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Effect of Sugarcane Stalks' Cutting Orientation on Required Energy for Biomass Products

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Abstract

The mechanical cutting properties of sugarcane stalks were studied using a linear blade cutting and size reduction device to determine of the effect of sample orientation with respect to the cutting element and quantify the possible cutting energy reduction. Also the effect of the dimensional parameters on mechanical cutting properties were studied on internodes and nodes for cutting force, energy, ultimate stress, and specific energy of sugarcane stalks. The device was used along with a universal test machine that quantified shearing stress and energy characteristics for applying force on sugarcane stalks through a blade device. Mean specific cutting energies of cane stalks at 0° ,45° and 90° orientation for internodes were 4.368, 6.978 and 10.021 kN/m and for nodes at 0° and 90° were 6.458 and 15.812 kN/m, respectively. Also other parameters of mechanical cutting such as ultimate stress, energy and peak force were presented and the results showed a significant difference between orientation, nodes and internode in mechanical cutting properties. The parallel orientation (along sample) compared to perpendicular (across sample) produced a significant reduction in the cutting stress and the specific energy by about one-fifth for internodes and nodes.

Keywords: Mechanical cutting, Biomass properties, Sugarcane stalk, Orientation, Cutting energy.

INTRODUCTION

A way to evaluate the development of a country is to check its energy consumption "per capita". There is a strong dependency between development and available energy [17]. There are more than 70 sugar-producer countries around the world. Especially for under-developed countries, the sugarcane residue energy use is very important; since, as a rule, these countries suffer from lack of energy [2].

Biomass, specifically in the raw form, has to pass over an early processing stage of size reduction before any downstream energy or changing procedure. In other words, any biomass utilization process requires the biomass in a freely flowable form, so that it can pass through various machinery and processes efficiently. It also needs increasing bulk density in general, and increasing new and reactive surfaces [9], [5], pore size, and hydrolysis reaction rates [18]. For example, some of the processes and their particle size necessity for corn stalks are: chemical conversion –1 mm [20], gasification – 6.4 mm [16], briquetting of corn stover – 5.6 mm [13] and simultaneous saccharification and fermentation to produce ethanol – 2 to 10 mm [14].

Shearing was shown to be an energy-efficient method of size reduction, and was achieved by devices that used knives, shear bars, and linear knife grids with ram [8], [9].

Perfect measurement of biomass cutting energy of plant stalks needs specialized fixtures or attachments or specially-designed knife fixtures [4], [6], [15]. These devices were either used with Universal Testing Machine (UTM) or transducers with dedicated data acquisition systems [11]. It is also common knowledge that it takes less energy to cut along the grain (ripping) than across the grain (cross cutting), even with tougher biomaterial such as wood. The difference in energy during size reduction presents opportunities to evolve new material feeding methods or develop new size reduction devices.

The objective of the research herein was to identify the effect of orientation of sugarcane stalks on the cutting process with respect to the knife cutting plane. Therefore, to determine the mechanical cutting strength properties of sugarcane stalks, peak force, peak energy, total energy, ultimate failure stress, and energy per unit area were measured. Results of this research will determine the variation in mechanical cutting strength properties and quantify the benefits of material (node and internode position) in cutting.

MATERIALS AND METHODS

Experimental Sugarcanes For Tests

Sugarcane stalks were harvested in October, 2011 from a field in Debel Khazaie, Ahvaz, Iran and were transferred to the Physical Properties of Materials Laboratory, Department of Agricultural Machinery Engineering, Faculty of Engineering and Technology, University of Tehran, Karaj, Iran. The stockpile sugarcane was stored (1 months) indoors until the experiments were carried out in a laboratory having air conditions of about 25° C and relative humidity of about 55%, where the canes naturally dried and balanced with the current ambient conditions. No degradation of the canes was observed after the field rise and the indoor storage, as the canes had maintained their structural integrity as was evident during material preparation cuts of the canes.

Preparation Of Test Material

The sugarcane samples were prepared by stripping off the leaves and husks. The moisture content of the prepared canes ranged from 15% to 20% w. b. [3]. Pieces of nodes and internodes of approximate length of 25 mm were cut using a bandsaw with a fine blade. To specify the effect of sugarcanes size on various mechanical properties of canes, three different cross-sectional sizes were sorted as small, medium, and large. Six repetitions on each size category both for internode and node for perpendicular oriented cuts (across the sample), and ten repetitions each for parallel (along the sample) and inclined (45°) oriented cuts were performed, respectively.

Measurement Of Sample Dimensions, Weight And Area

Length

A digital vernier caliper with ±0.01 mm accuracy and 15 cm potential of maximum reading was used for measuring the height of the canes and cuts.

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 [7], the cross section profile of the canes was an ellipse. The dimensions of the major (2a - cross-sectional width) and minor (2b - cross-sectional thickness) axes of the elliptical cross section were measured before testing and the estimated values were recorded.

Weight

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

Area Determining

From the major and minor diameter and the length samples, the cut sectional areas (90° and 45° - elliptical; or 0° - rectangular, through the cane axis) were determined according to the orientation of the canes with regard to the blade movement using the following geometric formulae:

$$A_p = \left(\frac{\pi}{4}\right) 2a \times 2b \tag{1}$$

$$A_{ste45} = \left(\frac{\pi}{4}\right) 1.414 \times \ 2a \times 2b \tag{2}$$

$$A_{pa} = l \times 2b \tag{3}$$

where: A_p is the cut area created when the blade is perpendicular to the cane axis (m^2), i.e. across the sample; 2a is the major-axis of the elliptical cross section of the cane (m); 2b is the minor-axis of the elliptical cross section of the cane (m); A_{ste45} is the cut area generated when the stalk axis is steeped at 45 to the blade (m^2); A_{pa} is the cut area created when the blade is parallel to the cane axis (m^2), i.e. along the sample; and l is the length of the sample piece (m).

The Shearing Device

The shearing device selected was originally used for cutting stalks of crops in a harvest machine. The blade was sharpened and used as cutting tool in shearing device developed (Fig. 1). The cutting edge was given a single slant angle of 30° that caused energy efficient cuts [21] and the notch angle was 60° (Fig. 1). 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 (Fig. 1). Also on top of the fixture three grooves were generated for simple control of the samples when cutting.

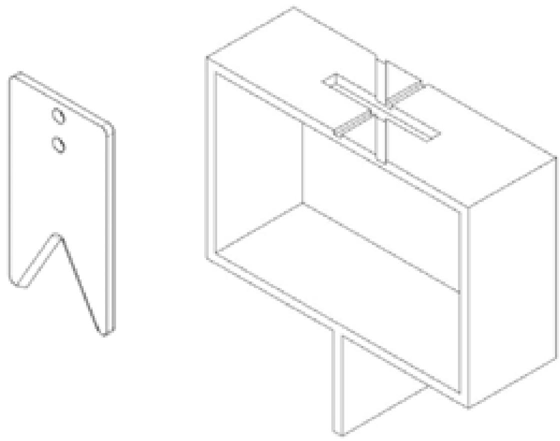

Fig.1. The cutting blades device and a view of fixture that used for fixing samples.

A proprietary tension/compression testing machine (Instron Universal Testing Machine /SMT-5, SANTAM Company, Karaj, Iran, 2007) was used as the measurement platform (Fig.2) in combination with a modified shearing device [12]. The cutting blade was fixed in a movable clamp and the fixture was fixed in a fixed clamp and the tests were performed.

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:

$$E_t = \left(\sum_{m=1}^{n} \frac{y_{m+1} + y_m}{2}\left(x_{m+1} - x_m\right)\right)_{samples} - \left(\sum_{m=1}^{n} \frac{y_{m+1} + y_m}{2}\left(x_{m+1} - x_m\right)\right)_{idle} \tag{4}$$

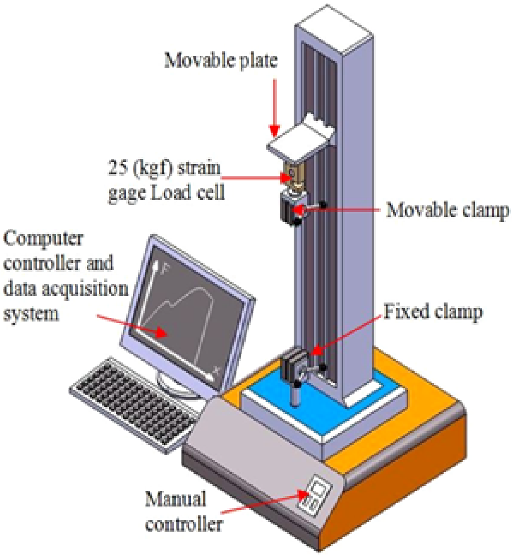

Fig.2. Instron Universal Testing Machine (Instron UTM/ SMT-5, SANTAM Company, Tehran, Iran)

where: E_t is the total cutting energy (Nm); y_m is the force at any moment m (N); x_m is the deformation at any moment 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 Eq. (4) was neglected. Furthermore, the software prepared for UTM was scheduled in advance of output 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:

$$\tau_u = \frac{F_{sp}}{A} \quad (5)$$

$$E_{ts} = \frac{E_t}{A} \quad (6)$$

where: τ_u is the ultimate cutting stress (Pa); F_{sp} is the peak cutting force (N); A is the cut sectional area based on the sample orientation (Eqs. (1) to (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).

The SPSS software [19] was used to determine the effect of size, sample material variation, and orientation on various mechanical strength parameters involved in cutting the cane samples.

RESULTS AND DISCUSSIONS

After accomplishing the cutting tests, the data were obtained for statistical analyses and force-deformation curves.

Mechanical Cutting Analysis With Respect To Dimensional Parameters

The mechanical cutting was evaluated as a function of sugarcane samples size. Various mechanical strength properties were compared statistically among different sizes and between internode and node (Table 1).

Table 1. Effect of size of the cane stalks on the mechanical cutting parameters while cutting perpendicular to the stalk axis.

Sample	Size	Dimension($\times10^{-3}$m)		Peak force (N)	Energy (kN m)	Ultimate stress (MPa)	Specific energy (kN m^{-1})
		$2r_1$	$2r_2$				
Internode	Small	17.15 ± 1.31 cA	17.64 ± 1.37cA	313.75 ± 63.49 cB	2.728 ± 0.824 cB	1.33 ± 0.297 bB	11.71 ± 4.537aB
	Medium	20.75 ± 0.97 bA	21.55 ± 1.27bA	425.03 ± 141.19 bB	4.126 ± 0.885 bB	1.21 ± 0.432 bB	11.82 ± 2.804aB
	Large	25.47 ± 2.27 aA	27.29 ± 2.67aA	529.74 ± 50.20 aB	4.990 ± 0.962 aB	0.98 ± 0.128 aB	9.107 ± 0.684aB
F values between sizes		0.000	0.000	0.011	0.018	0.732	0.996
Node	Small	17.23 ± 1.62 cA	17.88 ± 2.14 cA	350.30 ± 123.65 cA	3.187 ± 1.091 cA	1.41 ± 0.230 aA	12.82 ± 1.955 aA
	Medium	21.45 ± 1.06 bA	22.06 ± 1.44 bA	525.39 ± 55.68 bA	4.806 ± 0.664 bA	1.41 ± 0.098 aA	12.96 ± 1.601 aA
	Large	24.49 ± 1.37 aA	25.35 ± 1.48 aA	811.97 ± 147.53 aA	8.316 ± 2.472 aA	1.65 ± 0.153 aA	17.00 ± 4.315 aA
F values between sizes		0.000	0.001	0.001	0.007	0.081	0.141
F values between materials		0.544	0.706	0.014	0.023	0.006	0.012

In internodes, between the sample sizes, the means of dimensions ($2r_1$ and $2r_2$), peak force, and peak and total energy were significantly different (P < 0.05). These values increased from small to large sizes and according to ANOVA test, this difference is linear. The ultimate cutting stress and the specific energy were not significantly different. In nodes, between the canes sample sizes, the dimensional values, peak force and the energy differed, while stress mean groups showed some overlap as the nodes were more brittle than the internodes.

Between the internode and node materials, according to ANOVA test results between the same variables, diameter values of internodes and nodes were not significantly different. The peak force, cutting energy ultimate stress and specific energy parameters for nodes were usually larger than internodes and were significantly different (P<0.05). In overall, the results shown that for similar dimensional sizes, between internodes and nodes positions, , the mechanical cutting parameters were different (Table 1); this is perhaps due to the anatomical differences between nodes and internodes of sugarcane stalks. It has been expected with an increase in the moisture content, the mechanical cutting stress and energy parameters are increased [1], [4], [6], [9], [11]. Yu et al. (2006) [22] found that the ultimate tensile stress increased two-fold as the elapsed time after harvest increased, though they found that the ultimate shear stress was not affected by the moisture content.

Mechanical Strength Analysis With Respect To Orientation And Material Variation Of Sugarcane Stalks

In Table 2, the mechanical cutting was evaluated as a function of sugarcane samples orientation during the tests. The internodes tests on different orientations (0°, 45°, and 90°) of sugarcane stalks samples showed that the dimensional parameters are significantly similar in different orientation. Although, it can be revealed that peak force, energy, and ultimate stress and specific energy for mechanical cutting of samples vary significantly (P < 0.05) on overall basis (Table 2).

A tidy increment of force and energy was observed when the cutting orientation changed from parallel (0°) to perpendicular (90°), despite the fact that parallel orientation presented significantly larger new cut surface areas. Another reason for this increment was that only the available structural fibres on the cut surface area were split or ripped apart, whereas at other orientation angles (90° and 45°) the entire bundle of fibres of the stalk was cut to complete the cutting. However, the change in orientation from 0° to 90° progressively reduced the sectional area geometrically (elliptical-the least to rectangular-the most) and produced significant differences.

In nodes, two orientations (0° and 90°) dimensional parameters ($2r_1$ and $2r_2$) are significantly similar and the other parameters are significant different in mechanical cutting of samples (P < 0.05). Also, similar to the mechanical cutting parameters between groups in internode and node positions. lower values of force and energy were observed for cutting of samples in parallel (0°) orientation compared to perpendicular (90°) orientation.

With the internode and node materials, the dimensional parameters clearly did not show any significant difference with orientation. Among the various cutting energy parameters, only the ultimate stress at parallel orientation varied with the materials. However, in parallel orientation all the force, energy and specific energy parameters varied significantly between internodes and nodes. Also it can be indicated that values in node position are greater than those in internode position. The reason for the increased values with nodes can be imputed to the fact that the node section acted as a resistance to the possible easy formation of a failure plane on the otherwise uniform bundle of straight fibres of internodes [10]. Also it can be stated that the material of the nodes is densely compacted in the nodular disc and supports the leaves along the stalk, which is clearly different from the pith core of internodes.

Table 2. Effect of sugarcane stalk orientation on the mechanical cutting parameters.

Sample	Orientation	Dimension($\times 10^{-3}$m) $2r_1$	Dimension($\times 10^{-3}$m) $2r_2$	Peak force (N)	Energy (kN m)	Ultimate stress(MPa)	Specific energy (kN m^{-1})
Internode	0	20.12 ± 4.42 aA	21.20 ± 4.79 aA	164.65 ± 64.17 aA	2.904 ± 1.626 aA	0.260 ± 0.079 aA	4.386 ± 1.771 aA
	45	20.60 ± 3.26 a	21.24 ± 3.42 a	344.38 ± 144.90 b	3.500 ± 1.599 a	0.696 ± 0.267 b	6.978 ± 2.288 b
	90	21.22 ± 4.07 aA	22.15 ± 4.59 aA	413.79 ± 106.35 cA	3.711 ± 1.215 aA	1.156 ± 0.267 cA	10.021 ± 3.063 cA
F values between orientations		0.757	0.848	0.000	0.272	0.000	0.000
Node	0	21.47 ± 2.02 aA	22.86 ± 2.74 aA	239.29 ± 85.42 aB	4.712 ±1.642 aB	0.330 ± 0.132 aA	6.458 ± 2.290 aB
	90	21.11 ± 3.25 aA	21.86 ± 3.28 aA	598.83 ± 247.94 bB	5.938 ± 2.900 aB	1.602 ±0.350 bB	15.812 ± 5.178 bB
F values between orientations		0.691	0.325	0.000	0.126	0.000	0.000
F values between materials		0.873	0.786	0.015	0.037	0.001	0.011

Sugarcane Cutting Force-Deformation Characteristics

Representative force-deformation characteristics of prepared sugarcane stalks internodes and nodes at different orientations are presented in Fig. 3. Comprehensively, the force-deformation curves showed an initial extreme rise of cutting force, followed by an initial high peak, a quick drop, a second peak, and finally an insignificant force after the sample cutting. Due to the high moisture content of the material in tests, force-displacement curves indicated a wide base and peak.

The curves in Fig.3 indicate that in parallel cutting mode either in node or internode position, the regularity of peak forces is different from others. While in other orientation the first peak is high and the second peak is low, in parallel position, the second peak is high. This result was produced because in parallel orientation, first the two sides of the sample get involved with the cutting blade at cutting stage, while in other orientations, first the top of the blade gets involved with the cutting area. Besides, the compression in parallel position is lower than other orientations. Furthermore, after the blade pervaded the samples, the cutting continued, and after the first peak the force required for cutting decreased but when the top point of the blade got involved with the samples, the compression of sample increased and it caused the second peak be higher than the first peak. But clearly, the high peak force needed for cutting in parallel mode is lower than other orientations.

From the axis values, one can interpret that the peak force required for cutting the sugarcane stalks in the same orientation is higher for the nodes than the internodes. Igathinathane et al (2010) [10] studied corn stalks and reported that the force-displacement is divided into five perceptible regions: 1- Compression of stalks by the blade. 2- Initial cutting. 3- Progress of skin and pitch cutting. 4- Final cutting of skin 5- Completion of cutting and residual force (Fig. 4).

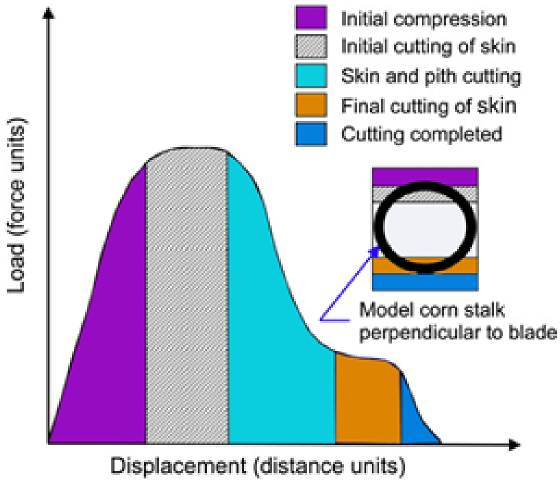

Fig.4. Distinct regions of the stalk cutting force-displacement characteristics

Final Comparison of The Mechanical Cutting Parameters on Sugarcane Stalks

A general comparison of significant mechanical cutting parameters was determined by taking perpendicular orientation as an index and calculating the ratios of other orientations, as well as between internode and node materials (Fig 5). For both internodes and nodes position ratios of peak load, ultimate failure stress, and specific energy reduced with reduction in angle of orientation significantly ($P < 0.05$). For both internodes and nodes these ratios ranged from 0.22 to 0.44 for sugarcane stalks in the parallel orientation with reference to perpendicular orientation.

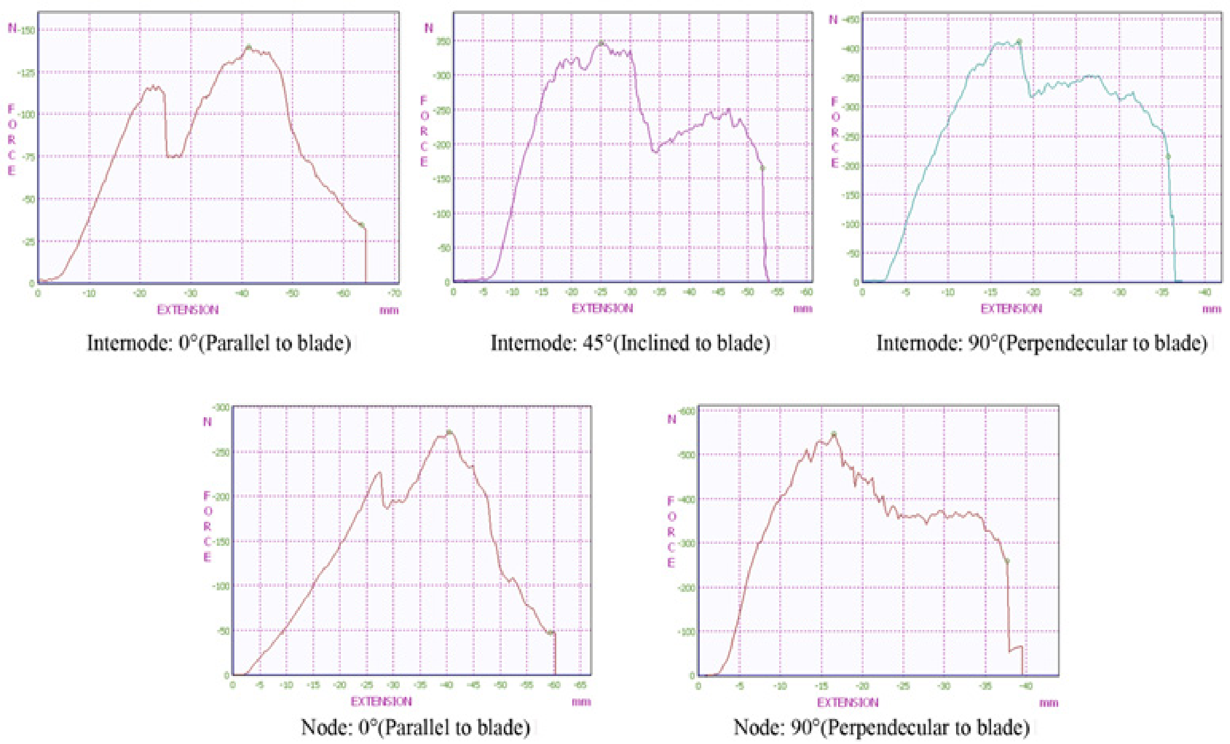

Fig.3. Force-displacement curves of cutting sugarcane stalks internodes and nodes at different orientations.

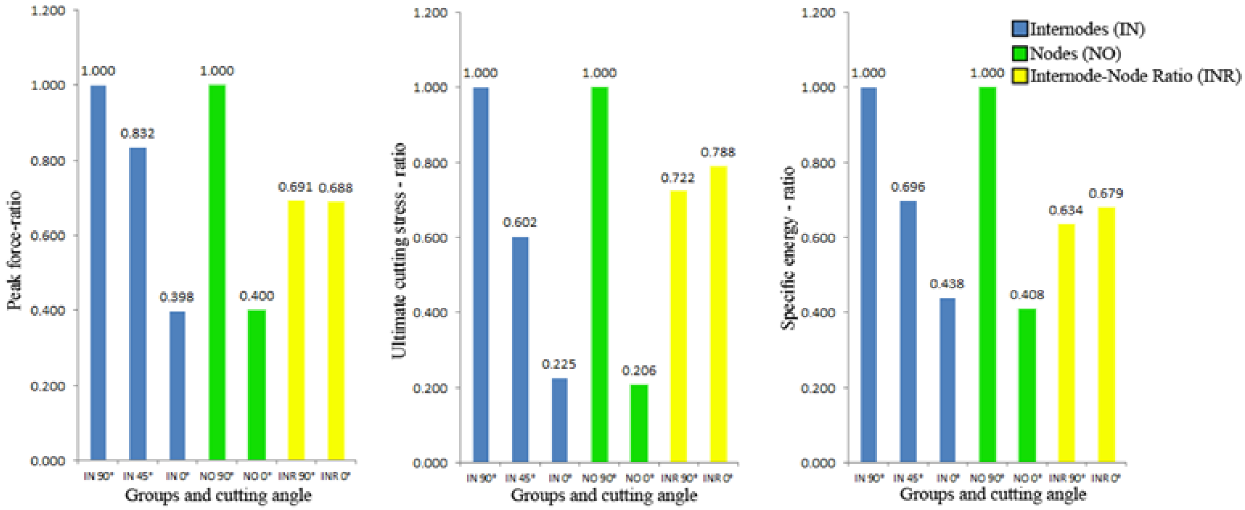

Fig.5. Comparison of mechanical cutting parameters of sugarcane stalks internodes and nodes at different orientations.

The ratios of internode to node cutting parameters of peak load, ultimate stress, and specific energy at parallel orientation were about 0.7 due to the node resistance in the cutting process. Also in perpendicular orientation the ratios of internode to node cutting parameters were about 0.7. While the values of ratios of paralle and perpendecular positions are approximately similar, it can be indicated that irrespective of material differences (internode and node), parallel orientation of the stalks to the cutting plane reduced the load, stress, and specific energy requirements drastically (≤ 0.788) compared to perpendicular orientation.

These lower cutting parameters of the sugarcane stalks in parallel orientation can be used profitably to develop feeding mechanisms or new machines that take orientation into account while presenting the material to the cutting elements, especially at the first stage of size reduction. It was also observed that any orientation other than the perpendicular also exhibited a reduction in the cutting energy requirements; therefore, any practical deviation from the best parallel orientation will also produce the corresponding energy efficiency in size reduction.

CONCLUSIONS

The effects of the dimensional parameters of sugarcanes, orientation of cutting samples from longitudinal axis and the type of material (node and internode) on ultimate stresses and energies involved in the size reduction of sugarcane stalks in linear cutting knife were determined. The equal size of cane stalks for all mechanical cutting properties consumed low level of energy at parallel position; whereas for perpendicular position, a high level of energy was consumed. Going from perpendicular to parallel position a decrease in the amount of energy occurred for the size reduction process. Therefore, cutting the internodes cane stalks is better than cutting the nodes for reducing the consumed energy for size reduction process. The results of this article can be used in designing mechanisms used for reducing the size of biomass, as well as designing and developing feeding machine systems.

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