Engineering Journal issn: 0125-8281

Article

Optimizing Shearing Characteristics of Sugarcane Leaves for Efficient Biomass Utilization and Machinery Design in the Sugar Industry

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Abstract. Sugarcane leaves, which are significant biomass residues from the globally important industrial crop, have potential as fuel sources for electricity generation. This study aimed to investigate the influence of moisture content, leaf region, and loading rate on shear strength and specific shearing energy of sugarcane leaves, focusing on the Khon Kaen 3 (KK3) cultivar. Experimental factors included four levels of moisture content (48.17%, 30.22%, 23.10%, and 8.90% w.b.), three leaf regions (lower, middle, and upper), and four loading rates (150, 250, 350, and 450 mm/min). Results showed significant impacts of moisture content, leaf region, and loading rate on shear strength and specific shearing energy ($P < 0.01$). The lower leaf region exhibited the highest shear strength (1.380 N/mm²) and specific shearing energy (12.184 mJ/mm²) at a moisture content of 48.17% w.b. and a loading rate of 150 mm/min. Conversely, the upper leaf region showed the lowest shear strength (0.372 N/mm²) and specific shearing energy (2.651 mJ/mm²) at a moisture content of 8.90% w.b. and a loading rate of 450 mm/min. To enhance cutting efficiency and minimize energy consumption during cutting leaves, it is recommended to sun-dry the leaves for 20-30 days before cutting to achieve a moisture content below 20% w.b. These findings could optimize cutting processes, machinery design, and agricultural practices in sugarcane harvesting and biomass utilization. This study is expected to contribute to understanding plant mechanical properties and provide insights for cutting devices and biomass processing systems. Further research should explore additional factors to advance efficiency and sustainability in the sugar industry and biomass utilization.

Keywords: Sugarcane leaves, shearing characteristics, shear strength, specific shearing energy, biomass utilization.

ENGINEERING JOURNAL Volume 28 Issue 1
Received 27 July 2023
Accepted 21 January 2024
Published 31 January 2024
Online at https://engj.org/
DOI:10.4186/ej.2024.28.1.1

DOI:10.4186/ej.2024.28.1.1

1. Introduction

Sugarcane (Saccharum officinarum L.) is a globally significant industrial crop primarily cultivated in tropical and subtropical regions. With an extensive cultivation area of approximately 26,269,819 hectares and an annual production yield of 1,907,024,730 tons, sugarcane plays a vital role in various industries [1]. The sugar industry generates substantial by-products during harvesting and sugar processing, such as sugar, molasses, filter mud, bagasse, sugarcane leaves, and sugarcane tops [1]. Notably, leaves and sugarcane tops constitute a significant portion of the harvested biomass, accounting for up to 40% [2]. These biomass residues hold potential as fuel sources for electricity generation in sugar factories and biomass power plants. However, to ensure complete combustion, the size of sugarcane leaves used as fuel must be reduced. Therefore, comprehending the mechanical properties of sugarcane leaves is crucial for designing machinery and analyzing agricultural material processing, including harvesting, threshing, and size reduction.

Previous research on plant mechanical properties has primarily focused on growth-related aspects, employing failure criteria such as force, stress, and energy. Investigations have centered around plant anatomy, lodging processes, harvest optimization [3], animal nutrition, industrial applications, and the decomposition of agricultural residues in soil [4-7]. Essential properties of cellular materials encompass cutting compression, tension, bending, shearing, and friction. These properties are influenced by factors such as species, variety, stalk diameter, maturity, moisture content, height of the plant stalk, and overall structure [8-12, 30-31].

Recent studies have explored the mechanical properties of various plant species, including wheatgrass and straw cutting [5, 12, 13], Alfalfa grass [15], sugarcane stems [16], corn [17, 18], and Kenaf [19]. Each plant requires specific cutting power due to variations in energy requirements during size reduction. Consequently, these energy differences present opportunities for developing novel material preparation methods and size reduction devices. However, there is a lack of comprehensive understanding regarding the shearing characteristics of sugarcane leaves, including shear strength and specific shearing energy, considering factors such as moisture content, leaf region, and loading rate.

This study aims to address this gap in the literature by investigating the shearing characteristics of sugarcane leaves and their mechanical properties. The specific objectives are to determine the effects of moisture content, leaf region, and loading rate on shear strength and specific shearing energy. By examining these factors, we aim to enhance the efficiency of cutting processes and reduce energy consumption. Additionally, we aim to compare our findings with prior studies and discuss the implications of the results in the context of agricultural material processing and biomass utilization.

In the following sections, we will present the methodology employed in this study, discuss the obtained results, and provide a comprehensive analysis of the findings. Furthermore, we will highlight the significance of this research in improving the understanding of sugarcane leaf mechanics and its implications for developing efficient machinery and agricultural practices.

2. Methodology

2.1. Sample Preparation

The research was conducted at the Department of Agricultural Engineering, Faculty of Engineering, Khon Kaen University, Thailand, in accordance with the journal's scope. The study utilized sugarcane leaves from the Thai sugarcane cultivar Khon Kaen 3 (KK3), which were grown in the Khon Kaen province of Northeastern Thailand (16° 25' 50" N / 102° 37' 0" E). The KK3 cultivar is commonly preferred by farmers, and the sugarcane harvesting season occurs annually from December to May. For this study, sugarcane leaves were harvested from 12-month-old plants by laborers. The top part of the sugarcane plants (Fig. 1) was separated from the stems during the harvesting process, , and used as the study samples.

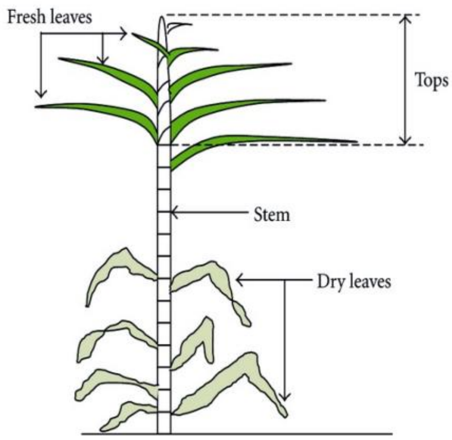


Fig. 1. Components of sugarcane [19].

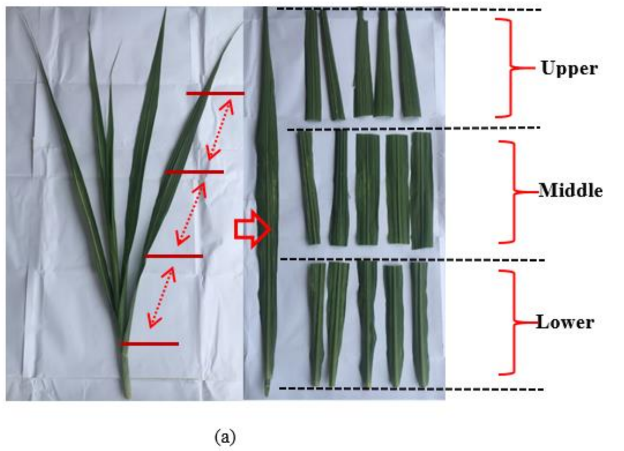
Uniform sugarcane tops with similar sizes and lengths were selected after harvesting. Each sugarcane top was covered with 4-5 leaves on the left and right sides. From each top, a single leaf with the strongest structure at the lowest position was chosen. The selected sugarcane leaves were divided into three parts, as depicted in Fig. 2(a), and measured from the lower to the top of the leaf. Each part was 30 cm long, which was further divided into three sections, resulting in 10 cm long samples. Hence, each experimental unit comprised five sugarcane leaves, totalling 15 samples (Fig. 2(b)). The width and thickness of the middle section of each part were measured using a Vernier Caliper (Mitutoyo brand) with an accuracy of ±0.03 mm.

To examine the moisture content of the sugarcane leaves, four groups were studied. The first group consisted of fresh leaves obtained directly after harvesting, while the second, third, and fourth groups included sun-dried leaves exposed to daytime temperatures of 30-36 °C and relative humidity ranging from 50-60% for 10, 20, and 30 days, respectively. The average moisture content for each group was determined as 48.17%, 30.22%, 23.10%, and 8.90% (w.b.), respectively. Additionally, four loading rates were employed in the study: 150, 250, 350, and 450 mm/min. In total, 80 sugarcane leaves were selected from 80 cane tops, resulting in a total of 720 samples for the experiments (4 moisture content levels × 3 leaf regions × 4 loading rates × 15 replications).

The average moisture content of the sugarcane leaves was determined by taking 30 g leaf samples and oven-drying them at 105 °C for 24 hours. The samples were then reweighed [21], and the moisture content was calculated using Eq. (1).

$$M.C=\frac{(W_{wm}-W_{dm})\times 100}{W_{wm}} \quad (1)$$

where M.C is the moisture content (%w.b.);
W_{wm} is the sample weight before being oven-dried (g);
W_{dm} is the sample weight after being oven-dried (g).



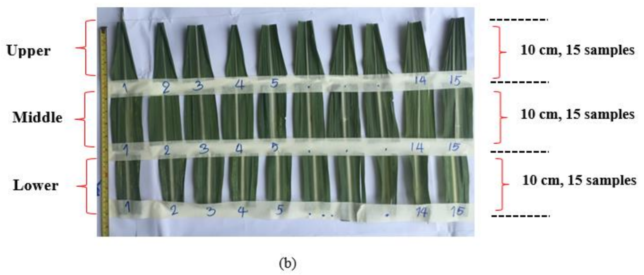


Fig. 2. (a) Division of sugarcane leaves into three parts: lower, middle, and upper. (b) Separation of samples used in each experiment.

2.2. Test Equipment

The developed testing equipment (Fig. 3) was securely fixed to the base of a Universal Testing Machine (UTM: model LR50K; Ametek, Meerbusch, Germany) (Fig. 4) available in the Department of Agricultural Engineering at Khon Kaen University. Data analysis was performed using NEXYGENPlus software, similar to the methodology described by Ince et al. [8]. Each sample was clamped with screws at both ends, and a cutting knife with specific dimensions (blade thickness: 8 mm, width: 65 mm, length: 120 mm, blade angle: 30 degrees) was attached to the cross head. The cross head, connected to the knife, was lowered, cutting the samples at their midpoint. The cutting test followed the procedure outlined by Chattopadhyay and Pandey [22], Khongthon and Sudajan [23], and Kaewwinud, Khokhajaikiat, and Boonma [24].

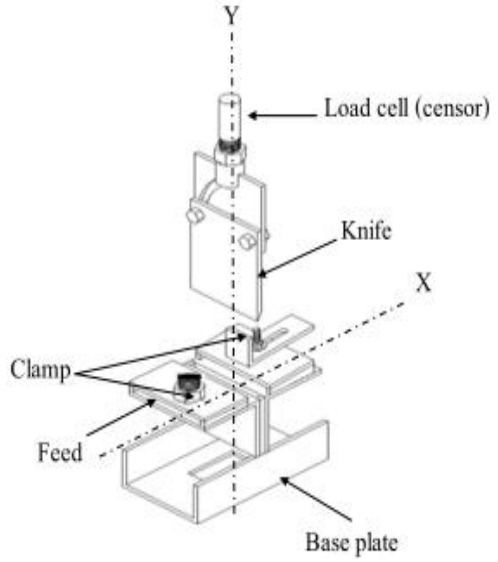


Fig. 3. Diagram of the testing equipment used in the study.

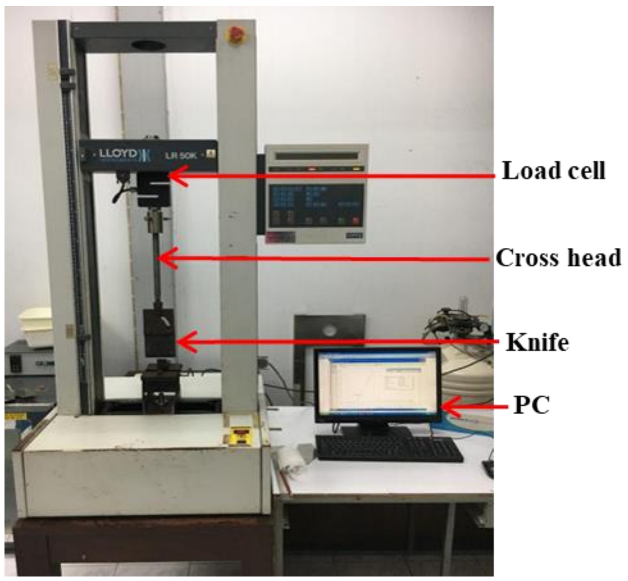


Fig. 4. Image of the Universal Testing Machine (UTM) used in the experiments.

2.3. Shearing Tests

Shearing tests were conducted to assess the mechanical properties of the sugarcane leaf material under shear force and measure shear stress. Shearing strength, shear energy, and specific shearing energy were determined by Universal Testing Machine (UTM) [17], and calculated using Eq. (2). Shear energy (Es) was calculated by integrating the area under the curves of shear force and displacement [25-27] through a standard computer program (NEXYGEN Plus). The curves were utilized to evaluate shear strength by considering the maximum recorded force and shearing energy, which represents the area under the curves (Eq. (3)).

$$\sigma_s = \frac{F_{s\ max}}{A} \quad (2)$$

where
σ_s is the maximum shearing strength (N/mm²);
$F_{s\ max}$ is the maximum shear force (N);
A is the cross-sectional area of sugarcane leaves cut by shear force (mm²).

$$E_{sc} = \frac{E_s}{A} \quad (3)$$

where
Esc is the specific shearing energy (mJ /mm²);
Es is the shearing energy (mJ).

2.4. Experimental Design and Statistical Analysis

A 4x3x4 factorial statistical design within a randomized complete block design (RCBD) was employed for this study. Statistical variance was analyzed using SPSS Statistics version 26 [28]. Mean values were compared using the Least Significant Difference (LSD) method at a 95% significance level, and the correlation between independent and dependent variables was investigated.

3. Results and Discussion

3.1. Shear Strength and Specific Shearing Energy

To investigate the influence of various factors on shear strength and specific shearing energy, a comprehensive data analysis was performed using variance analysis (ANOVA). The factors considered in this study were moisture content (A), leaf region (B), and loading rate (C). The results revealed that these factors exhibited a significant impact on both shear strength and specific shearing energy, with a statistical significance level of 99%. Additionally, the interactions between moisture content and leaf region (AB), moisture content and loading rate (AC), as well as leaf region and loading rate (BC), were found to have a significant effect on shear strength and specific shearing energy. Moreover, the combined effect of moisture content, leaf region, and loading rate (ABC) was observed to influence the specific shearing energy, while having no discernible effect on shear strength (Table 1). The specific details of each indicator are elucidated as follows.

Table 1. Results of analysis of variance (ANOVA) for average shear strength and average specific shearing energy at different moisture content, leaf region, and loading rate.

Source	Dependent Variable	Df	Mean Square	F-value	P-value
Moisture content (A)	Shear strength	3	3.580	294.925 **	0.000
	Specific shearing energy	3	1372.281	3949.910 **	0.000
leaf region (B)	Shear strength	3	9.559	787.613 **	0.000
	Specific shearing energy	3	178.883	514.887 **	0.000
Loading rate (C)	Shear strength	2	0.319	26.280 **	0.000
	Specific shearing energy	2	49.985	143.875 **	0.000
AB	Shear strength	6	1.139	93.879 **	0.000
	Specific shearing energy	6	9.339	26.882 **	0.000
AC	Shear strength	9	0.039	3.192 **	0.001
	Specific shearing energy	9	4.295	12.362 **	0.000
BC	Shear strength	6	0.057	4.725 **	0.000
	Specific shearing energy	6	3.309	9.524 **	0.000
ABC	Shear strength	18	0.011	0.940 ns	0.529
	Specific shearing energy	18	0.831	2.391 **	0.001
Error	Shear strength	672	0.012		
	Specific shearing energy	672	0.347		

** Highly significant at 99% level, * significant at 95% level, ns non- significant.

3.1.1. Effect of moisture content, leaf region, and loading rate on shear strength and specific shearing energy

The impact of moisture content, leaf region, and loading rate on shear strength and specific shearing energy was examined and is summarized in Table 2. Significant differences in shearing energy were observed at moisture levels of 8.90% and 48.17% w.b. for the lower, middle, and upper leaf regions, across all loading rates, with a 95% significance level ($p < 0.05$). However, no significant differences were found at moisture levels of 23.10% and 30.22% w.b. The average shear strength ranged from 0.423 to 0.766 N/mm² as the moisture content varied from its lowest to highest value in this study.

An increase in moisture content from 8.90% to 48.17% w.b., at loading rates of 150, 250, 350, and 450 mm/min, resulted in an increase in shear strength of the lower leaf region; from 0.514 to 1.380 N/mm², 0.500 to 1.171 N/mm², 0.494 to 1.117 N/mm², and 0.479 to 1.031 N/mm², respectively. Similarly, the shear strength of the middle leaf region increased from 0.408 to 0.779 N/mm², 0.400 to 0.745 N/mm², 0.390 to 0.685 N/mm², and 0.378 to 0.625 N/mm², respectively. The shear strength of the upper leaf region increased from 0.385 to 0.450 N/mm², 0.377 to 0.424 N/mm², 0.372 to 0.397 N/mm², and 0.373 to 0.385 N/mm², respectively

Table 2. Effect of moisture content and leaf region on shear strength at different loading rates.

Moisture content, % w.b.	Loading rate 150 mm/min			Loading rate 250 mm/min			Loading rate 350 mm/min			Loading rate 450 mm/min			Avg.
	Leaf region												
	Lower	Middle	Upper	Lower	Middle	Upper	Lower	Middle	Upper	Lower	Middle	Upper	
8.90	0.514	0.408	0.385	0.500	0.400	0.377	0.494	0.390	0.372	0.479	0.378	0.373	0.423c
23.10	0.834	0.556	0.523	0.790	0.524	0.502	0.769	0.521	0.490	0.703	0.499	0.478	0.599b
30.22	0.910	0.520	0.432	0.823	0.505	0.409	0.757	0.478	0.402	0.698	0.450	0.394	0.565b
48.17	1.380	0.779	0.450	1.171	0.745	0.424	1.117	0.685	0.397	1.031	0.625	0.385	0.766a

Note: Identical characters in each column were not statistically different, as compared using LSD at 5 percent significance. ($LSD_{0.05}$ = 0.039 N/mm²)

Figure 5 illustrates the relationship between moisture content, leaf region, and loading rate on shear strength. The results indicated that an increase in moisture content from 8.90% to 48.17% w.b. led to an increase in shear strength at all loading rates (150, 250, 350, and 450 mm/min). The lower leaf region exhibited the highest shear strength, followed by the middle and upper leaf regions, respectively. Furthermore, shear strength decreased as the loading rate increased. The physical structure of the sugarcane leaf contributes to the thicker, harder, and more resilient surface observed in the lower cutting region. Consequently, higher moisture content corresponded to higher shear strength in sugarcane leaves, which aligned with the findings of Ince et al. [8] who studied the cutting of sunflower stems with moisture content ranging from 20% to 80% w.b. Similar observations were reported by Annoussamy et al. [4] and Galedar et al. [15].

The mean specific shearing energy for different moisture content levels in each leaf region and at each loading rate is presented in Table 3. Significant differences were found in the specific shearing energy at moisture levels of 8.90%, 23.10%, 30.22%, and 48.17% w.b. for the lower, middle, and upper leaf regions across all loading rates, with a significance level of 95% ($p < 0.05$). The specific shearing energy for the highest and lowest moisture content levels exhibited a three-fold difference for each leaf region and loading rate.

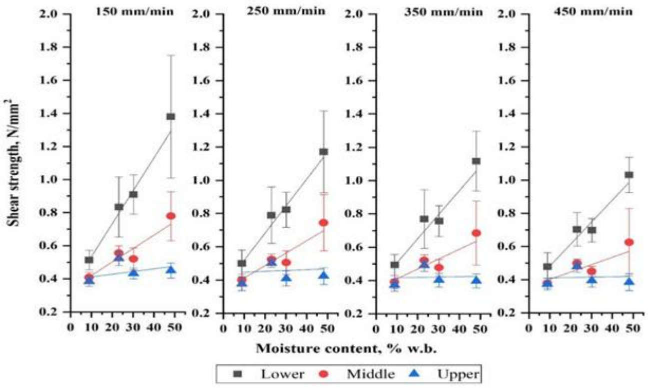


Fig. 5. Effect of moisture content and leaf region on shear strength at different loading rates.

When the moisture content increased from 8.90% to 48.17% w.b. at loading rates of 150, 250, 350, and 450 mm/min, the specific shearing energy of the lower leaf region increased from 3.997 to 12.184 mJ/mm², 3.764 to 10.817 mJ/mm², 3.701 to 10.171 mJ/mm², and 3.561 to 9.350 mJ/mm², respectively. The specific shearing energy of middle leaf region increased from 3.589 to 11.052 mJ/mm², 3.347 to 10.103 mJ/mm², 3.125 to 9.120 mJ/mm², and f 3.019 to 8.499 mJ/mm², respectively. Similarly, the specific shearing energy of the upper leaf region increased from 3.016 to 9.429 mJ/mm², 2.903 to 9.139 mJ/mm², 2.789 to 8.772 mJ/mm², and 2.651 to 8.448 mJ/mm², respectively. The highest specific shearing energy was observed in the lower leaf region, which had the highest moisture content.

Table 3. Effect of moisture content and leaf region on specific shearing energy at different loading rates.

Moisture content, % w.b.	Loading rate 150 mm/min			Loading rate 250 mm/min			Loading rate 350 mm/min			Loading rate 450 mm/min		
	Leaf region											
	Lower	Middle	Upper	Lower	Middle	Upper	Lower	Middle	Upper	Lower	Middle	Upper
8.90	3.997d	3.589d	3.016d	3.764d	3.347d	2.903d	3.701d	3.125d	2.789d	3.561d	3.019d	2.651d
23.10	7.966c	5.086c	5.082c	7.255c	5.015c	4.863c	6.723c	4.811c	4.762c	6.080c	4.570c	4.583c
30.22	9.662b	7.465b	7.423b	9.053b	7.186b	7.139b	8.499b	6.975b	6.768b	7.504b	6.382b	6.443b
48.17	12.184a	11.052a	9.429a	10.817a	10.103a	9.139a	10.171a	9.120a	8.772a	9.350a	8.499a	8.448a

Note: Identical characters in each column were not statistically different, as compared using LSD at 5 percent significance. (LSD0.05 = 0.423 mJ/mm²)

DOI:10.4186/ej.2024.28.1.1

Figure 6 depicts the relationship between moisture content, leaf region, and loading rate on specific shearing energy. The results indicated that an increase in moisture content from 8.90% to 48.17% w.b. was accompanied by an increase in specific shearing energy across all loading rates. The lower leaf region exhibited the highest specific shearing energy, followed by the middle and upper leaf regions, respectively. The specific shearing energy decreased gradually as the loading rate increased. These findings were consistent with previous studies by Announssamy et al. [4] on wheat straw, Chen et al. [25] on cannabis stems, and Galedar et al. [15] on alfalfa grass.

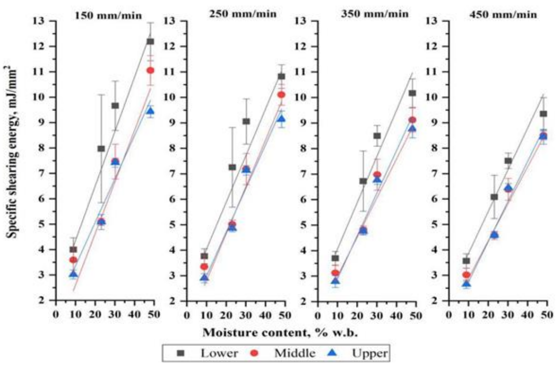


Fig. 6. Effect of moisture content and leaf region on specific shearing energy at different loading rates.

3.1.2. Effect of leaf region, loading rate, and moisture content on shear strength and specific shearing energy

The impact of leaf region, loading rate, and moisture content on shear strength and specific shearing energy was examined. The results, presented in Table 4, demonstrated variations in average shear strength across different leaf regions, loading rates, and levels of moisture content. The statistical analysis revealed significant differences in shear strength among the lower, middle, and upper leaf regions at each loading rate and moisture content within the range of 8.90% to 48.17% w.b. ($p < 0.05$). The average shear strength ranged from 0.811 to 0.425 N/mm² as the leaf regions transitioned from lower to middle and upper regions, respectively.

Furthermore, the shear strength of the lower, middle, and upper leaf regions was evaluated for moisture levels of 8.90%, 23.10%, 30.22%, and 48.17% w.b., under loading rates of 150 mm/min, 250 mm/min, 350 mm/min, and 450 mm/min. The results indicated a decrease in shear strength across all leaf regions as the loading rate increased. For instance, at a loading rate of 150 mm/min, the shear strength decreased from 0.514 to 0.385 N/mm², 0.834 to 0.523 N/mm², 0.910 to 0.432 N/mm², and 1.380 to 0.450 N/mm² for the lower, middle, and upper leaf regions, respectively. Similar trends were observed for loading rates of 250 mm/min, 350 mm/min, and 450 mm/min.

The relationship between the leaf region, loading rate, and moisture content on shear strength is illustrated in Fig. 7. It was observed that the shear strength was highest in the lower leaf region and gradually decreased towards the upper cutting region. This behavior can be attributed to the higher lignin content in the in the lower region of the leaves, resulting in stronger and tougher fibers compared to the middle and upper regions. This finding is consistent with previous studies conducted by Ince et al. [8] on sunflower and Galedar et al. [15] on alfalfa grass.

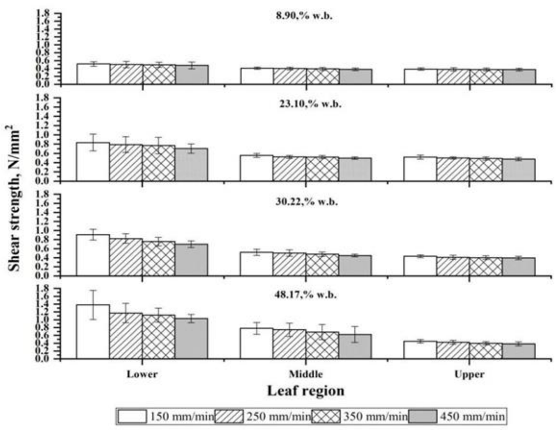


Fig. 7. Effect of leaf region and loading rate on shear strength at different moisture levels.

Table 4. Effect of leaf region and loading rate on shear strength at different moisture content levels.

Leaf region	Moisture content 8.90 % w.b.				Moisture content 23.10 % w.b.				Moisture content 30.22 % w.b.				Moisture content 48.17 % w.b.				Avg.
	Loading rate, mm/min																
	150	250	350	450	150	250	350	450	150	250	350	450	150	250	350	450	
Lower	0.514	0.500	0.494	0.479	0.834	0.790	0.769	0.703	0.910	0.823	0.757	0.698	1.380	1.171	1.117	1.031	0.811a
Middle	0.408	0.400	0.390	0.378	0.556	0.524	0.521	0.499	0.520	0.505	0.478	0.450	0.779	0.745	0.685	0.625	0.529b
Upper	0.385	0.377	0.372	0.373	0.523	0.502	0.490	0.478	0.432	0.409	0.402	0.394	0.450	0.424	0.397	0.385	0.425c

Note: Identical characters in each column were not statistically different, as compared using LSD at 5 percent significance. ($LSD_{0.05}$ = 0.046 N/mm²)

To further investigate the shear strength, Table 5 compares the shear strength of different leaf regions across various loading rates and moisture levels. The results indicated significant differences in shear strength between the upper leaf region at a moisture content of 8.90% w.b. and loading rates of 150 mm/min and 250 mm/min, compared to the lower leaf region at a moisture content of 8.90% w.b. and loading rates of 350 mm/min and 450 mm/min ($p < 0.05$). However, no significant differences were observed between the middle and upper leaf regions at loading rates of 350 mm/min and 450 mm/min, as well as between the lower and middle leaf regions at loading rates of 150 mm/min and 250 mm/min.

Moreover, the specific shearing energy was examined for the lower, middle, and upper leaf regions at moisture levels of 8.90%, 23.10%, 30.22%, and 48.17% w.b., and loading rates of 150 mm/min, 250 mm/min, 350 mm/min, and 450 mm/min. The specific shearing energy decreased as the loading rate increased and varied across different leaf regions. For example, at a loading rate of 150 mm/min, the specific shearing energy decreased from 3.997 to 3.061 mJ/mm², 7.966 to 5.082 mJ/mm², 9.662 to 7.423 mJ/mm², and 12.184 to 9.429 mJ/mm² for the lower, middle, and upper leaf regions, respectively. Similar trends were observed for loading rates of 250 mm/min, 350 mm/min, and 450 mm/min.

Table 5. Effect of leaf region and loading rate on shearing energy at different moisture content levels.

Leaf region	Moisture content 8.90 % w.b.				Moisture content 23.10 % w.b.				Moisture content 30.22 % w.b.				Moisture content 48.17 % w.b.			
	Loading rate, mm/min															
	150	250	350	450	150	250	350	450	150	250	350	450	150	250	350	450
Lower	3.997a	3.764a	3.701a	3.561a	7.966a	7.255a	6.723a	6.080a	9.662a	9.053a	8.499a	7.504a	12.184a	10.817a	10.171a	9.350a
Middle	3.589a	3.347a	3.125b	3.019b	5.086b	5.015b	4.811b	4.570b	7.465b	7.186b	6.975b	6.382b	11.052b	10.103b	9.120b	8.499b
Upper	3.016b	2.903b	2.789b	2.651b	5.082b	4.863b	4.762b	4.583b	7.423b	7.139b	6.768b	6.443b	9.429c	9.139c	8.772b	8.448b

Note: Identical characters in each column were not statistically different, as compared using LSD at 5 percent significance. ($LSD_{0.05}$ = 0.423 mJ/mm²)

Figure 8 provides an overview of the relationship between the leaf region, loading rate, and moisture content on specific shearing energy. The lower leaf region consistently exhibited the highest specific shearing energy, while the upper leaf region showed the lowest values. This finding aligned with those of Announssamy et al. [4] for wheat straw, Pachanawan et al. [32] for maize, Chen et al. [25] for cannabis stems, and Galedar et al. [15] for alfalfa grass.

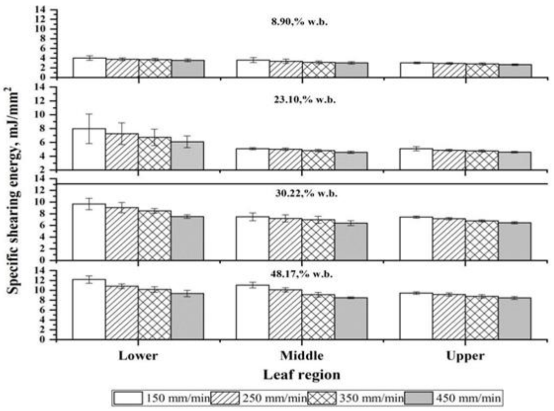


Fig. 8. Effect of leaf region and loading rate on shearing energy at different moisture levels.

3.1.3. Effect of loading rate, leaf region, and moisture content on shear strength and specific shearing energy

In this section, the impact of loading rate, leaf region, and moisture content on shear strength and specific shearing energy is examined. The findings presented in Table 6 illustrate that the average shear strength was affected by different loading rates, leaf regions, and moisture levels. Notably, at loading rates of 150 and 450 mm/min, significant differences in shearing resistance were observed for the leaf region at moisture contents of 8.90%, 23.10%, 30.22%, and 48.17% w.b. (water content basis) with a 95% confidence level ($p < 0.05$). However, no significant differences were observed at loading rates ranging from 250 to 350 and 350 to 450 mm/min. The average shear strength varied between 0.641 and 0.541 N/mm² as the loading rate varied across its range.

Furthermore, when the loading rate increased from 150 to 450 mm/min, the shear strength decreased for the lower, middle, and upper leaf regions at different moisture levels. For instance, at a moisture content of 8.90% w.b., the shear strength decreased from 0.514 to 0.479 N/mm² for the lower leaf region, 0.408 to 0.378 N/mm² for the middle leaf region, and 0.385 to 0.372 N/mm² for the upper leaf region. Similarly, at moisture levels of 23.10%, 30.22%, and 48.17% w.b., the shear strength exhibited decreasing trends with an increase in the loading rates. Notably, the loading rate of 450 mm/min resulted in lower shear strength compared to all other tested loading rates.

Figure 9 shows the relationship between loading rate, moisture content, and leaf region with respect to shear strength. As the loading rate increased from 150 to 450 mm/min, the shear strength demonstrated a decreasing trend. This observation was consistent for the lower and middle leaf regions at moisture levels of 48.17%, 30.22%, 23.10%, and 8.90% w.b.. The decreasing trend in shear strength was also observed for the upper leaf region at each moisture content. The higher loading rates caused greater shearing forces, resulting in the rapid tearing of

DOI:10.4186/ej.2024.28.1.1

plant fibers compared to lower loading rates. Sugarcane leaves, with their low moisture content, are inherently dry and brittle, making them susceptible to deformation and tearing. These findings aligned with previous research by Chattopadhyay and Pandey [22] on millet stalks, which reported a decrease in shear strength as the loading rate increased from 10 to 100 mm/min. Similarly, Li et al. [29] found that wheat exhibited the highest shear strength at a loading rate of 3 m/s and the lowest at a loading rate of 9 m/s.

Table 6. Effect of loading rate and moisture content on shear strength at different leaf regions.

Loading rate, mm/min	Lower				Middle				Upper				Avg.
	Moisture content, % w.b.												
	8.90	23.10	30.22	48.17	8.90	23.10	30.22	48.17	8.90	23.10	30.22	48.17	
150	0.514	0.834	0.91	1.38	0.408	0.556	0.52	0.779	0.385	0.523	0.432	0.45	0.641c
250	0.5	0.79	0.823	1.171	0.4	0.524	0.505	0.745	0.377	0.502	0.409	0.424	0.598b
350	0.494	0.769	0.757	1.117	0.39	0.521	0.478	0.685	0.372	0.49	0.402	0.397	0.573ab
450	0.479	0.703	0.698	1.031	0.378	0.499	0.45	0.625	0.373	0.478	0.394	0.385	0.541a

Note: Identical characters in each column were not statistically different, as compared using LSD at 5 percent significance. ($LSD_{0.05}$ = 0.039 N/mm²)

Table 7 presents the average specific shearing energy influenced by the loading rate, leaf region, and moisture content. Significant differences were observed at loading rates of 150, 250, 350, and 450 mm/min for the lower leaf region at moisture levels of 23.10%, 30.22%, and 48.17% w.b., as well as for the middle leaf region at 48.17% w.b., with a 95% confidence level ($p < 0.05$). However, no significant differences were found for the lower leaf region at a moisture content of 8.90% w.b. and the middle leaf region at moisture levels of 8.90%, 23.10%, and 30.22%. The loading rate of 450 mm/min exhibited lower specific shearing energy compared to the other tested loading rates.

Moreover, as the loading rate increased from 150 to 450 mm/min, the specific shearing energy decreased for the lower, middle, and upper leaf regions at a moisture content of 8.90% w.b. Specifically, the specific shearing energy decreased from 3.997 to 3.561 mJ/mm² for the lower leaf region, 3.589 to 3.019 mJ/mm² for the middle leaf region, and 3.016 to 2.651 mJ/mm² for the upper leaf region. Similar trends were observed at moisture content levels of 23.10%, 30.22%, and 48.17% w.b., indicating a decrease in specific shearing energy with increasing loading rates.

Figure 10 provides a visual representation of the relationship between loading rate, moisture content, and leaf region, illustrating their impact on specific shearing energy. The lower, middle, and upper cutting regions at moisture content levels of 48.17%, 30.22%, 23.10%, and 8.90% w.b. displayed a decreasing trend in specific shearing energy as the loading rate increased from 150 to 450 mm/min. These findings were consistent with the research conducted by Tavakoli et al. [14] on barley straw.

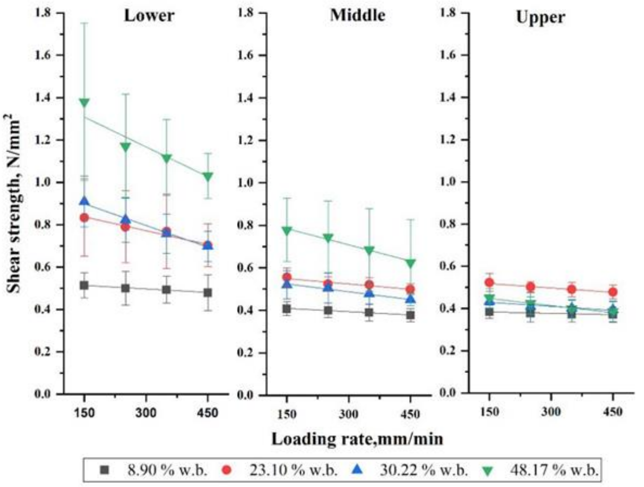


Fig. 9. Effect of loading rate and moisture content on shear strength at different leaf regions.

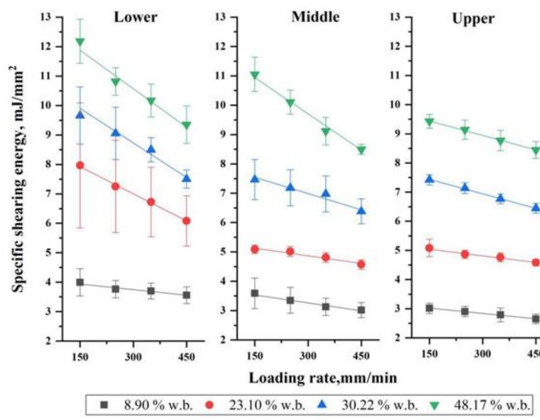


Fig. 10. Effect of loading rate and moisture content on shearing energy at different leaf regions.

Table 7. Effect of loading rate and moisture content on shearing energy at different leaf regions.

Loading rate, mm/min	Lower				Middle				Upper			
	Moisture content, % w.b.											
	8.90	23.10	30.22	48.17	8.90	23.10	30.22	48.17	8.90	23.10	30.22	48.17
150	3.997a	7.966a	9.662a	12.184a	3.589a	5.086a	7.465a	11.052a	3.016a	5.082a	7.423a	9.429a
250	3.764ab	7.255b	9.053b	10.817b	3.347ab	5.015a	7.186ab	10.103b	2.903a	4.863ab	7.139ba	9.139ba
350	3.701ab	6.723c	8.499c	10.171c	3.125b	4.811ab	6.975b	9.120c	2.789a	4.762ab	6.768bc	8.772bc
450	3.561b	6.080d	7.504d	9.350d	3.019b	4.570b	6.382c	8.499d	2.651a	4.583b	6.443c	8.448c

Note: Identical characters in each column were not statistically different, as compared using LSD at 5 percent significance. ($LSD_{0.05}$ = 0.423 mJ/mm²).

4. Conclusion

This study delved into the investigation of shearing characteristics and mechanical properties of sugarcane leaves to better understand their behavior during size reduction processes. The study examined the impact of moisture content, leaf region, and loading rate on shear strength and specific shearing energy. The results revealed that these factors had substantial influences on both shear strength and specific shearing energy.

Moisture content exhibited a noteworthy effect on shear strength and specific shearing energy of sugarcane leaves. Higher moisture content levels led to amplified shear strength and specific shearing energy. For instance, at a moisture content of 8.90% w.b., the shear strength ranged from 0.479 to 1.380 N/mm², while at a moisture content of 48.17% w.b., the shear strength ranged from 0.450 to 1.380 N/mm². The lower leaf region exhibited the highest shear strength and specific shearing energy, followed by the middle and upper regions. These findings underscore the significance of moisture control in optimizing cutting processes of sugarcane leaves and reducing energy consumption.

Loading rate also played a significant role in the mechanical properties of sugarcane leaves. Higher loading rates resulted in reduced shear strength and specific shearing energy. For instance, at a loading rate of 150 mm/min, the shear strength ranged from 0.479 to 0.514 N/mm², while at a loading rate of 450 mm/min, the shear strength ranged from 0.385 to 0.450 N/mm². Increased loading rates caused more rapid tearing and deformation of the plant fibers. Therefore, thoughtful consideration of the loading rate is crucial for achieving efficient size reduction of sugarcane leaves.

Variations in shear strength and specific shearing energy were observed across different leaf regions. The lower leaf region exhibited the highest values due to its thicker, harder, and more resilient surface. For example, the shear strength of the lower leaf region ranged from 0.479 to 1.380 N/mm², while that of the upper leaf region ranged from 0.372 to 0.450 N/mm². The middle and upper leaf regions displayed lower shear strength and specific shearing energy. This divergence in mechanical properties among leaf regions emphasizes the necessity of comprehending the unique characteristics of each region for effective machinery design and agricultural practices.

The findings of this study provide valuable insights into the mechanical properties of sugarcane leaves, contributing to the development of efficient machinery and improved agricultural practices. The results can be applied to designing and optimizing cutting devices in sugar factories and biomass power plants. By comprehending the factors that influence shear strength and specific shearing energy, it becomes possible to enhance the efficiency of size reduction processes and decrease energy consumption in utilizing sugarcane biomass residues.

In conclusion, this study enriches the existing knowledge regarding the mechanical properties of sugarcane leaves and their implications for agricultural material processing. The results highlight the significance of moisture content, leaf region, and loading rate in determining shear strength and specific shearing energy. Further research should focus on exploring additional factors influencing the mechanical properties of sugarcane leaves and investigating their application in the development of advanced cutting devices and biomass utilization systems.

Acknowledgement

The authors gratefully acknowledge the valuable support provided by the following organizations: Rajamangala University of Technology Isan, Khon Kaen Campus; the Postharvest Technology Innovation Center, Ministry of Higher Education, Science, Research and Innovation, Bangkok, Thailand; the Agricultural Machinery and Postharvest Technology Center, Khon Kaen University, Khon Kaen, Thailand; and Rajamangala University of Technology Suvarnabhumi. Their contributions greatly enhanced the research conducted in this study.

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