Models of mechanical cutting parameters in terms of moisture content and cross section area of sugarcane stalks

Javad Taghinezhad, Reza Alimardani*, Ali Jafari

(*Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering and Technology University of Tehran, P.O. Box 4111, Karaj 31587-77871, Iran*)

Abstract: The objective of this study was to find optimizing moisture content and cutting area of sugarcane stalk cutting parameters using multiple regressions and to verify the optimum levels of the variables. The effect of moisture content and cutting section area on mechanical cutting properties of sugarcane stalks was studied using a linear blade cutting and UTM (Universal Testing Machine) size reduction device. Data obtained in the laboratory were divided into four different groups in order to determine the peak force, cutting energy, ultimate stress and specific energy. Additional criterions were also proposed and used as an indicator of the cutting performance. These were the marginal cutting parameter (MCP) and return to scale (RTS). The data obtained in the laboratory were then used to develop functions in polynomial form that allowed the calculation of the optimum level of each independent variable considered in the study. Moisture content had the highest effect on peak force, ultimate stress and specific energy with an impact of -15.936, -0.147 and -0.179, respectively. Also cutting energy affected with cutting section area with a 36.06 coefficient. The high moisture content level compared to low moisture content level produced a significant reduction in the peak force, ultimate stress and specific energy. Cutting parameters were relatively insensitive to moisture content of sugarcane stalk more than cutting section area of that.

Keywords: mechanical cutting, moisture content, sugarcane stalk, cutting energy

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1 Introduction

Biomass is a renewable feedstock for conversion to products and/or industrial and domestic energy (Kitani, 2004). Size reduction of biomass is a pre-processing operation that increases bulk density, improves flow properties, generates new surface area (Drzymala, 1993), increases pore size, and increases rates of hydrolysis reactions (Schell and Harwood, 1994; Igathinathane et al, 2010). Typical size reduction machines for bio-mass are hammer-, knife-, and disk-mills, and various choppers, chippers, and shredders (Yu et al., 2003). Moisture content, bulk density, true density and particle size and shape of biomass were important for downstream processing for 62 kinds of biomass (Ebling and Jenkins, 1985). Lack of engineering/ scientific knowledge of biomass fiber grinding hinders the use of some feed stocks for biomass use. Appropriate size reduction processes reduce the volume of the biomass, and are a first step in densification (Yu et al., 2003). Any biomass utilization process requires the biomass in a freely flowable form, so that it can pass through various machinery and processes efficiently.

Sugarcane (*Saccharum officinarm L.*) is an important raw material for the sugar industries (Frank, 1984) and strategically conceived as biomass for bioenergy and bio-based industrial products. As a perennial crop, one planting of sugarcane will generally allow for three to six or more annual harvests before replanting is necessary.

Sugarcane is the feedstock used in the ethanol industry (Dias et al., 2012; Murali and Hari, 2011) and

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* **Corresponding author: R. Alimardani**, Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering and Technology University of Tehran, Iran, P.O. Box 4111, Karaj 31587-77871. Email: rmardani@ut.ac.ir.

has the potential as a renewable energy source (Santos et al., 2006) and the highest rate of energy per hectare (0.5–2 GJ/ha) (Chen and Chou, 1993) having rich typologies of high energetic content by-products (leaves and tops, bagasse, and molasses). Biomass of sugarcane is one of the main energy sources that modern technologies could widely develop (Bocci et al., 2009). Today, sugar is produced in 121 countries and global production exceeds 120 million tons per annum (Müller and Coetsee, 2008). Especially for under-developed countries, the sugarcane residue energy use is very important; since, as a rule, these countries suffer from lack of energy (Alonso-Pippo et al., 2009). In Iran, sugarcane is widely cultivated on an area of about 68,352 ha with an annual production of about 5,685,090 tons (FAO, 2010).

To develop appropriate equipment for cutting processes such as harvesting, mechanical oil extraction and proceeding of agricultural products, their physical and mechanical properties have to be known (Davies and El-Okene, 2009). Linear cutting of biomass is an alternative action that may be applied with or with-out impact. Biomass compression occurs before cutting (Chancellor, 1958), and is more pronounced in failure with-out impact. Cutting force of fibrous material is based on knife cutting speed, material, and knife geometry (Dowgiallo, 2005; Igathinathane et al., 2008; Womac et al., 2005). Researchers have studied the size reduction process of plant materials (Akritidis, 1974; Annoussamy et al., 2000; Burmistrova et al., 1963; Chattopadhyay and Pandey, 1999; Dowgiallo, 2005; McRandal and McNulty, 1980; O'Dogherty et al., 1995; Prince, 1961; Iwaasa et al., 1995; Kretschmann and Green, 1996) and reviewed (Miu et al., 2006; O'Dogherty, 1982; Yu et al., 2003). These studies showed that cutting energy is related to maximum cutting force, stem shear strength, stem diameter, dry matter density, and moisture content (Igathinathane et al., 2008).

In this research, we study the effect of moisture content and amount of cutting section area of sugarcane stalks on the cutting process. Therefore, the specific objective was to identify shearing characteristics of sugarcane stalks, such as peak force, peak energy, total energy, ultimate failure stress, and energy per unit area. This paper presents empirical equations relating clear sugarcane stalks properties to moisture content and cutting section are using the sugarcane stalks cutting property data developed in the first part of our research (Taghinezhad et al., 2013).

2 Materials and methods

2.1 Preparation of sugarcane stalks for tests

Sugarcane stalks have been obtained from Debel Khazaie institute in Khouzestan province, Ahvaz city. Stalks were manually cleaned, leaf blades and sheaths were removed prior to any treatment or measurement and 45 samples of sugarcane stalks of approximate length of 5 cm and different diameter were cut using a bandsaw with fine blade for tests. After preparation of samples, they were stored one month and the canes naturally dried and balanced in air conditions of about 25°C and relative humidity of about 55%, and no degradation was observed in samples. To achieve high moisture contents, calculated amount of water was added and mixed thoroughly (Balasubramanian et al., 2012), so the samples were put in saturated air in an isolated box at 30˚C for 24 h. To achieve the lower moisture content level, the oven method was used at 103˚C for providing low level of moisture content. Before each test, the required amount of the samples was allowed to warm up to room temperature (Izli et al., 2009).

2.2 Measurement of sample dimensions, weight and area

2.2.1 Diameter

A digital vernier caliper with ±0.01 mm accuracy and 15 cm potential of maximum reading was used for measuring the minor and major canes diameters. As the shape of canes was a tapered elliptical cylinder (Igathinathane et al., 2006) the cross section profile of the canes was an ellipse. The dimensions of the major (D_1- cross-sectional width) and minor (D_2 - cross-sectional thickness) axis of the elliptical cross section were measured before testing and the estimated values were recorded.

2.2.2 Weight

The weights of the blade and stalk samples were recorded using weight balance with an accuracy of ±0.01 g.

2.2.3 Area determining

From the major and minor diameter the cut sectional areas were determined according to the following geometric formulae:

$$A_p = \left(\frac{\pi}{4}\right) D_1 \times D_2 \tag{1}$$

where, A_p is the cut area created when the blade is perpendicular to the cane axis, mm^2, in other words across the sample; D_1 is the major-axis of the elliptical cross section of the cane, mm; D_2 is the minor-axis of the elliptical cross section of the cane, mm.

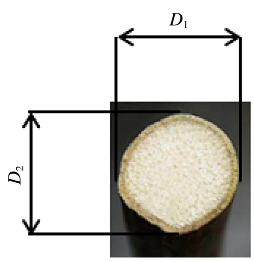

Figure 1 Stalk and its axis

2.3 Shearing device

The shearing device selected was originally used for cutting stalks of crops in a harvest machine that used in the commercial sugarcane choppers. The blade was sharpened and used as cutting tool in shearing device developed (Figure 2). The cutting edge was given a single slant angle of 30° that caused energy efficient cuts (Womac et al., 2005) and the notch angle was 60° (Figure 2). This design provides alignment of the fixture and allows rapid changes. The triangular notch of the blade self-centered the samples during cutting. The blade freely passed through the groove of the fixture that served as a platform to hold the sample (Figure 2).

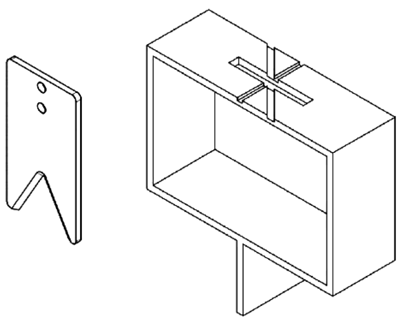

Figure 2 Cutting blades device and a view of fixture that used for fixing samples

A proprietary tension/compression testing machine (Instron Universal Testing Machine /SMT-5, SANTAM Company, Karaj, Iran, 2007) was used as the measurement platform (Figure 3) in combination with a modified shearing device. The cutting blade was fixed in a movable clamp and the fixture was fixed in a fixed clamp and the tests were performed.

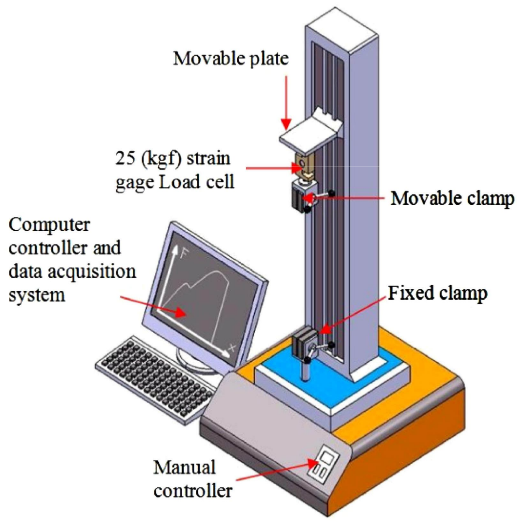

Figure 3 Instron Universal Testing Machine (Instron UTM/ SMT-5, SANTAM Company, Tehran, Iran)

2.3.1 Data collection and analysis

The Instron UTM plotted the force-displacement parallel to the cutting characteristics of the cane samples at different sizes and orientations. Regularly, the total cutting energy consumed was appraised from the original data stream of the force-displacement characteristics using the following expression (Igathinathane et al., 2010):

$$E_t = \left(\sum_{m=1}^{n}\frac{(y_{m+1}+y_m)}{2}(x_{m+1}-x_m)\right)_{samples} - \left(\sum_{m=1}^{n}\frac{(y_{m+1}+y_m)}{2}(x_{m+1}-x_m)\right)_{idle} \tag{2}$$

where, E_t is the total cutting energy, N·m; y_m is the force at any instant m, N; x_m is the deformation at any instant m , m; and n is the total number of observations of the force-displacement data.

As the cutting blade had enough clearance and moved without limits through the groove, the idle energy part of Equation (2) was neglected. Furthermore, the software prepared for UTM was scheduled in advance of outputting the peak load, peak energy, and total energy directly from the force-displacement characteristics. From these results, the ultimate cutting stress and specific energy were calculated from the cut sectional areas as (Tavakoli et al., 2009b):

$$\tau_u = \frac{F_{sp}}{A} \quad (3)$$

$$E_{ts} = \frac{E_t}{A} \quad (4)$$

where, τ_u is the ultimate cutting stress, Pa; F_{sp} is the peak cutting force, N; A is the cut sectional area (Equation (1), mm^3; E_{ts} is the total specific energy, N/m^1; and E_t is the total energy consumed in cutting the canes, N·m.

2.4 Experiments

For studying the effect of moisture content and cross section area on mechanical strength parameters 45 samples of sugarcane stalks with various thicknesses in three level of moisture content were classified and tested by Instron UTM with 10 mm/min loading rate. The UTM equipped with the shearing device that was originally used for cutting stalks of crops in a sugarcane harvester. The Cutting indices as peak force, total cutting energy, ultimate cutting stress and specific energy were calculated via previous researches (Tavakoli et al., 2009b; Taghinezhad et al., 2013). Table 1 indicated classification of moisture content and cross section area for sugarcane stalks samples.

Table 1 Moisture content and area classification in tests

	Level	Mean	Std
Moisture Content/%	Low	5.42	1.33
	Medium	31.62	14.43
	High	62.29	4.2
Area/mm^2	Small	118.89	34.56
	Medium	276.29	39.93
	Large	437.65	59.93

Each stalk was laid on its side and cutting was parallel to the major axis. After preparing of samples peak force and consumed energy for cutting of each sample was measured. Also, ultimate stress and specific energy were calculated. For weighting samples, a digital balance with ±0.01 g accuracy was used. Finally, the initial moisture content of the samples was determined by oven drying (Aghkhani et al., 2012; Altuntas and Yildiz, 2007), samples kept in oven at 103°C for 72 h to determine the absolute moisture content of samples in each level. Moisture content (M.C) was computed on dry basis by Equation (5):

$$M.C\% = \frac{w_w}{w_d} \times 100 = \frac{w_i - w_d}{w_d} \times 100 \quad (5)$$

where, w_i is the initial weight of sample, kg; w_w is the weight of sample water, kg and w_d is the weight of dried sample, kg.

Multiple regression technique was used for modeling cutting parameters at different moisture content and cross section area of sugarcane stalks. Also, marginal cutting parameters (MCP) technique based on response coefficient of cutting area and moisture content was utilized to analyze the sensitivity of variables on cutting parameters.

The MCP of the various variables was computed using the α_j of the various variables:

$$MCP_{xj} = \frac{change\ in\ cutting\ parameter}{change\ in\ variable} = \frac{GM(Y)}{GM(X_j)} \times \alpha_j \quad (6)$$

where, MCP_{xj} is marginal cutting parameter of jth variable; α_j is the regression coefficient of jth variable; $GM\ (Y)$ geometric mean of cutting parameter, and $GM\ (X_j)$ is geometric mean of jth variable.

The returns to scale (RTS) refer to changes in cutting parameter subsequent to a proportional change in all variables (where all variables increase by a constant factor). If the sum of the coefficients is greater than unity $\sum_{j=1}^{n} \alpha_j > 1$, it indicates increasing returns to scale (IRS). That means an increase in variables may result in an increase in cutting parameter in greater proportion than the variable increase.

If the function becomes less than unity $\sum_{j=1}^{n} \alpha_j < 1$, it indicates decreasing returns to scale (DRS). That means an increase in variables may result in an increase in cutting parameter in less proportion than the variable increase; and if the result is unity $\sum_{j=1}^{n} \alpha_j = 1$, it shows constant returns to scale, which implies that despite changing variables, the cutting parameter is constant.

The IBM SPSS Statistics V.20 software and Microsoft Excel 2010 were used to determine the effect of moisture content and area on various mechanical strength parameters involved in cutting the sugarcane stalks.

3 Results and discussion

3.1 Effect of stalks moisture content and cutting section area on mechanical cutting parameters

The high mean peak force (N) obtained at low moisture content of stalks are shown in Figure 4. The moisture content had a significant effect ($P<0.01$) on the peak force. The peak force decreased with an increase in the moisture content which may be due to the drier stalk being more firm because the ratio of material in area unit for dry stalks is higher than that of high moisture contents. However, the effect of cutting section area on peak force is not distinguishable as the values obtained at small and large areas are statistically the same at 95% level of confidence. There is no-significant difference between energy consumption for cutting and moisture content of stalks. The influence of energy is not statistically significant, although it reduces at low moisture contents. Similar results have been reported by many researchers such as Tavakoli et al. (2009a) and Igathinathane et al. (2009), etc. The mean ultimate stress and specific energy are affected by moisture content and cutting section area of stalks. The ultimate stress and specific energy are highest with low moisture content, and at small area of cutting section significantly.

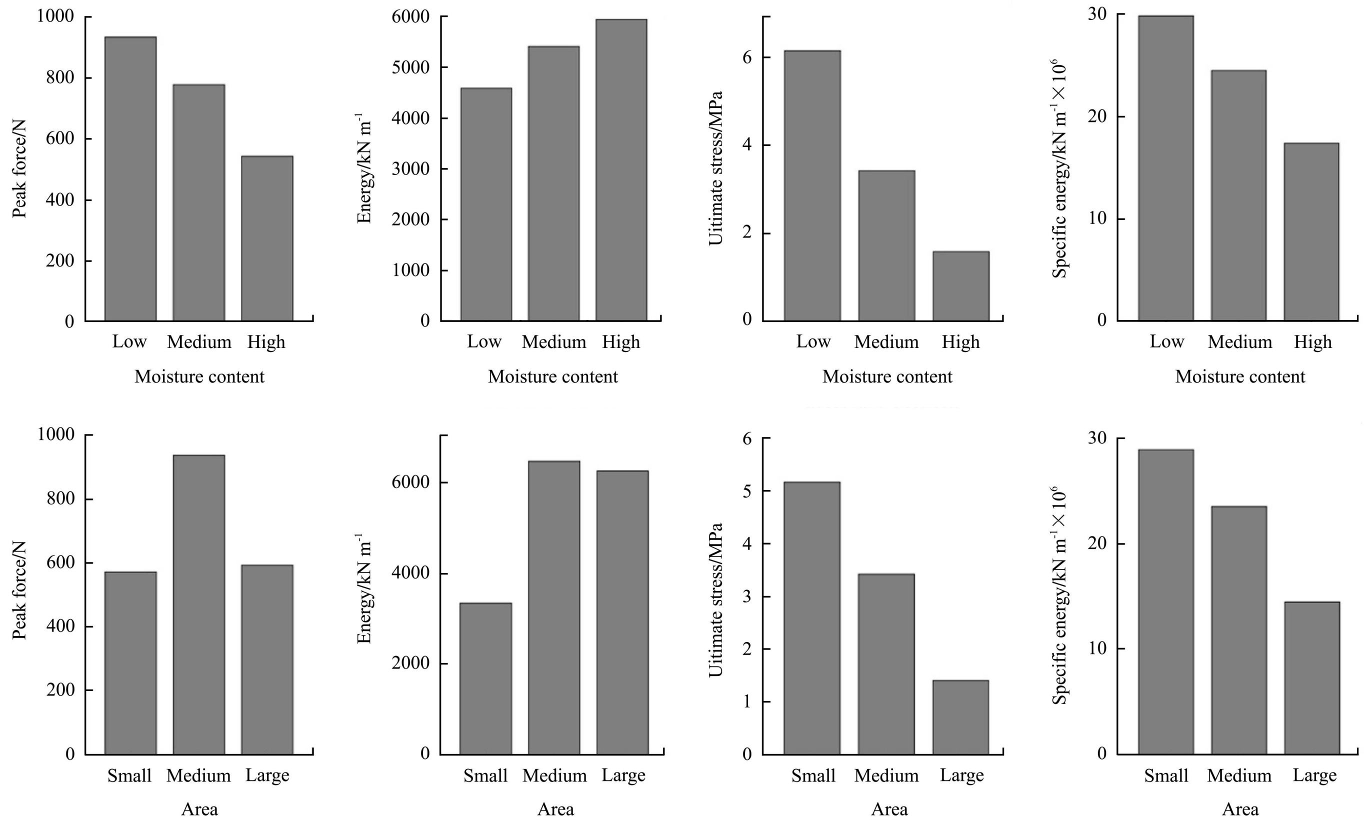

Figure 4 Comparison of different cutting parameters for moisture contents levels and cutting section area level

As can be seen from Figure 4 the cutting process at high moisture content and large cutting section area gives a satisfactory result in terms of ultimate stress and specific energy. This result could be explained as good selection of the ranges for the independent variables and their values. The following multiple regression functions were developed using three replications in each case for the peak force F_p, the cutting energy E_c, the ultimate stress S_u and the specific energy E_s models:

$$F_p = p_1 + p_2 A - p_3 M - p_4 A^2 + p_5 0.119 M^2 - p_6 A.M \tag{7}$$

where, p_1 = 110.903 N, p_2 = 7.188 N/m^2, p_3 = 15.936 N, p_4 = 6.52×10^{-3} N/m^4, p_5 = 0.119 N, p_6 = 0.032 N/m^2.

$$E_c = c_1 + c_2 A - c_3 M - c_4 A^2 + c_5 M^2 - c_6 A.M \tag{8}$$

where, c_1 = -71.394 kN·m, c_2 = 36.06 kN/m^3, c_3 = 11.438 kN·m, c_4 = 0.027 kN/m^4, c_5 = 0.282 kN·m, c_6 = 0.159 kN/m^3.

$$S_u = u_1 - u_2 A - u_3 M - u_4 A^2 - u_5 M^2 + u_6 A.M \tag{9}$$

where, u_1 = 7.452 MPa, u_2 = 8.4×10^2 N, u_3 = 0.147 MPa, u_4 = 17 N·m^2, u_5 = 5.53×10^{-4} MPa, u_6 = 1.67×10^2 N.

$$E_s=(s_1-s_2A-s_3M-s_4A^2+s_5M^2-s_6=3.3\times10^{-5}A.M)10^{-6} \quad (10)$$

where, s_1 = 34.417 kN/m^1, s_2 = 0.02 kN/m^3, s_3 = 0.179 kN/m, s_4 = 9.3×10^{-6} kN/m^5, s_5 = 8.57×10^{-4} kN/m, s_6 = 3.3×10^{-5} kN/m^3.

where, A is the area of the cutting section, m$^{2;}$ and M is the moisture content of stalks in the Equations (7)-(10), %. The results from multiple regression analysis for each function are given in Tables 2 to 5.

The coefficient of determination (R^2) values for F_p, E_c, S_u and E_s models were reported as 95%, 94%, 97% and 93%, respectively.

The models are valid for the following conditions where 546.96 mm^2 > A > 64.54mm^2 and 71.21% > M > 3.54%.

Regression results for peak force (F_p model) showed the significant impact of area, moisture content, area square (A^2) and multiple of area and moisture content ($A.M$) on peak force at probability level of 1% (Table 2). Also moisture content square (M^2) had significant impact at 5% probability level.

Table 2 Results from multiple regression analysis for the peak force model

Variable	Coefficient	Standard error	t-ratio	MCP
Constant	110.903	57.45	1.93^c	
A	7.188	0.557	12.896^a	2.38
M	-15.936	3.142	-5.072^a	-0.52
A^2	-6.52×10^{-3}	1.499×10^{-3}	-4.347^a	-0.476
M^2	0.119	0.047	2.555^b	0.085
$A.M$	-0.032	0.010	-3.194^a	-0.23
R^2	95			
RTS	-8.667			

Note: a. Indicates significance at 1% probability level.
b Indicates significance at 5% probability level.
c. Indicates significance at 10% probability level.

Among all variables, moisture content had the highest impact (-15.936) and followed by area (7.188) and square moisture (0.119). The regression results (model F_p) expressed with 10% increasing in moisture content peak force for cutting will decrease about 1.6 times approximately.

The results of MCP values indicated one unit increase in area and moisture content led to 2.38 N increases and 0.52 N decreases in the peak force of cutting sugarcane stalks, respectively.

The absolute value of return to scale index (RTS) for F_p model is upper than unit with minus sign which shows an increasing return to scale. It is concluded that a proportionate increase in all variables results in an upper than proportionate decrease in required peak force for cutting sugarcane stalks.

To realize the relationship between required energy for cutting sugarcane stalks in different moisture content and cutting section area, a regression analysis (E_c model) was performed (Table 3). It became evident that the impact of area (A), square area (A^2) and area cross moisture content ($A.M$) on cutting energy for sugarcane stalks was significant at 1% level with coefficient values of 36.06, -0.027 and 0.159, respectively.

The regression results (E_c model) expressed that there is a high influence of cutting section area significantly on cutting energy for example with 10% increase in area, energy for cutting will increase about 3.6 times approximately. The return to scale index (RTS) for cutting is greater than unit, which shows an increasing return to scale. It is concluded that a proportionate increase in all variables results in a greater than proportionate increase in required energy for cutting sugarcane stalks. The results of MCP values indicated one unit increase in area led to 1.584 (kN·m) increase in the cutting energy of sugarcane stalks.

Table 3 Results from the multiple regression analysis for the cutting energy model

Variable	Coefficient	Standard error	t-ratio	MCP
Constant	-71.394	299.831	-0.238^{ns}	
A	36.06	2.909	12.397^a	1.584
M	-11.438	16.399	-0.697^{ns}	-0.05
A^2	-0.027	0.008	-3.465^a	-0.261
M^2	0.282	0.244	1.158^{ns}	0.027
$A.M$	-0.159	0.052	-3.04^a	-1.611
R^2	94			
RTS	24.718			

Note: a. Indicates significance at 1% probability level.
ns Indicates no-significance level.

The regression coefficients of independent variables on ultimate stress were investigated (S_u model). As it can be seen in Table 4, the impact of moisture content and square moisture content was -0.147 and 5.53×10^{-4} at a probability level of 1%, respectively.

The MCP value of moisture content was -1.06. As the MPP values specified, more moisture content leads to more ultimate stress for cutting sugarcane stalks. The absolute return to scale index (RTS) for S_u model is less than unit, which shows a decreasing return to scale with minus sign. It is concluded that a proportionate increase in all variables results in a less than proportionate decrease in ultimate stress.

Table 4 Results from the multiple regression analysis for the ultimate stress model

Variable	Coefficient	Standard error	t-ratio	MCP
Constant	7.452	0.238318	31.27079^a	
A	-8.4×10^{-4}	2.312×10^{-3}	-0.36329^{ns}	-0.061
M	-0.147	0.013	-11.3062^a	-1.06
A^2	-1.7×10^{-5}	6.22×10^{-6}	-2.67528^b	-0.274
M^2	5.53×10^{-4}	1.94×10^{-4}	2.856524^a	0.087
$A.M$	1.67×10^{-4}	4.16×10^{-5}	4.011215^a	0.265
R^2	97			
RTS	-0.147			

Note: a. Indicates significance at 1% probability level.
b. Indicates significance at 5% probability level.
ns. Indicates no-significance level.

Table 5 presents a model for specific energy for cutting sugarcane stalks in different cutting section area and moisture content of stalks. As it can be seen from Table 5, regression coefficients of moisture content and area are significant at 1% and 10% probability level, respectively, and other variables had no-significant influence on model.

Table 5 Results from the multiple regression analysis for the specific energy model

Variable	Coefficient	Standard error	t-ratio	MCP
Constant	34.417	1.12	30.723^a	
A	-0.02	0.011	-1.851^c	-0.194
M	-0.179	0.061	-2.924^a	-0.171
A^2	-9.3×10^{-6}	2.92×10^{-5}	-0.32^{ns}	-0.02
M^2	8.57×10^{-4}	9.11×10^{-4}	0.941^{ns}	0.018
$A.M$	-3.3×10^{-5}	1.95×10^{-4}	-0.17^{ns}	-0.007
R^2	93			
RTS	-0.198			

Note: a. Indicates significance at 1% probability level.
b. Indicates significance at 5% probability level.
c. Indicates significance at 10% probability level.
ns. Indicates no-significance level.

The regression results (model E_s) expressed with 10% increasing in moisture content specific energy decreases by 1.79%. The results of MCP values indicated one unit increase in moisture content and area led to 1.71×10^5 and 1.94×10^5 (kN/m^1) decrease in the specific energy of cutting sugarcane stalks, respectively. The absolute return to scale index (RTS) for E_s model is less than unit, which shows a decreasing return to scale with minus sign. It is concluded that a proportionate increase in all variables results in a less than proportionate decrease in specific energy.

4 Conclusions

The effects of moisture content and cutting section area of sugarcane stalks on ultimate stresses and specific energies involved in the mechanical cutting of sugarcane stalks in linear cutting knife were determined. The multiple regression equation is a useful tool and provides a way for optimizing the performance of cutting parameters. The regression model applied to peak force (F_p), cutting energy (E_c), ultimate stress (S_u) and specific energy (E_s) and coefficient of determination (R^2) for models were 95%, 94%, 97% and 93%, respectively. Based on the present study, the following conclusion may be listed.

(1) The optimum level of moisture content is between 50%-75% for sugarcane samples used in experiments.

(2) The cutting section area of sugarcane stalks affects the cutting energy with 1.584 MCP also affects the peak force and specific energy after moisture content significantly.

(3) The value of return to scale index (RTS) indicated that a proportionate increase in all variables results in a more than proportionate decrease for peak force, a more than proportionate increase for cutting energy, a less than proportionate decrease for ultimate stress and a less than proportionate decrease for specific energy models.

(4) Therefore, cutting the high level of moisture content cane stalks in large size is better than cutting the low level of moisture content cane stalks in small size for reducing the consumed energy for mechanical cutting process.

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