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Influence of the moisture content and speed on the cutting force and energy of tannia cormels

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Abstract: This study investigated the influence of the moisture content and speed on the cutting force and energy of tannia cormels using the response surface methodology (RSM). The moisture content and cutting speed were varied over five levels each [95.79, 113.68, 136.68, 168.42, 242.11% moisture content (dry basis) and 10, 15, 20, 25, 30 mm·min^{-1}, respectively]. The highest and lowest cutting forces were 114.09 and 63.99 N at the corresponding moisture contents of 168.42 and 113.68% and at cutting speeds of 10 and 20 mm·min^{-1}, respectively. The highest and lowest cutting energies of 0.92 and 0.49 J were both obtained at a 136.68% moisture content, at the 10 and 20 mm·min^{-1} cutting speeds, respectively. The regression models for predicting the cutting force and energy as a function of the cutting speed and moisture content showed that there was no linear relationship between the investigated properties and the independent variables considered which could be attributed to the non-homogeneous nature of tannia cormels. The optimum cutting force and energy were 72.89 N and 0.60 J, respectively, at a 95.79% moisture content and a 22.33 mm·min^{-1} speed with a desirability of 0.80. These findings could serve as a guide for the development of chipping and cutting machines for tannia cormels.

Keywords: cocoyam; cutting resistance; cutting speed; moisture-dependence; regression models

Tannia [(*Xanthosoma sagittifolium* (L.) Schott)] is an important member of root and tuber crops, which is cultivated for its corms and cormels. It serves as a major source of dietary carbohydrates to a large populace in Nigeria and other developing nations (Owusu-Darko et al. 2014). It also contains protein, vitamin A and C, calcium, phosphorus, iron, niacin, and thiamine in varying proportions. A tannia cormel has a nutritional value which is comparable to other important root and tuber crops although it is easier to digest than the others (Sefa-Dedeh and Sackey 2002; Owusu-Darko et al. 2014).

Tannia cormels have a wide range of uses from immediate consumption as food and feed products after a minimal amount of processing to usage as a raw or semi-processed material for industrial applications. It can be eaten boiled, fried, roasted or made into pudding or pounded into fufu and eaten with soup (Foodinfo 2020). It can also be used as a thickener in soup or sauce preparation (Falade and Okafor 2014).

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Harvested tannia cormels are highly susceptible to bio-deterioration within a few days; hence, the immediate processing of the cormels into some end-products such as chips, flakes and flour, with better storage stability and improved shelf life is a necessary and viable option (Iwuoha and Kalu 1995; Raji and Oyefeso 2017). The cormel undergoes various unit operations during its processing such as peeling, washing, size reduction (cutting/slicing), blanching, boiling, fermentation, frying, drying, packaging, etc (Adeyanju et al. 2019).

Whole tannia cormels can be too large to handle during processing and they are often reduced into smaller sizes for easier handling and better workability (Asonye et al. 2019). Size reduction is, therefore, an important unit operation in tannia processing and it can be achieved by various methods such as compression, impact, shearing and cutting.

Cutting involves the process of pushing or forcing a thin, sharp knife into the cormels to reduce their size, thereby creating new surfaces with open pores which are better suited for further processing such as leaching, blanching, drying and frying. The cutting of a tannia cormel as a size reduction procedure is energy-intensive and time consuming (Asonye et al. 2019). Knowledge of the cutting resistance of the cormels (in terms of the amount of force and energy required) is important for optimisation of the cutting process and for the proper development of equipment for cutting the cormels. The elastic properties of the tannia cormel, as affected by the moisture level and orientation of the force application under compressive loading, was investigated by Raji and Oyefeso (2017), while a mathematical model for estimating the energy required for cutting taro cormels was developed by Asonye et al. (2019). There appears to be a scarcity of information on the cutting force and energy of tannia cormels, which will be useful in the design and development of size reduction equipment, such as chipping and cutting machines for the cormels. This study, therefore, investigated the influence of the moisture content level and speed on the cutting force and energy of tannia cormels using the response surface methodology of Historical Data Design (HDD) (version 10.0.1).

MATERIAL AND METHODS

Sample procurement and preparation. The pink-fleshed tannia (*X. sagittifolium*) cormels used for the study were purchased from Towobowo market, Igboora, Oyo State, Nigeria. The bulk quantity of the freshly harvested tannia cormels were cleaned by washing with water to remove any sand particles and dirt and then allowed to drain. The cormels were peeled manually using a sharp stainless-steel knife and prepared for use in carrying out the experiments.

Moisture content determination. The moisture content of the cormel was determined with the aid of the hot air oven method according to the ASABE (2008a). This involved drying thin slices of tannia cormels of a known initial weight at 105 °C until constant weights were obtained for three consecutive measurements. The moisture contents of the cormels were also adjusted by pre-drying known weights of the cormel at 60 °C for 15, 30 45 and 60 min, respectively. The mass of the moisture removed from the cormel was obtained by subtracting the final weight of the dry cormel from the initial weight of the fresh sample before drying. The moisture content of the cormels was calculated according to Equation (1) (Raji and Oyefeso 2017).

$$MC_{\mathrm{db}} = \frac{M_{\mathrm{w}}}{M_{\mathrm{dp}}} \times 100 \tag{1}$$

where: MC_{db} – moisture content of the cormel (%, dry basis); M_{w} – mass of the moisture removed from the cormel (kg); M_{dp} – mass of the dry matter in the cormel (kg).

Cutting experiments. The cutting resistance was experimentally obtained in terms of the cutting force and energy of the cormels at five moisture content levels using a universal testing machine (UTM) (Testometric M500 – 100AT, Testometric Co. Ltd, UK) with a digital data logging system. Cylindrical-shaped samples (28 mm height, 22 mm diameter) were taken with a borer for examining the properties of interest (Raji and Oyefeso 2017). All the linear dimensions were measured with the aid of digital vernier callipers (0–150 mm range, reading to 0.01 mm; Carrera Precision, UK). The samples at different moisture content levels were then subjected to cutting tests on the UTM at five speed levels (10, 15, 20, 25 and 30 mm·min^{-1}) according to the ASABE (2008b). The speed levels were pre-set on the UTM controls before the commencement of all the experiments which were undertaken in three replicates. Force-deformation curves were obtained from the cutting experiments and the experimental set-up is as shown in Figure 1.

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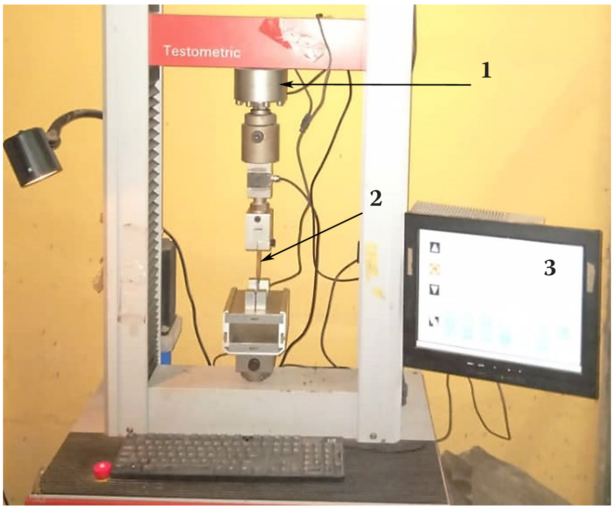

Figure 1. Experimental set-up for the cutting experiments
1 – kN load cell; 2 – cutting blade; 3 – visual display unit

Optimisation, modelling and data analysis. The historical data package of the RSM was adopted for the data analysis, modelling and optimisation using Design Expert Software (version 10.0.1). The moisture content and speed levels were considered as the independent variables while the responses (dependent variables) were the cutting force and cutting energy. The factorial experiment, which simultaneously tested the effects between and within the parameters, was also used and all the experiments were carried out in triplicate. The means of the obtained data were recorded and subjected to a statistical analysis. Mathematical models were developed to predict the relationship between the independent and dependent variables by applying multiple linear regressions at a 95% level of confidence.

Six different models (mean, linear, two factorial interactions, quadratic, cubic and quartic models) were tested and the goodness of fit of the models was assessed with their coefficients of determination (R^2) and probability of the prediction F-ratio test (Ogunlade and Aremu 2019). Due to regression coefficient, a 2[nd] order polynomial equation was adopted in estimating the cutting force and energy of the tannia cormels as affected by the moisture content and speed levels. The suitability of the models was determined on the basis of a highest order polynomial, where the additional terms are significant and the model is not aliased with an insignificant lack of fit and the maximisation of the "adjusted R^2 value" and the "predicted R^2 value" (Ogunlade and Aremu 2020). The general predictive expression from which a specific solution is obtainable is presented in Equation (2).

$$R = \beta_o + \sum_{i=1}^{k} \beta_i X_i + \sum_{i} < \sum_{j=3}^{k} \beta_{ij} X_i X_j X_k + \\ + \sum_{i=1} \sum_{j=1}^{k} \delta_{ij} X_i X_j X_k + \varepsilon \qquad (2)$$

where: R – the individual dependent parameters (cutting force and energy); $ß_0$ – the intercept of the model;

$\sum_{i=1}^{k} \beta_i X_i$ – the main linear effects of the individual process conditions (moisture content and speed);

$\sum_{i} < \sum_{j=2}^{k} \beta_{ij} X_i X_j$ the relationship between the variables

$\sum_{i=1} \sum_{j=1}^{k} \delta_{ij} X_i X_j$ – shows the main quadratic influences of the variables;

ε – random error of experimentation; X_i, X_j, X_k – the matrix of the uncoded process variables.

The unknown coefficients β_0, β_i, β_{ij} and δ_{ij} were obtained through regression analysis using empirical data from the experiments. The unknown coefficients of Equation (2) were determined by applying a design matrix formulated by transformation of the actual values of the processing variables at various levels over which the experiments were executed.

RESULTS AND DISCUSSION

Effects of moisture content and speed on the cutting force of tannia cormels. The cutting force of tannia cormels was significantly influenced by the moisture content and cutting speed. The initial average moisture content on the dry basis (db) of the fresh tannia cormel was obtained to be 242.11% while the adjusted moisture contents of the samples were 95.79, 113.68, 136.68 and 168.42% for 60, 45, 30 and 15 minutes pre-drying times, respectively, as shown in Table 1. The highest and lowest cutting forces obtained were 114.09 and 63.99 N at the corresponding moisture content (db) of 168.42 and 113.68% and at cutting speed of 10 and 20 mm·min^{-1}, respectively. The cutting force followed an increasing trend with the moisture content while it decreased with an increase in the cutting speed as shown in Figure 2. The increase in the cutting force with the moisture content could be due to the structural arrangement and orientation of the tannia cormels. However, the cutting force decreased with an increase in the cutting speed due to the greater impact being exerted which enhanced the cutting edge to overcome its

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Table 1. Cutting force and energy of the tannia cormels

Runs	Independent variables		Responses	
	moisture content (% db)	speed (mm·min^{-1})	cutting force (N)	cutting energy (J)
1	95.79	10	86.51	0.62
2	95.79	15	86.71	0.62
3	95.79	20	71.94	0.69
4	95.79	25	77.19	0.58
5	95.79	30	95.51	0.63
6	113.68	10	92.00	0.68
7	113.68	15	88.42	0.91
8	113.68	20	63.99	0.49
9	113.68	25	71.63	0.53
10	113.68	30	83.56	0.64
11	136.68	10	98.71	0.92
12	136.68	15	70.92	0.49
13	136.68	20	85.85	0.67
14	136.68	25	67.37	0.58
15	136.68	30	87.16	0.75
16	168.42	10	114.09	0.81
17	168.42	15	86.31	0.78
18	168.42	20	77.14	0.65
19	168.42	25	78.01	0.62
20	168.42	30	87.56	0.62
21	242.11	10	96.13	0.7
22	242.11	15	76.39	0.56
23	242.11	20	87.95	0.87
24	242.11	25	77.63	0.63
25	242.11	30	79.49	0.64

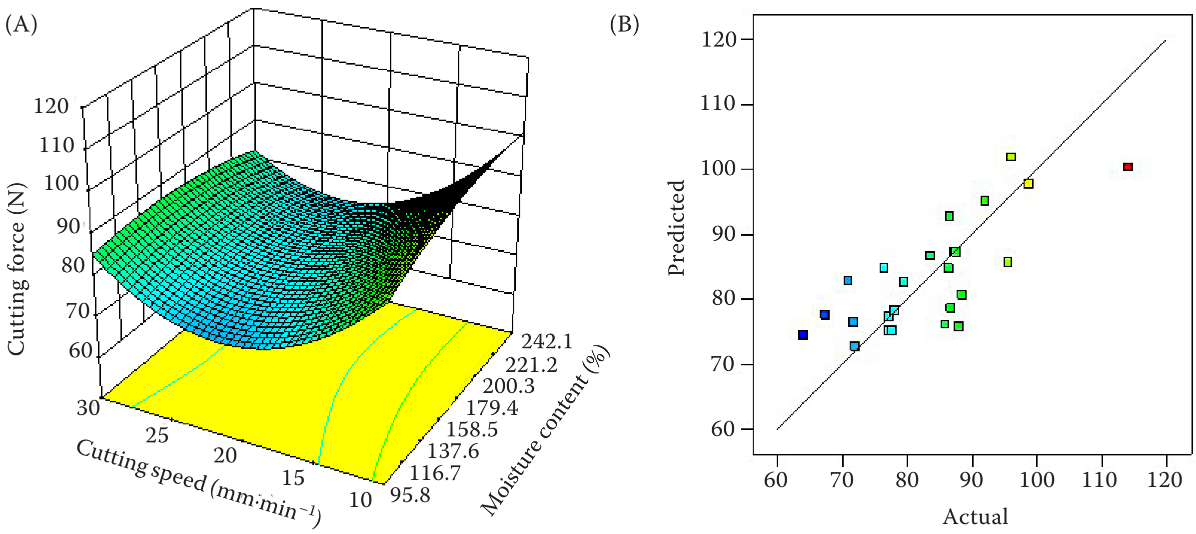

Figure 2. (A) Cutting force of the tannia cormels as influenced by the moisture content and cutting speed and (B) the predicted vs actual cutting force at the specified moisture content and speed

resistance and rupture the material with a lower force. The relationship that exists between the cutting force and the moisture content with the cutting speed was quadratic.

It was observed that the relationships between the cutting force and the speed levels were sinusoidal in nature as the amount of force required to cut the cormels at a given moisture content had several

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interplays of increasing and decreasing trends. For instance, the cutting forces for the fresh cormels at a 242.11% moisture content was found to be 96.13 ± 18.98 N at a 10 mm·min^{-1} cutting speed after which it decreased to 76.39 ± 10.45 N at a 15 mm·min^{-1} speed, followed by an increase to 87.95 ± 11.95 N at a 20 mm·min^{-1} speed. The cutting speed afterwards decreased to 77.63 ± 15.86 N at a 25 mm·min^{-1} speed and a subsequent increase to 79.49 ± 6.90 N at a 30 mm·min^{-1} speed was obtained.

Modelling and optimisation of the cutting force. The optimum value obtained for the cutting force was found to be 72.89 N at the corresponding moisture content and cutting speed levels of 95.79% and 22.33 mm·min^{-1}, respectively, with a desirability of 0.80. The desirability value indicates the nearness of the experimental data to the predicted values as well as the adequacy of the model established in estimating the experimental data (Fadele and Aremu 2018). The quadratic model predicting the relationship between the moisture content, speed and cutting force of tannia cormels is presented in Equation (3). The values obtained are in tandem with Adetan et al. (2003) who reported the cutting force of the cassava root to be within the range of 0.54 to 2.30 N·mm^{-1} based on its thickness and Ramachandran and Asokan (2020) who reported a minimum cutting force of 16.14 N at 1.0 m·s^{-1} for cutting a 3 to 4.5 mm stem diameter of a Bengal gram crop with a 14.08 to 15.1% moisture content of the stem and a maximum cutting force of 39.83 N at 0.25 m·s^{-1} for cutting more than a 6 mm diameter with a 20.2 to 20.45% moisture content of the stem. Similarly, Yisa et al. (2017) also reported a cutting force of 68.99 N for the cassava root.

The regression model relating the cutting force to the moisture content and cutting speed is presented in Equation (3) while the results of ANOVA showing its statistical significance at a 95% confidence level ($P < 0.05$) is presented in Table 2. It was observed that the regression models for the optimisation of the cutting force was found to have an F-value of 5.36 which implied that the model is significant. The probability that an F-value as large as this could occur due to error is only 0.31%. This showed that at least one of the independent variables (moisture content and cutting speed) contributed to the response observed in the force applied in cutting the cormels.

The cutting force was significantly influenced by the cutting speed as shown in Table 2. This showed that the effect of the variation in the independent parameters on the cutting force was not by chance. The regression model established for the relationship between the cutting force and the moisture content with the cutting speed is presented in Equation (3). The R^2 value obtained was 0.60. This showed that the variation in the moisture content and cutting speed accounted for 60% of the total variability in the cutting force of the tannia cormels.

$$Cf = 122.1954 + 0.2969a - 6.5111b - 0.00418a \times b - \\ - 0.0005699a^2 + 0.16407b^2 \quad (3)$$

SD = 8; R^2 = 0.60; mean = 83.53

where: Cf – the cutting force (N); a – the moisture content (% db); b – the cutting speed (mm·min^{-1}).

Effects of moisture content and cutting speed on the cutting energy of tannia cormels. The cutting energy of tannia cormels was not significantly affected by the moisture content and cutting speed. The highest and lowest cutting energies (0.92 and

Table 2. ANOVA of the cutting force of the tannia cormels: Response surface methodology: Quadratic model

	Partial sum of squares – Type III				
Source	Sum of Squares	*df*	mean square	*F*-value	*P*-value*
Model	1 717.93	5	343.59	5.36	0.0031**
a	60.39	1	60.39	0.94	0.3437
b	347.87	1	347.87	5.43	0.031**
ab	57.88	1	57.88	0.9	0.3537
a^2	38.39	1	38.39	0.6	0.4483
b^2	1 177.68	1	1 177.68	18.39	0.0004**
Residual	1 216.92	19	64.05		
Cor. total	2 934.85	24			

*Probability > F-value; **significant; *df* – degree of freedom; *a* – moisture content; *b* – speed; Cor – corrected total of the SS

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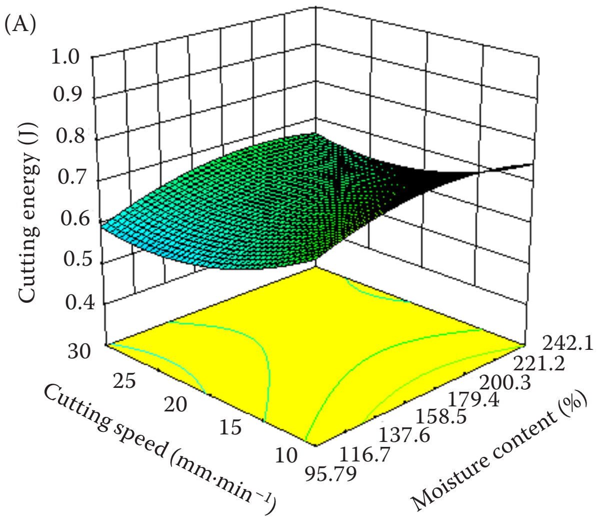
0.49 J, respectively) were both obtained at a 136.68% moisture content (db), at the cutting speeds of 10 and 20 mm·min^{-1}, respectively. The cutting energy followed an increasing trend with the moisture content while it decreased with an increase in the cutting speed as shown in Figure 3. The increase in the cutting energy with the moisture content could be due to the increase in the toughness of the cormel as the moisture content increased. However, the cutting energy tends to decrease with an increase in the cutting speed due to the greater impact being exerted which enhances the cutting edge to overcome its resistance and to rupture the material with a smaller amount of energy. This is in agreement with the findings of Azadbakht et al. (2015) and Nascimento et al. (2017). The relationship that exists between the cutting energy and the moisture content with the cutting speed was quadratic (polynomial of degree 2).



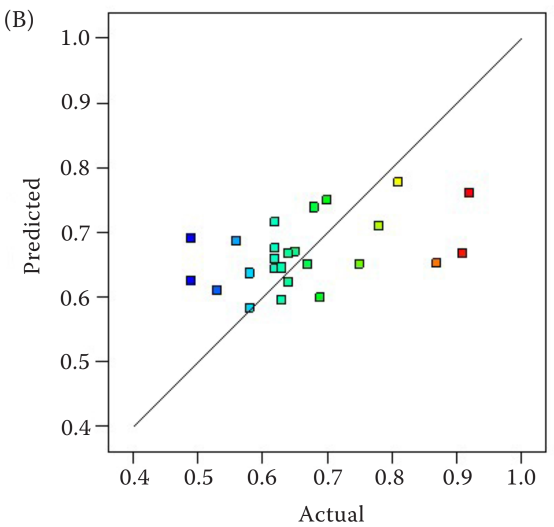


Figure 3. (A) Cutting energy as affected by the moisture content and cutting speed and (B) the predicted *vs* actual cutting energy at the specified moisture content and speed

Table 3 shows the analysis of variance of the cutting energy. It was observed that the regression models for the optimisation of the cutting energy have an *F*-value of 0.93 which implied that the model is not significant. There is only a 48.6% chance that the low value obtained for the *F*-value this large could be due to the anisotropic and irregularity nature of tannia cormels. The model developed was not significant, as indicated by the *F*-value. This showed that none of the independent variables, such as the moisture content and cutting speed, contributed to the response observed in the cutting energy applied in cutting the cormels. Equation (4) presents the regression model for the relationship between the cutting energy and moisture content with the cutting speed. The R^2 obtained was 0.20. This showed that the variation in the moisture content and cutting speed accounted for 20% of the total variability in the cutting force of the tannia cormels.

$$Ce = 0.7393 + 0.002925a - 0.02958b + 0.00001258a \times b - 0.00000834a^2 + 0.00056b^2 \quad (4)$$

SD = 0.12; R^2 = 0.20; mean = 0.67

where: *Ce* – the cutting force (N).

Modelling and optimisation of the cutting energy. The optimum value obtained for the cutting energy was found to be 0.60 J at the corresponding moisture content and cutting speed values of 95.79% and 22.33 mm·min^{-1}, respectively, with a desirability of 0.80, which indicates the nearness of the experimental data to the predicted values. The equation representing the relationship between the cutting energy, moisture content and speed is not significant (with a *P* value of 0.4859) as presented in Table 3, while the coefficients determined from the regression analysis for both the cutting force and energy of the tannia cormels are presented in Table 4.

CONCLUSION

This study investigated the influence of the moisture content and speed on the cutting force and energy of tannia cormels. The relationships between the dependent variables (cutting force and energy) and the independent variables (moisture content and speed levels) were non-linear. There were several interplays of increasing and decreasing

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Table 2. ANOVA of the of the cutting energy of the tannia cormels: Response surface methodology: Quadratic model

Partial sum of squares – Type III					
Source	Sum of Squares	*df*	mean square	*F*-value	*P*-value*
Model	0.064	5	0.013	0.93	0.4859
a	0.015	1	0.015	1.07	0.3139
b	0.035	1	0.035	2.54	0.1277
ab	5.24E-04	1	5.24E-04	0.038	0.8479
a^2	8.22E-03	1	8.22E-03	0.59	0.4506
b^2	0.014	1	0.014	0.99	0.3323
Residual	0.26	19	0.014		
Cor total	0.33	24			

*Probability > *F*-value, values are not significant; *df* – degree of freedom; *a* – moisture content; *b* – speed

Table 4. Coefficients of the cutting force and energy

Response	Intercept	*a*	*b*	*ab*	a^2	b^2
Cutting force (N)	76.3533	1.4387	–2.6898	–0.5720	–0.4269	4.1017
P-value		0.3437	0.0310	0.3537	0.4483	0.0004
Cutting energy (J)	0.6537	0.0226	–0.0270	0.0017	–0.0062	0.0140
P-value		0.3139	0.1277	0.8479	0.4506	0.3323

a – the moisture content (% db); *b* – the speed (mm·min^{-1}); *ab* – the interaction between moisture content and speed

trends within the range of speed levels and moisture contents investigated. The regression models predicting the cutting force and energy of tannia cormels as a function of the cutting speed and moisture content showed a good representation. The data will be useful in predicting the amount of energy required for the size reduction of tannia cormels under specified conditions and also serve as a good guide in the design of the size reduction for the equipment for the cormels.

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