the peel from the root tuber. The outstanding merit of the concept is that, using it, good peeling is achieved with virtually no loss of useful tuber flesh. A mechanical cassava peeling machine developed on the basis of this new concept was run at various combinations of the process and material parameters. The resulting data were used to validate the model.

CONCLUSIONS

1. The mathematical model developed is about 95.46% accurate in predicting the peel removal efficiency of a machine developed on the basis of the concept investigated in this work. It is, therefore, a sound scientific basis for carrying out further investigation into the new peeling concept with a view to developing a machine having a peel removal efficiency as high as 100% *ie C* = 1.

2. For a machine developed on the basis of the peeling concept investigated in this work, the efficiency of peel removal is inversely proportional to the speed of conveyance of roots through the peeling zone.

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