

# Cutting force and cutting energy investigation of sesame stalks at quasi-static cutting process

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**Abstract:** Due to the high loss of sesame seeds during harvesting, the cutting of stalks is an important process in sesame harvesting and there is an essential need for complementary information on the cutting properties of sesame stalk. This study primarily aimed to investigate and analyze the important cutting parameters of cutting force and specific cutting energy of sesame stalk in quasi-static cutting process. The samples were taken from the bottom, middle, and top regions of the stalk and tested at moisture content levels of 15%, 30%, and 60% on wet basis. Shearing tests were performed at four cutting speeds (1, 2, 3, and 4 mm min<sup>-1</sup>) following a factorial experiment in a completely randomized design. The effects of stalk moisture content, stalk cutting position, and cutting speed on the mentioned traits, as well as the interaction between moisture content and stalk cutting position on specific shear energy, were significant at the 1% probability level. The results indicated that increasing stalk moisture content from 15% to 60%, cutting speed from 1 to 4 mm min<sup>-1</sup>, and moving from the bottom to the top of the stalk, reduced the specific shear energy and cutting force of sesame stalks. The maximum specific shear energy was 31.08 J mm<sup>-2</sup>, and the maximum cutting force was 1093 N, both at a cutting speed of 1 mm min<sup>-1</sup>. The results also showed that in the first, second and third stages of sesame stalk cutting, the stalk resistance to blade penetration values are different and the sesame stalk has different resistance to the movement of the cutting blade inside the stalk.

**Keywords:** cutting speed, stalk moisture content, specific shear energy, cutting force

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## 1 Introduction

Sesame (*Sesamum indicum L.*) is one of the oldest cultivated oilseed crops, known for its resilient growth in arid conditions and highly valued seeds for their oil and nutritional content (Teklu et al., 2022). Sesame production is important in agriculture, food industry, and the crop diversity due to its rich nutritional profile and health benefits. In the past 60 years, global sesame production has substantially increased, with Asia and

Africa being the primary producers (Sanni et al., 2024). In 2021, global sesame production reached 6.67 million tons, with an average yield of 514.3 kg ha<sup>-1</sup>. The total land area under sesame cultivation worldwide was 12.97 million hectares (FAO, 2023). Iran's share of global sesame production in 2022 was 0.7%. Additionally, in 2022 Iran accounted for 0.3% of the world's cultivated area for sesame. Iran's production of sesame is about 39,000 tons cultivated in approximately 42,000 ha in 2022 (Gholamhoseini et al.,

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2024). In Iran sesame harvesting is done manually and starts when 75% of capsules are ripe. In harvesting sesame, the plants are cut, bundled, and shocked to dry. In some areas, the shocks are left on the field and in other areas, the bundles are moved to a shocking fence or to a threshing floor. As the plants dry, the capsules open, and some of the seeds can fall out. On a sesame threshing production floor, the shocks can be moved every few days, and the seed collected. If this is done on the field, the fallen seeds are lost. Harvesting sesame is challenging due to the plant's unlimited growth and the asynchronous ripening of its capsules. The crop's production rate is often low, attributed to uneven capsule maturation, the lack of mechanized harvesting, and the low yield of existing cultivars (Uzun et al., 2012). The majority of sesame fields worldwide are harvested manually due to significant seed losses that occur when using grain harvesters (Naydenov et al., 2020). Manual harvesting is the most labor-intensive and time-consuming process in sesame production, accounting for an estimated 60%–70% of the total production cost (Elebaid et al., 2016). Harvesting sesame seeds with a grain harvester has been shown to increase seed losses by approximately 50%. Research involving various devices and machines revealed seed losses ranging from 20% to 65% (Ishpekov et al., 2019). The mechanized harvesting of sesame causes significant seed losses depending on many factors of two groups: The first group includes the factors associated with susceptibility of sesame plants for releasing seeds during harvest. In the second

group, the factors characterize the mechanical impact for feeding stems in harvester. These are the direction, application point, speed and acceleration of the impact on stem (Ishpekov et al., 2017). The main reason for sesame cultivation decrement is the significant loss of seed at mechanized harvesting, which is a problem worldwide. For solving the problem, research can be conducted in two directions: Selection sesame varieties, suitable for mechanized harvesting and adaptation of existing equipment and development of new for harvesting sesame (Ishpekov et al., 2019b). So, it is necessary to determine mechanical properties of sesame stalk for suitable equipment design in order to decrease seed loss and improve operational parameters. The purpose of analyzing the shear behavior of sesame stalk is to design and fabrication a new harvesting machine that could cut the stalk with latest seed losses. This study examines the mechanical properties of sesame stalks as a function of their moisture content, stalk cutting position and cutting speed.

## 2 Materials and methods

Stalk samples of sesame (Halil variety) were collected from the experimental farm at the University of Jiroft, Jiroft, Iran. The farm located at latitude 28 degrees 40 minutes north and longitude 57 degrees 44 minutes east at an altitude of 650 meters above sea level. Crop management was conducted from planting to harvest, and single-branch stalks were manually selected and harvested during the experiment (Figure 1).

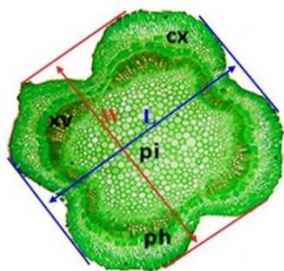


Figure 1 The experimental sesame farm at the University of Jiroft, Iran

The sesame stalk cross-section dimensions decrease towards to the top of the plant stalk, and it has different physico-mechanical properties at different heights of stalk due to different cross-section areas (Nazari Galedar et al., 2008; Shahbazi et al., 2012). Thus, the stalks were equally divided into three regions: (A) upper region, (B) middle region, and (C) lower region (Figure 2a). Morphological studies of the stalk show that the cross-section is in the form of a quatrefoil with a longitudinal (*L*) and a transverse (*W*) dimension (Figure 2b).



(a) Sesame stalk and three selected regions



W: Transverse dimension  
L: Longitudinal dimension

(b) Sesame stalk transection

Figure 2 Sesame stalk transection and stalk cutting positions

**Table 1 Mean and standard deviation of sesame stalk cross-sectional dimensions**

Stalk Position	Transverse dimension range (mm)	Longitudinal dimension range (mm)
Upper Region	4.60±0.45	5.12±0.47
Middle Region	5.70±0.48	6.16±0.43
Lower Region	6.35±0.30	7.19±0.31

Table 1 shows the mean and deviations of sesame stalk cross-sectional dimensions in three different stalk regions.

Finally, the ASAE standard was used to determine the moisture content of the sesame stalks (ASAE, 2005; Tavakoli et al., 2009). The stalk moisture content of the used sample is determined by the standard method

before each experiment. The samples were harvested during different growth periods and divided into three groups based on their moisture content at harvest: 10% (maturation of most of the capsules), 30% (maturation of about 70% of the capsules), and 50% (maturation of about 50% of the capsules) on a wet basis. The cutting characteristics of sesame stalks were assessed using a

proprietary tension/compression testing machine (Instron Universal Testing Machine SMT-5, SANTAM Co., Iran). The experiments were carried out by a double shear using a shear box consisting essentially of two fixed parallel hardened steel plates, between which a third plate can slide freely in a close sliding fit (Figure 3).

A series of holes with diameter ranging from 1.5 to 15 mm were drilled through the plates to accommodate internodes of different diameter. Shear force was applied to the stalk specimens by mounting the shear box in the tension/compression testing machine. The applied force was measured by a strain-gauge load cell and a force-time record obtained up to the specimen failure. During the sample cutting, the instantaneous

cutting force versus blade displacement data was recorded by data acquisition system. To determine the shearing energy, we calculated the area under the force-displacement curve in Excel using the trapezoidal rule. This method approximates the area by dividing the curve into small trapezoids and summing their areas. This research was employed as completely randomized design, conducting experimental tests with four replicates for each treatment. The specific shear energy and cutting force were opted as dependent variables. Finally, the collected data were analyzed using analysis of variances (ANOVA) and the means were separated by 5% and 1% probability levels applying Duncan's multiple range test.

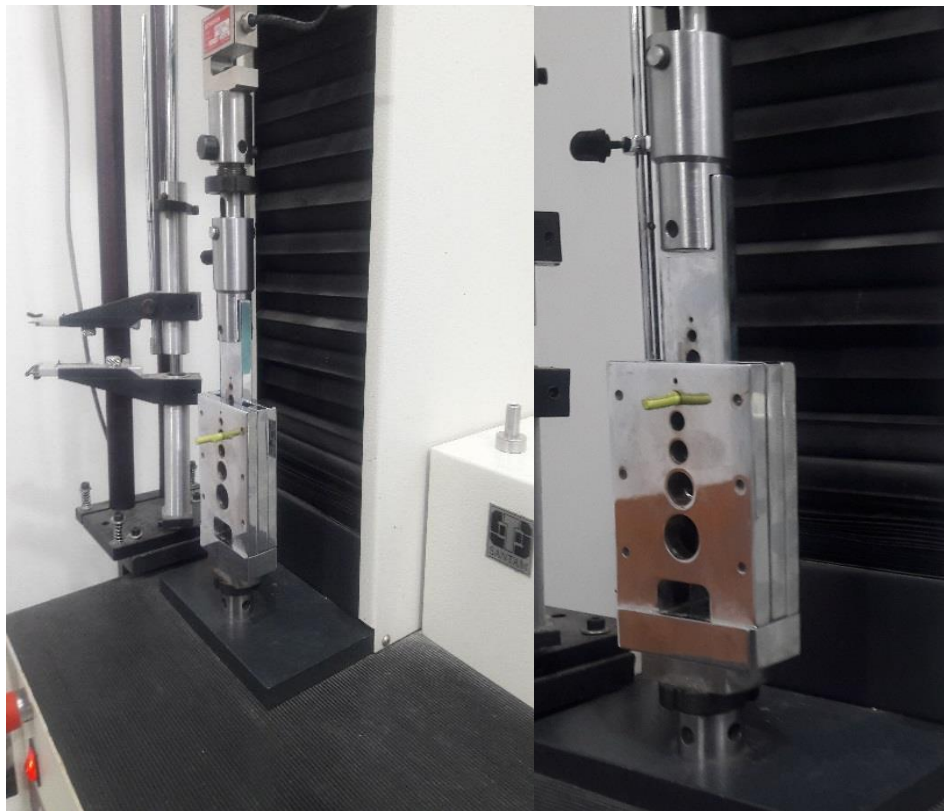


Figure 3 Equipment used to measure the cutting characteristics of sesame stalk

### 3 Result and discussion

The variance analysis of the effect of loading rate, cutting position, moisture content and their interaction effects on the specific shear energy and cutting force as shown in Table 2.

The results showed that the moisture content (A), stalk position (B), and cutting speed (C) had a significant effect on the specific shear energy and

cutting force ( $P < 0.01$ ). The interaction effects of  $A \times B$ , and  $B \times C$  on the specific shear energy and cutting force parameters were significant, respectively ( $P < 0.01$ ). It was observed that increasing the stalk moisture content from 15% to 60%, raising the cutting speed from 1 to 4  $\text{mm min}^{-1}$ , and transitioning from the bottom to the top of the stalk all resulted in a decrease in the values of specific shear energy and cutting force. At a stalk

moisture content of 60%, the lowest average specific shear energy is  $14.70 \text{ J mm}^{-2}$ , while the minimum average cutting force of 520 N is observed when cutting the upper region of the stalk, as shown in the table. The highest specific cutting energy of  $31.08 \text{ J mm}^{-2}$  and the maximum average cutting force of 881 N were both achieved at a cutting speed of  $1 \text{ mm min}^{-1}$ . In the following sections, the description and analysis of cutting force and specific cutting energy has been discussed in detail at selected stalk moisture levels, stalk cutting positions and cutting speeds.

**Table 2** Variance analyses of cutting sesame stalk at different loading rates, moisture contents and cutting positions

Source of variation	Degree of freedom	Specific shear energy ( $\text{J mm}^{-2}$ )	Cutting force (kN)
Loading rate (A)	3	1026**	0.32**
Cutting position (B)	2	705**	0.83**
Moisture content (C)	2	2193**	0.52**
Interaction A×B	6	15 <sup>ns</sup>	0.074**
Interaction B×C	4	301**	0.055 <sup>ns</sup>
Interaction A×C	6	57 <sup>ns</sup>	0.032 <sup>ns</sup>
Interaction A×B×C	12	41 <sup>ns</sup>	0.007 <sup>ns</sup>
Error	72	32.09	0.04

Note: \*\*and \*significant in statistic level of 1% ( $P < 1\%$ ) and 5% ( $P < 5\%$ ). ns not significant

### 3.1 Cutting force analysis

During the experimental tests, the instantaneous

cutting force versus blade displacement data were recorded by the apparatus. A model of the cutting process with four examples of cutting force variation versus blade displacement curves are shown in Figure 4 (Cutting speeds: 1, 2, 3, and  $4 \text{ mm min}^{-1}$ , stalk position: lower region, moisture content: 15%).

Figure 4 shows an example of the obtained cutting force variation versus blade displacement curves of sesame stalks at the lower region, the cutting speeds of 1, 2, 3, and  $4 \text{ mm min}^{-1}$ , and moisture content of 15%. According to the figure, the changes in cutting force are the same or similar to those of blade displacement for all cutting force curves at different cutting speeds. It is clear that the cutting force values are different between the cutting force curves at the same blade displacement. The maximum shear force value was achieved at the cutting speed of  $1 \text{ mm min}^{-1}$  and was about 34%, 40%, and 62% lower at the cutting speeds of 2, 3, and  $4 \text{ mm min}^{-1}$ , respectively. To analyse the instantaneous shear force variation of the sesame stalk versus blade displacement, the curve of shear force versus displacement at a cutting speed of  $3 \text{ mm min}^{-1}$  is shown in Figure 5. It had the highest value of shear force compared with others. To better illustrate the results, this diagram has been enlarged at both the beginning and end parts of the graph and a centre section has also been removed.

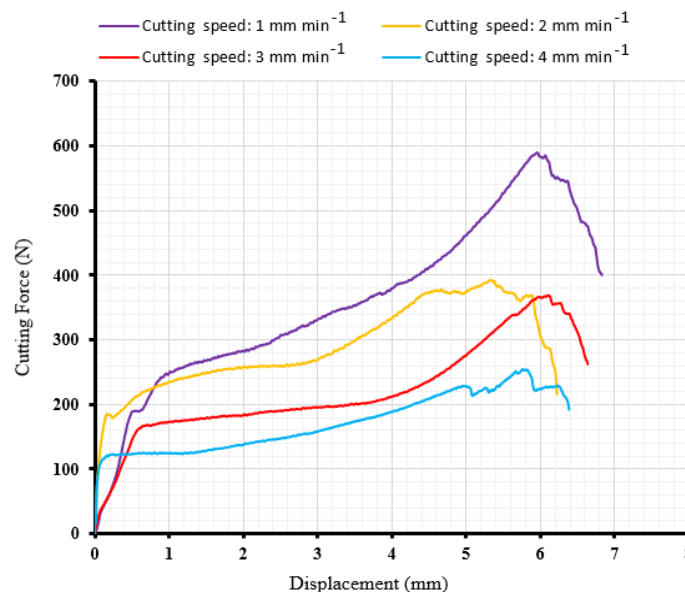


Figure 4 Cutting force variation versus displacement curves

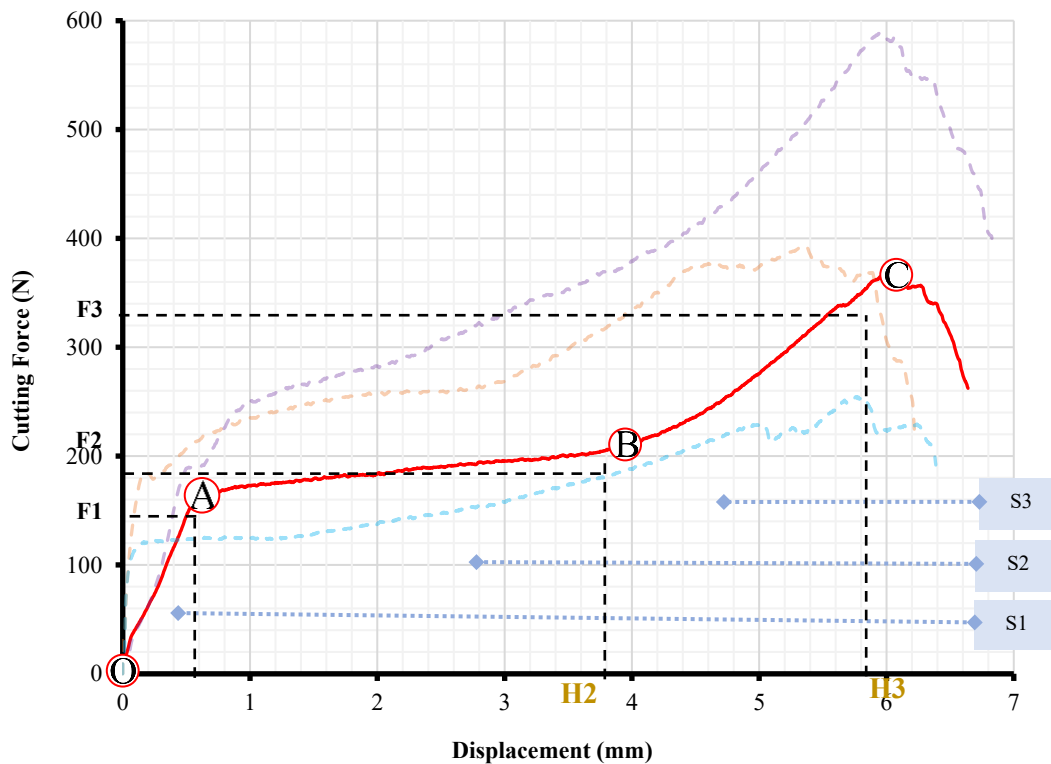


Figure 5 Segmentation of shear force variation versus blade displacement curve of sesame stalks (S1: useless cutting energy, S2: useful cutting energy, S3: useless cutting energy)

As shown in Figure 5, the cutting process of sesame stalk has three main phases (*OA*, *AB* and *BC*). In the following, each of these phases will be explained (Cutting speed:  $3 \text{ mm min}^{-1}$ , stalk position: lower region, moisture content: 15%):

**First stage:** at the first stage (*OA*) the cutting blade involves preliminary compaction of stalk outer layer. It is clear that the cutting force applied by the cutter blade first compresses the outer layer of sesame stalk (blade displacement equal to  $H_1=0.6 \text{ mm}$ ) in which the cutting force increases linearly to the first force  $F_1 (\cong 167 \text{ N})$ . The force  $F_1$  is not a useful cutting force to sesame stalk cutting.

**Second stage:** The second stage starts when the material under the cutting blade yields and the motion of the cutting blade in the stalk material cuts the stalk (*AB*). At the second stage, the outer layer material of sesame stalk is compressed up to a special amount until the cutting resistance of the stalk is overcome and then penetrates as far as the centre of the stalk (blade displacement equal to  $H_2-H_1=3.3 \text{ mm}$ ) in which the cutting force increases to the second force  $F_2 (\cong 210 \text{ N})$ . At the second stage and after initial compaction, force  $F_1$  which is not the maximum shear

force applied to the stalk ( $F_1 \leq F_2$ ), cuts the stem to a thickness of  $H_2$ . The force  $F_2$  is a useful cutting force to sesame stalk cutting.

**Third stage:** After cutting the outer layer of the stalk, the third stage starts and the motion of the cutting blade in the stalk material cuts the stalk (*BC*). At this stage, the cutting blade moves to cut the stalk (blade displacement equal to  $H_3-H_2=2.2 \text{ mm}$ ) and the cutting force increases strongly to the third force  $F_3 (\cong 366 \text{ N})$ . In fact at this stage, the final motion of the cutting blade in the stalk material cuts the other side of the outer layer of sesame stalk and the cutting force increases until the end of cutting and the cutting force increases to maximum value ( $F_2 \leq F_3$ ).

Figure 5 shows, the stalk material is compressed up to a blade displacement of  $H_1$  until the cutting resistance is overcome, and the energy required is given by the area  $S_1$  under the curve (useless cutting work to compression of stalk outer layer). So, the sesame stalk material is cut up to a blade displacement of  $H_2$  and energy requirements of effective cutting are given by  $S_2$  (useful cutting work to stalk cutting). Finally, the stalk material is cut up to a blade displacement of  $H_3$  and energy requirements of

effective cutting are given by  $S_3$ . The total shear consumption energy is the sum of  $S_1$ ,  $S_2$  and  $S_3$ . The analysis of shear force versus displacement curves showed the amount of  $S_1$  decreased by shear speed increment. So, the increase of deformation outer layer of sesame stalk is the important reason for increase the shear consumption energy and cutting force. It seems the variation of the cutting characteristics is a function of the layer deformation of the stalk and with increasing preliminary compaction amount, the proportion of outer layer deformation work increases

and the shear consumption energy also increases. Considering Figure 5, the three phases of the blade displacement versus cutting force curve, have different slopes. If we consider the slope of the first, second, and third stages as  $(\alpha_1, \alpha_2, \text{ and } \alpha_3)$  respectively, there is different resistance to blade penetration by the sesame stalk at quasi static cutting process. Therefore, the stalk resistance to blade penetration at each stage of cutting force variation versus displacement curve can be expressed in Table 3.

**Table 3 Determination of stalk resistance to blade penetration**

	Force-displacement curve stages		
	1	2	3
Curve slope	$RP_1 = \alpha_1 = F_1/H_1$	$RP_2 = \alpha_2 = (F_2 - F_1)/(H_2 - H_1)$	$RP_3 = \alpha_3 = (F_3 - F_2)/(H_3 - H_2)$
Required cutting energy	$S_1 = F_1 * H_1$	$S_2 = F_2 * (H_2 - H_1)$	$S_3 = F_3 * (H_3 - H_2)$
Linear density	$D_1 = \pi * \rho * H_1^2$	$D_2 = \pi * \rho * (H_2 - H_1)^2$	$D_3 = \pi * \rho * (H_3 - H_2)^2$
Resistance to penetration	$RP_1 = S_1 * \pi * \frac{\rho}{D_1}$	$RP_2 = S_2 * \pi * \frac{\rho}{D_2}$	$RP_3 = S_3 * \pi * \frac{\rho}{D_3}$
Resistance to penetration	$RP_1 = S_1 * \pi * \frac{\rho}{D}$	$RP_2 = S_2 * \pi * \frac{\rho}{D}$	$RP_3 = S_3 * \pi * \frac{\rho}{D}$

If we consider:  $D_1 \cong D_2 \cong D_3 = D$   
By consider to figure 5:  $S_1 \leq S_3 \leq S_2$

Comparison between sesame stalk penetration resistance at different stages of the quasi static cutting process:  $RP_1 \leq RP_3 \leq RP_2$

Where  $RP$  is the stalk resistance to blade penetration in  $kN m^{-1}$ ,  $\rho$  is the stalk bulk density in  $kg m^{-3}$  and  $D$  is the stalk linear density in  $kg m^{-1}$ . According to the mentioned information in Table 3, a series of results can be obtained, which are described as below:

(1) In the first, second and third stages of the stalk cutting curve, the stalk resistance to penetration values are different. It is clear that the sesame stalk has different resistance to the movement of the cutting blade inside the stalk.

(2) According to last row of the table ( $RP_1 \leq RP_3 \leq RP_2$ ), the resistance to penetration of the stalk is higher in the second stage than other stages due to the amount of required cutting energy by the stalk.

(3) The amount of resistance to penetration in the third stage shows that some of the cutting energy is used to re-cut the outer layer of the stalk when the blade leaves the stalk.

(4) It is clear that, the maximum amount of cutting

energy of the blade is used to cut the middle stage of the sesame stalk (the second stage).

The results showed (Table 2) that the moisture content, stalk position, and cutting speed had a significant effect on the cutting force of sesame stalk ( $P < 0.01$ ). Also, interaction effect of stalk cutting position and cutting speed on the cutting force was significant ( $P < 0.01$ ). In the following sections, the description of mentioned factors effects on the cutting force has been discussed in detail.

**3.2 Effect of moisture content**

As shown in Table 2, moisture content significantly affects cutting force at the 1% probability level. The maximum cutting force of 880 N occurs at 15% moisture content, while the minimum cutting force of 520 N is observed at 60% moisture content, as illustrated in Figure 6. As stalk moisture increases from 15% to 60%, cutting force decreases rising 25% at 15% moisture vs. 30%, 21% at 30% vs. 60%, and 41% at 15% vs. 60%.

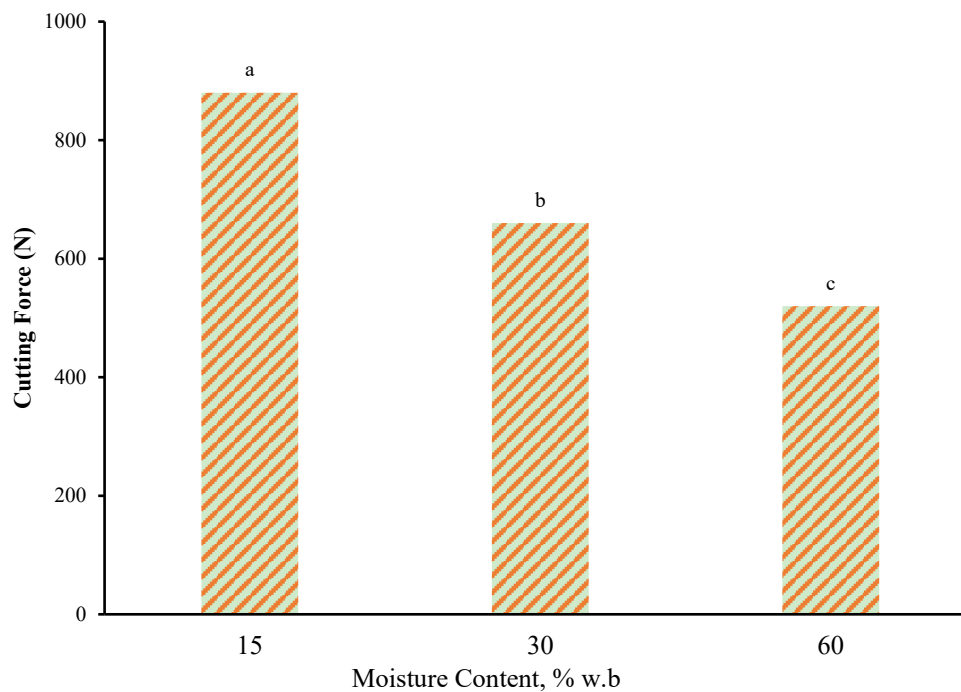


Figure 6 Effect of moisture content on cutting force

Reduced moisture content, particularly at 15%, resulted in higher stalk density, which increased the cutting force of sesame stalk internodes. The bending and shearing characteristics of the canola stem were investigated. The results showed, the moisture content significantly influences shearing stress at the 1% probability level, with shearing stress at low moisture content (35%) being about 35% higher than at high moisture content (57%) (Hoseinzadeh et al., 2012). Cutting sesame stalk at four moisture contents (10%, 20%, 40% and 60% d. b.) and at different stalk sections (upper, middle and lower) showed moisture content had a significant effect ( $p < 0.01$ ) on maximum force in shearing (Yilmaz et al., 2009). The effect of moisture content and dimensional parameters were studied on shearing characteristics of sugarcane stalks. It was reported that the mean ultimate stress of the stalks was 7.086 MPa at low moisture content value, 2.586 MPa at medium moisture content value, and 1.656 MPa at high moisture content value. A significant reduction in ultimate stress was observed at high moisture content value compared with low moisture content value (Taghinezhad et al., 2013). It was reported that in cutting millet stems at a cutting speed of  $300 \text{ mm min}^{-1}$  and moisture contents of 14.10%, 24.60%, 41.33%, 55.27%, and 72.59%, the shear strength increased with

increasing stem moisture content up to 41.33% (Zhang et al., 2018).

It was reported that showed that cutting the stems of corn and sorghum forage crops at different growth stages, different stem diameters, and stem moisture range of 20% to 80%, with a decrease in stem moisture from 80% to 20%, the rate of increase in shear strength of sorghum stems was 3.89% and the rate of increase in shear strength of corn stems was 3.63% (Jekendra, 1999). It was reported that the ultimate shear strength of alfalfa stems decreases with increasing moisture content throughout the stem length (Halyk et al., 1968). According to the results of sesame stalk cutting and also the results of similar research conducted on quasi-static cutting of stalks of other plants, it is clear that at high stalk moisture content, the holding force between the fibers can inhibit the reduction of stalk volume, and the cells of the stalk tissues are still scattered and not dense. This causes the critical shear strength of the stem to decrease. With a further decrease in stem moisture content, the force between the stalk fibers gradually decreases and the volume of the stalk internodes samples decreases sharply and the stalk tissues become completely dense. This high density of dense tissue due to the decrease in dense moisture content, especially at 15%, caused the critical shear

strength of the sesame dense internodes to increase.

### 3.3 Effect of stalk cutting position

Stalk cutting force varies significantly at the 1% probability level between the lower, middle, and upper regions of the sesame stalk, with the decreasing progressively from the lower to the upper region (Figure 7). The cutting force of the sesame stalk increased by approximately 19% in the lower region compared to the middle region, 24% in the middle region compared to the upper region, and 38% in the lower region compared to the upper region. The maximum cutting force was 815 N in the lower stalk region, while the minimum was 427 N in the upper region. The lower region of the sesame stalk exhibits maximum cutting force due to its lower moisture content, higher fiber density, and thicker walls compared to the upper region. Research on the effect of stalk position on cutting force in quasi-static cutting for other plants corresponds with the results of this study. The highest mean shear strength values

recorded were 32.86 MPa at the fifteenth internode and 25.06 MPa at the fifth internode of the privet stalk. Shear strength was significantly influenced by the internode position, with values increasing toward the lower regions of the stalk (Kamandar et al., 2018). Bioyield force values of sesame stalk increased from 10%–40% in the middle and lower stalk sections, and subsequently decreased. This is probably due to the fibrous material and tubular section of sesame stalk. The shearing of fibers is achieved by compression which causes the hollow tubes to collapse before the fibers are severed. The lowest bioyield force value was observed at 20% moisture content at section a (upper section) of the stalk. The highest bioyield force was 215.64 N in section c (lower section) at 40% moisture content, while the lowest bioyield force was 70.25 N in section a (upper section) at 20% moisture content. The bioyield force values of section c (lower) were higher than those of sections a (upper) and b (middle) (Yilmaz et al., 2009).

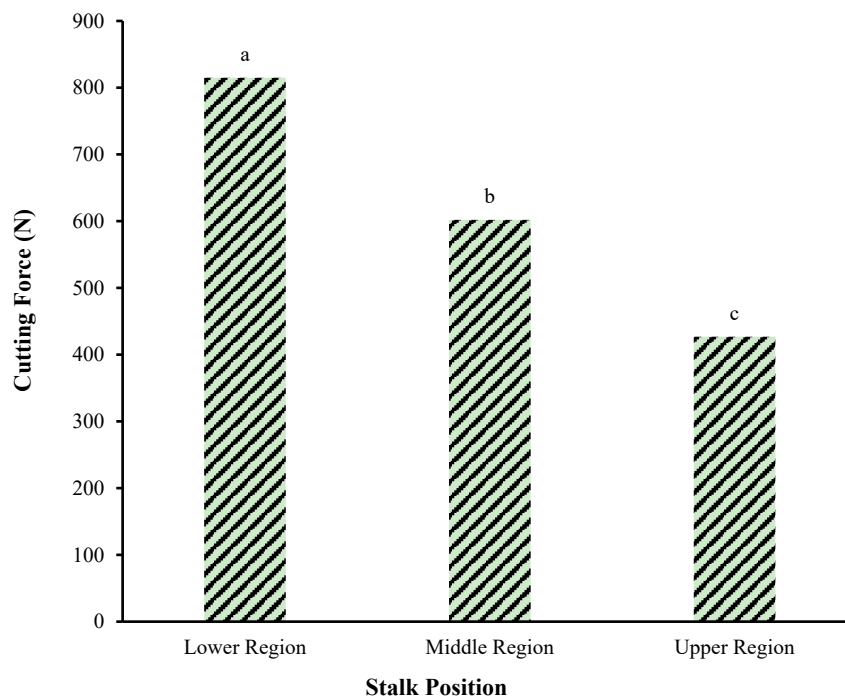


Figure 7 Effect of stalk position on cutting force

The shearing stress decreased as the cutting height of the wheat stem of the Alvand variety increased. Raising the cutting height from 100 to 300 mm resulted in a 13% reduction in shearing stress (Eshaghbeygi et al., 2009). The shearing strength ranged from 3.407 MPa at the lower level to 3.059 MPa at the upper level

of the stem, with the shearing strength at the top node being 11% lower than at the first node (Hemmatian et al., 2012). The results of investigating the effects of stem region, moisture content, and blade oblique angle on the mechanical cutting of millet stems showed that the cutting stress decreased from the lower region of

the stem to the upper region, and the cutting force and energy were much higher in the lower region than in the other areas due to the cross-sectional parameters (Zhang et al., 2018). It was reported that with increasing diameter and cross-sectional area of the wheat stem wall from the first to the fourth node, the shear strength of the stem increases from 4.91 to 7.26 MPa (O'Degherty et al., 1995). According to the results of cutting sesame stalks and also the results of similar research conducted on quasi-static cutting of stalks of other plants, it is clear that the maximum shear strength is in the lower part of the sesame stalk and the reason for this is the lower moisture content, more fibers and thicker wall of the lower part of the stalk compared to its upper part (Amer Eissa et al., 2008).

### 3.4 Effect of cutting speed

Cutting speed significantly affects cutting force at the 1% probability level. Mean comparison results revealed a significant difference in stalk cutting force among cutting speed levels of 1, 2, 3, and 4 mm min<sup>-1</sup> at the 1% probability level. At a cutting speed of 1 mm min<sup>-1</sup>, the maximum stalk cutting force was 881 N,

while at 4 mm min<sup>-1</sup>, the minimum was 408 N (Figure 8). According to the figure, the cutting strength of sesame stalk decreases with increasing cutting speed. The rate of decreasing cutting strength at speed of 2 compared to speed of 1 mm min<sup>-1</sup> is about 17%, at speed of 3 compared to speed of 2 mm min<sup>-1</sup> is about 17%, and at speed of 4 compared to speed of 3 mm min<sup>-1</sup> is about 1%. Finally, increasing the speed from 1 to 4 mm min<sup>-1</sup> reduces the cutting strength of sesame stalk by about 32%. It was found that shear velocity significantly influenced the shear strength and energy per unit area of pyrethrum flowers. As shear velocity increased from 20 to 500 mm min<sup>-1</sup>, shear strength decreased from 2.4 to 1.9 MPa, and shear energy per unit area dropped from 3.3 to 2.8 mJ mm<sup>-2</sup> (Khazaei et al., 2002). The static and dynamic cutting forces of stems in Iranian rice varieties investigated. The findings indicated that shear strength decreased from 234.4 kPa to 137.4 kPa as the blade cutting speed increased from 0.6 to 1.5 m s<sup>-1</sup> (Tabatabaee Kolor et al., 2006).

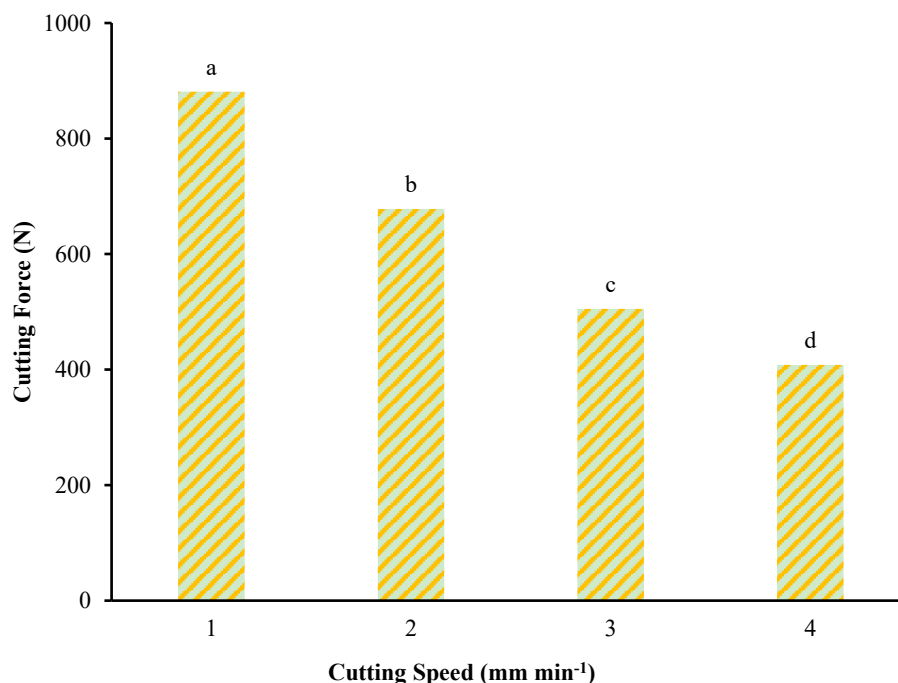


Figure 8 Effect of cutting speed on cutting force

Shearing properties of sugar cane stems were determined at five moisture content levels (46%, 54%, 62%, 70% and 78% w.b.), three shearing speed (5, 10 and 15 mm min<sup>-1</sup>) and at ten positions on the stem. It

was reported that with the increase in shearing speed from 5 to 15 mm min<sup>-1</sup>, shearing strength increased 3.2% (Hemmatian et al., 2012). The cutting force of sesame stalks decreases as cutting speed increases. At lower

speeds, the stalk is compressed against the blade, allowing the elastic cell walls to transfer force to the viscous fluid inside the cells. However, at higher speeds, the cell walls lack sufficient time for this force transfer, causing the stalk to be cut more quickly and with less force. Consequently, the cutting force of the stalk reduces at higher cutting speeds.

### 3.5 Interaction effect of stalk cutting position and cutting speed

The interaction effect of stalk position and cutting speed on the cutting force of sesame stalks was significant at the 1% probability level. Figure 9

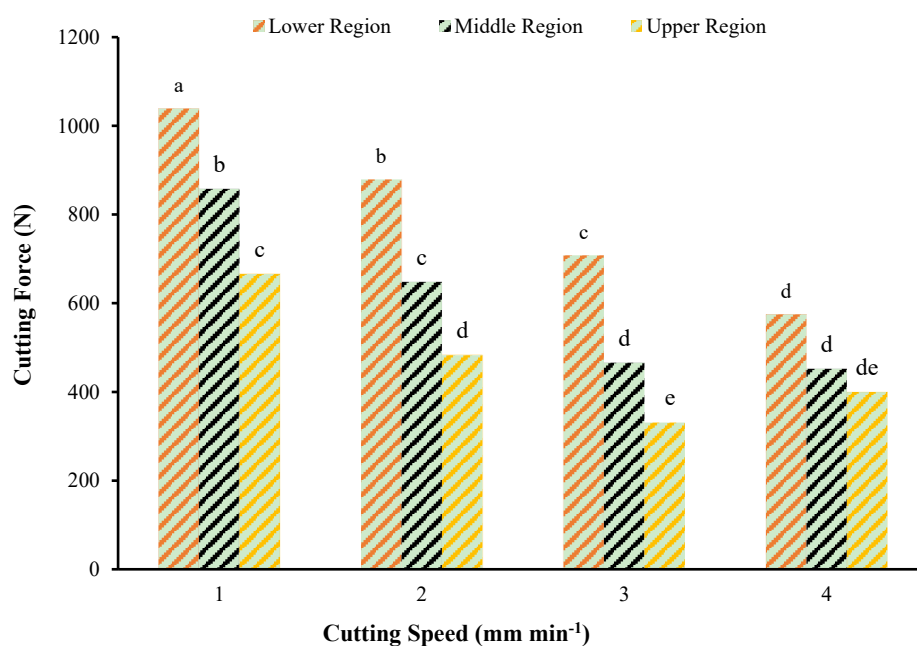


Figure 9 Interaction effect of stalk position and cutting speed on cutting force

### 3.6 Specific shear energy analysis

The results showed (Table 2) that the moisture content, stalk position, and cutting speed had a significant effect on the specific shear energy ( $P < 0.01$ ) and also interaction effect of moisture content and stalk cutting position on the specific shear energy was significant ( $P < 0.01$ ). In the following sections, the description of mentioned factors effects on specific cutting energy has been discussed in detail.

#### 3.6.1 Effect of moisture content

The effect of moisture content on specific shear energy was significant at the 1% probability level, with a significant difference observed among the three moisture content levels of 15%, 30%, and 60%. At 15% moisture content, the maximum specific shear energy

compares the average effects of various treatment combinations of stalk position and cutting speed on cutting force. The highest cutting force, 1093 N, was observed at a cutting speed of 1 mm min<sup>-1</sup> in the lower region of the stalks. In contrast, the lowest cutting force, 331 N, occurred at a cutting speed of 3 mm min<sup>-1</sup> in the upper region of the stalk. It was studied the impact of bevel angle and shear velocity on the shear strength and energy of rose (*Rosa hybrid* L.) flowers. They found that as shear velocity increased from 10 to 500 mm min<sup>-1</sup>, shear strength decreased from 2.75 MPa to 1.2 MPa (Heidari et al., 2011).

was 26.6 J mm<sup>-2</sup>, while at 60% moisture content, the minimum was 14.7 J mm<sup>-2</sup> (Figure 10). According to the Figure 10, it is clear that as the stalk moisture increased, the amount of specific shear energy sesame stalks decreased. The reason is that as the moisture content increases, the dry matter content in the stalk decreases relatively, the specific shear energy and shear strength decreases. It was investigated the cutting of basket willow stems at various cutting positions and moisture contents of 16.61%, 31.76%, and 47%, using a cutting speed of 5 mm min<sup>-1</sup>. The study revealed that as the stem moisture content increased from 16.61% to 47%, the average specific energy required for cutting decreased from 144.09 to 85.88 mJ mm<sup>-2</sup> (Nowakowski, 2012).

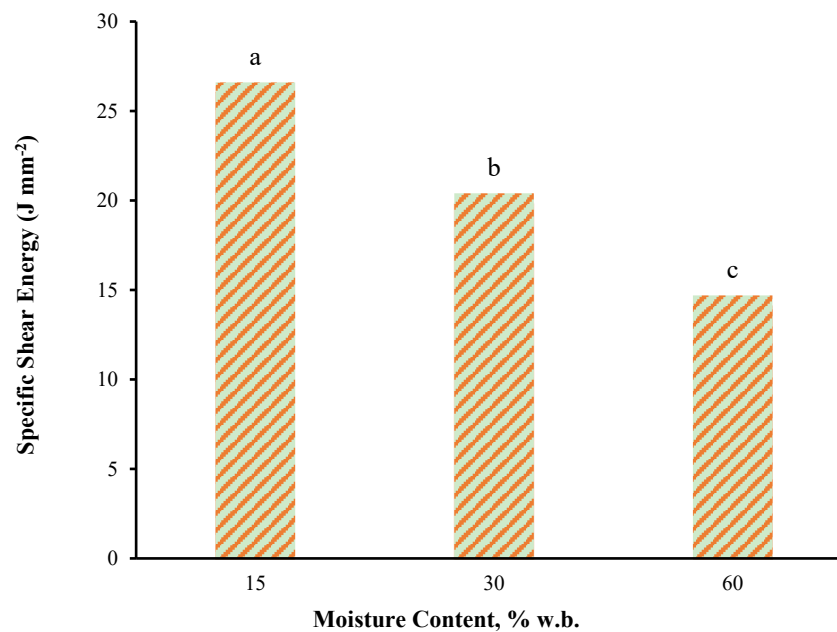


Figure 10 Effect of moisture content on specific shear energy

It was reported that in cutting cotton stalks at a cutting speed of  $500 \text{ mm min}^{-1}$  and stalk moisture contents of 35, 55, and 72 percent, the energy consumption of stalk cutting decreases with increasing stalk moisture content (Dauda et al., 2014). The stem cutting report of three types of forage plants stated that the stem cutting energy of all three plants decreases with an increase in stem moisture content from 26 to 57 percent (Bright et al., 1964). In cutting properties of olive suckers at three moisture content levels (17.05%, 34.44%, and 39.47%) and four cross-sectional areas (12.56, 28.27, 50.26 and  $78.54 \text{ mm}^2$ ) reported that the cutting energy requirement of olive suckers decreased with increasing moisture content (Sessiz et al., 2013).

According to the results of cutting sesame stems and also the results of similar research conducted on cutting stalks of other plants, the harder nature of dry stalks compared to wet stalks and the higher density of fibers in dry stalks compared to wet stalks can be stated as the reasons for the higher shear energy specific to dry stalks compared to wet stalks. In fact, the higher density of corn stalk fibers with reduced moisture content causes the holding force between the fibers to increase and the energy consumed in cutting the stalk to increase (Wanyuan et al., 2021).

### 3.6.2 Effect of stalk cutting position

ANOVA results indicated that specific shear

energy was affected by stalk cutting position at the 1% probability level. The specific shear energy reached its maximum of  $27.34 \text{ J mm}^{-2}$  in the lower region of the stalk, while the minimum value of  $18.69 \text{ J mm}^{-2}$  was observed in the upper region of the stalk (Figure 11). As shown in the figure, shifting the stalk cutting position from the bottom to the top, reduces the specific shear energy. Specifically, the specific shear energy at the bottom of the stalk is approximately 10% higher than at the middle, and the top region exhibits about a 24% reduction compared to the middle of the stalk. The results obtained are consistent with the results of stalk cutting of other plants. Cutting sesame stalk at four moisture contents (10%, 20%, 40% and 60% d. b.) and at different stalk sections (upper, middle and lower) stalk section had a significant effect ( $p < 0.01$ ) on maximum energy and the maximum energy decreased toward the upper regions of the stalk. The highest value was  $931.93 \text{ J}$  in the lower section at 40% moisture content, the lowest was  $186.23 \text{ J}$  in the upper section at 10% moisture content (Yilmaz et al., 2009). An experiment was conducted to cutting chickpea stem at four moisture contents and at the bottom, middle and top regions of the stem. It was obtained the maximum specific shearing energy was found to be  $34.81 \text{ mJ mm}^{-2}$  and occurred at the bottom region (Amirian et al., 2017). It was reported that in

cutting privet stalks at a cutting speeds of 5, 10, 15 and 20  $\text{mm min}^{-1}$ , three internode positions: fifth, tenth and fifteenth and stalk moisture contents of 58% wet base, the highest average shear consumption energy occurred in the lower region (at the fifteenth internode), while the lowest was observed in the upper region (at the fifth internode) (Kamandar et al., 2018). Sessiz et al. (2013) reported that in cutting properties of olive suckers at three moisture content levels (17.05%, 34.44%, and 39.47%) and four cross-sectional areas

(12.56, 28.27, 50.26 and 78.54  $\text{mm}^2$ ) the cutting energy requirement of olive suckers increased with increasing cross-sectional area. Nazari Galedar et al. (2008) reported that in cutting of alfalfa stems at four moisture content levels of 10, 20, 40 and 80% and three cutting positions of upper, middle and lower regions, the shearing stress and the specific shearing energy were found to be higher in the lower region of the stalk due to structural heterogeneity.

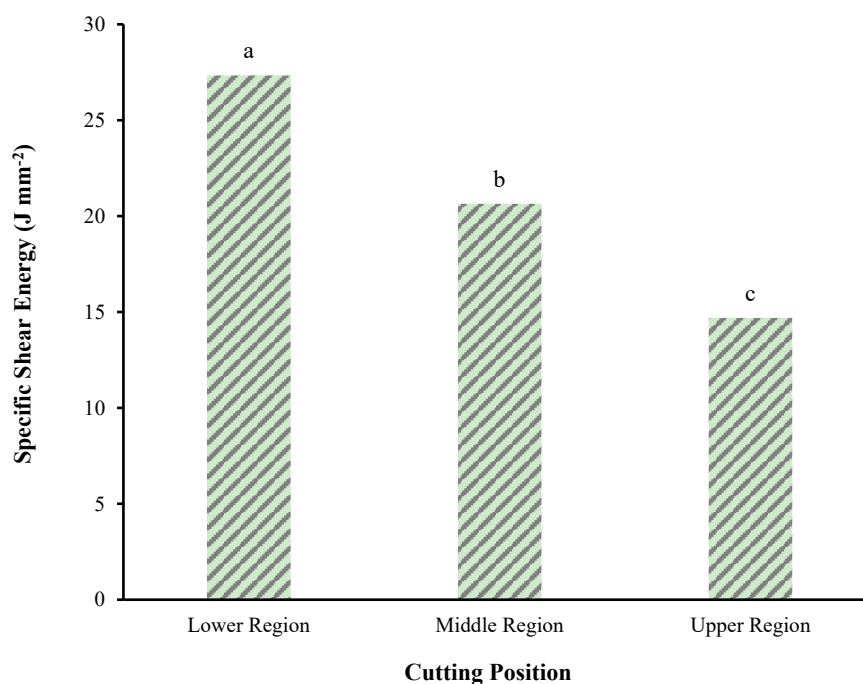


Figure 11 Effect of stalk cutting position on specific shear energy

A study was carried out on the bending and shearing characteristics of sunflower stalk residue. It was reported that the specific shearing energy decreased towards the upper regions. Its values varied between 1.86–8.5, 1.7–10.7, and 2.4–11.0  $\text{mJ mm}^{-2}$  for the upper, middle, and lower regions, respectively. It was greater in the lower regions because of the accumulation of more mature fibers in the stem (Ince et al., 2005). In shearing properties of sugarcane stems across five moisture content levels, three shearing speeds, and ten stem positions reported that specific shearing energy decreased from 112.200  $\text{mJ mm}^{-2}$  in the lower regions to 86.020  $\text{mJ mm}^{-2}$  in the upper regions, showing higher values at the lower levels of the stem (Hemmatian et al., 2012). Based on the results of sesame stalk shearing and similar studies on the

stalk shearing of other plants, it can be concluded that the specific shear energy is higher in the lower regions of the stalk due to the accumulation of more mature fibers.

### 3.6.3 Effect of cutting speed

The specific shear energy reached its maximum of 31.08  $\text{J mm}^{-2}$  at the lowest cutting speed of 1  $\text{mm min}^{-1}$ , while its minimum value of 17.05  $\text{J mm}^{-2}$  occurred at a cutting speed of 4  $\text{mm min}^{-1}$  (Figure 12). Figure 12 illustrates that the specific shear energy decreases with an increase in the cutting speed of the sesame stalk. Specifically, the specific shear energy reduces by approximately 17% when the cutting speed increases from 1 to 2  $\text{mm min}^{-1}$ , by about 21% when increasing from 2 to 3  $\text{mm min}^{-1}$ , and by around 16% when rising from 3 to 4  $\text{mm min}^{-1}$ .

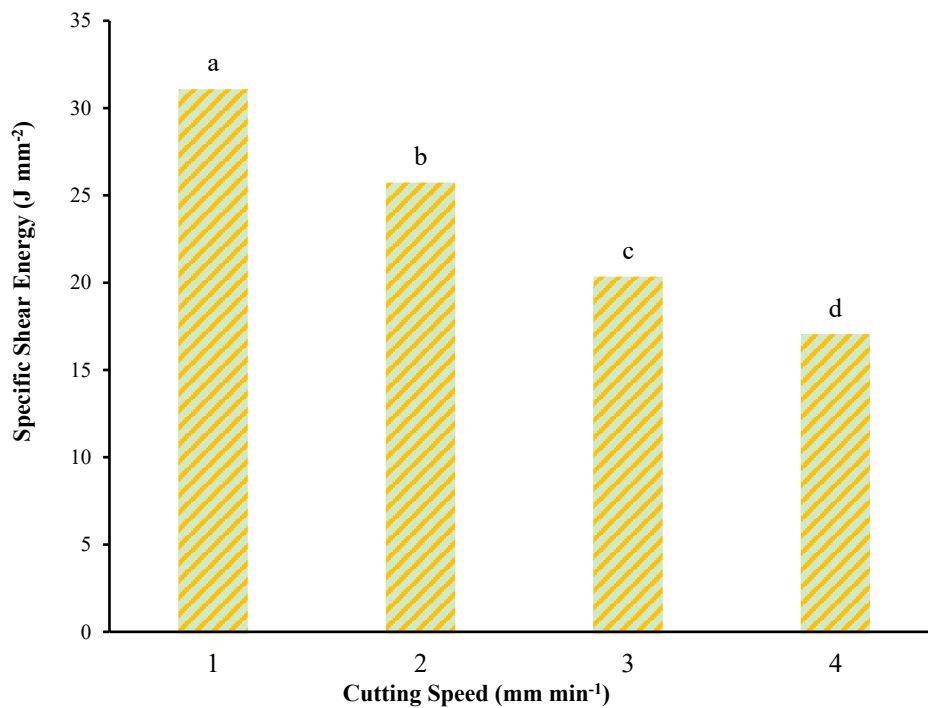


Figure 12 Effect of cutting speed on specific shear energy

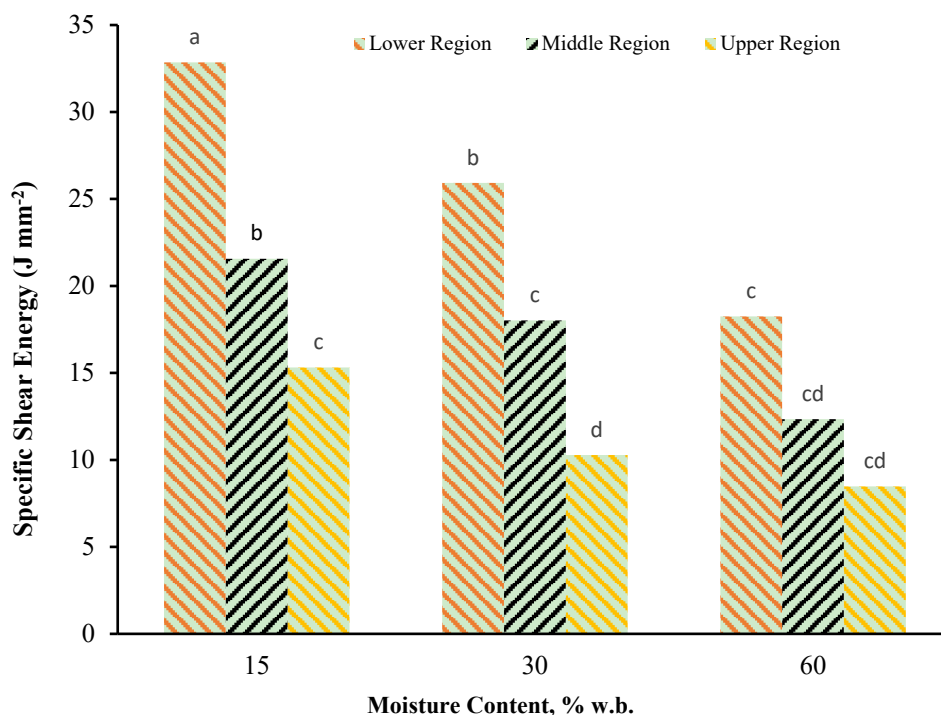


Figure 13 Interaction effect of moisture content and stalk position on specific shear energy

It was reported that increasing the shear velocity of saffron (*Crocus sativus* L.) stems from 20 to 200 mm min<sup>-1</sup> significantly reduced shear energy per unit area from 0.467 to 0.340 mJ mm<sup>-2</sup> (Vale Ghozhedi et al., 2010). Also, a research was studied on shear strength and shearing energy of pyrethrum flower stem by using double shear tests. It was reported that, when cutting pyrethrum flower stems the specific energy of stem decreased from 3.23 to 2.76 mJ mm<sup>-2</sup> as the

cutting speed increased from 200 to 500 mm min<sup>-1</sup> (Khazaei et al., 2002). According to the results of cutting sesame stalk and similar research conducted on cutting stem of other plants, the reason for the reduction in energy required for cutting with increasing cutting speed is that the stem is initially compressed against the blade, but as the cutting speed increases, the elastic cell wall does not have enough time to transfer force to the viscous fluid inside the cell,

and therefore it is cut faster and with less force.

### 3.6.4 Interaction effect of moisture content and stalk cutting position

The ANOVA results indicated that the specific shear energy parameter was significantly influenced by the interaction between moisture content and stalk position (A×B), with significance observed at the 1% probability level. The average specific shear energy of different treatment combinations of moisture content and stalk position is compared in Figure 13. The highest specific shear energy (32.85 J mm<sup>-2</sup>) was observed at 15% moisture content when cutting the lower region of the stalk, while the lowest value (8.48 J mm<sup>-2</sup>) occurred at 60% moisture content when cutting the upper region of the stalk. The reason is that an increase in moisture content reduces the relative dry matter content in the stalk, which in turn lowers cutting resistance and decreases the effort required for cutting and breaking the stalk. In shearing properties of safflower stems at four moisture levels of 8.61%, 16.37%, 25.26%, and 37.16% and at three cutting positions of the lower, middle, and upper regions, the minimum energy consumption of cutting was obtained at the upper cutting position and moisture level of 61.8%, and the maximum energy consumption of cutting was obtained at the lower cutting position and moisture level of 37.16% (Shahbazi et al., 2012). Shearing properties of sugar cane stems were determined at five moisture content levels (46%, 54%, 62%, 70% and 78% w.b.), three shearing speed (5, 10 and 15 mm min<sup>-1</sup>) and at ten positions on the stem. It was reported decrease in moisture content of stem from 78% to 46% w.b. led to 16.7% decrease in the specific shearing energy. The specific shearing energy were found to be higher in the lower region of the stem due to structural heterogeneity (Hemmatian et al., 2012). This is in line with the trial of Amirian et al. (2017), who reported a maximum specific shear energy of 34.81 mJ mm<sup>-2</sup> for chickpea stalks, observed at the bottom region with a moisture content of 25% (w.b.). An experiment was conducted to cutting chickpea stem at four moisture contents of 10%, 15%,

20% and 25% w.b. and at the bottom, middle and top regions of the stem. It was obtained the maximum specific shearing energy was found to be 34.81 mJ mm<sup>-2</sup> and occurred at the bottom region with the moisture content of 25% w.b.

## 4 Conclusion

In this study, the effect of cutting speed, cutting position and moisture content of sesame stalk on cutting force and specific shear energy was investigated. The results of this research are as follows:

As the stalk moisture content increased, both specific shear energy and cutting force decreased.

It can be concluded that the cutting force and specific shear energy are greater in the lower regions of the stalk.

With increasing cutting speed, the shear force and specific shear energy decreased.

The lower region of the sesame stalk demonstrates maximum cutting force due to its lower moisture content, greater fiber density, and thicker cell walls compared to the upper region.

It was observed that increasing the stalk moisture content from 15% to 60%, raising the cutting speed from 1 to 4 mm min<sup>-1</sup>, and transitioning from the bottom to the top of the stalk all resulted in a decrease in the values of specific shear energy and cutting force.

At a stalk moisture content of 60%, the lowest average specific shear energy is 14.70 J mm<sup>-2</sup>, while the minimum average cutting force of 520 N is observed when cutting the upper region of the stalk.

The highest specific cutting energy of 31.08 J mm<sup>-2</sup> and the maximum average cutting force of 881 N were both achieved at a cutting speed of 1 mm min<sup>-1</sup>.

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