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Cutting energy of rice stem as influenced by internode position and dimensional characteristics of different varieties

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Abstract

The exact knowledge of stem cutting energy is one of the main parameters for optimizing design of cutting elements in harvesting machines. In this study, cutting energy of rice stem at different internode positions was examined. Four common Iranian rice varieties, namely Khazar, Hybrid and Dorfak (high-yielding and lodging tolerance varieties) and Tarom (local and lodging susceptible variety) were used in the experiment. A pendulum impact type testing apparatus was fabricated and used for the tests. The results indicated that cutting energy significantly (p<0.01) affected by internode position and dimensional characteristics of rice stem. Among the varieties, the highest cutting energy (324 mJ) was registered for Khazar, while the lowest value (79 mJ) was measured for Tarom. There was a highly significant and positive correlation between the cutting energy and stem wall thickness, Major and minor diameters and cross-sectional area of rice stem. The results also revealed that the cutting energy of rice stem in the second internode was decreased by the average of 32.5% compared to third internode position. It was concluded that with increasing cutting height toward the second internode, more energy saving can be achieved by harvesting machines.

Keywords: Rice stem, cutting energy, internode position, pendulum impact.

Abbreviations:

A	The stem cross-sectional area (mm^2)
a, b and t	The major diameter, minor diameter and thickness of the stems, respectively (mm)
V_c	Peripheral velocity of the pendulum arm (ms^{-1})
$V_{c\max}$	Maximum peripheral velocity of the pendulum arm (ms^{-1})
θ_d	The initial angle (dropping angle) of the pendulum arm (°)
W	The weight of pendulum (N)
R	The distance between the rotational center and center of gravity (m)
I	Moment of inertia (kg m^2)
L	The length of the pendulum (m)
E_c	The cutting energy consumption (mJ)
θ_c	The final angle of the pendulum arm (°)
D	Major diameter (mm)
d	Minor diameter (mm)
IN	Internode position

Introduction

The variation in the physical properties of plant stalks and the resistance of cutting equipment have to be known in order to understand the behavior of material with respect to different operation of conditions. Increasing interest in mechanized rice harvesting and commercial use of rice straw has prompted the need for engineering data on stem properties (Yore et al., 2002). Comparative performance of cutting elements applied in harvester design can be judge by their cutting energy requirements, cutting force and stress applied (Chakraverty et al., 2003). Hence, it is necessary to determine the cutting energy requirements for suitable knife design and also operational parameters (Yilmaz et al., 2009). Many researchers have reported on the cutting strength of the plant stem and effective parameters on cutting energy as wheat (Hoseinzadeh et al., 2009; Esehaghbeygi et al., 2009; Muller, 1988), barely (Tavakoli et al., 2009), sesame (Yilmaz et al., 2009), sorghum (Chattopadhyay and Pandey, 1999), potato vines (Godesa, 2004), soya bean (Mesquita and Hanna, 1995), sunflower stalk (Kocabiyik and Kayisoglu, 2004) and alfalfa (Nazari Galedar et al., 2008). In the case of rice, Lee

Table 1. Some determined physical properties of rice paddy stem for the tested varieties

Item		Variety			
		Tarom	Hybrid	Khazar	Dorfak
Stem height* (mm)		118.77±6.81**	79.46±5.01	88.02±5.94	72.57±3.85
Panicle weight (g)		2.28±0.85	3.97±0.96	5.14±0.95	3.94±0.86
Internode length (mm)	IN1	47.00±5.26	38.12±4.21	46.79±3.75	32.06±1.74
	IN2	31.48±3.01	17.64±3.70	22.64±1.87	16.96±1.12
	IN3	24.35±2.70	11.36±2.06	11.20±2.89	10.36±1.76
	IN4	13.41±6.40	7.69±2.35	5.16±2.41	8.35±2.29
Major diameter (mm)	IN1	2.83±0.33	4.11±0.35	5.07±0.50	3.55±0.28
	IN2	4.28±0.63	7.38±0.54	8.36±0.87	7.01±0.84
	IN3	5.15±0.67	8.55±0.80	9.32±0.85	8.46±0.98
	IN4	5.98±0.82	9.29±0.93	9.36±0.88	9.16±1.12
Minor diameter (mm)	IN1	2.66±0.32	3.82±0.32	4.81±0.48	3.40±0.28
	IN2	3.92±0.67	6.09±0.67	7.58±0.84	5.34±0.48
	IN3	4.65±0.78	7.38±0.70	8.37±0.77	6.67±0.71
	IN4	5.10±0.65	7.57±0.83	8.48±0.78	7.53±0.67
Thickness of internode (mm)	IN1	0.72±0.80	1.03±0.08	1.44±0.12	0.88±0.08
	IN2	0.92±0.12	1.53±0.23	1.93±0.17	1.35±0.14
	IN3	1.08±0.15	1.71±0.21	2.21±0.23	1.69±0.15
	IN4	1.35±0.19	1.89±0.19	2.46±0.21	1.84±0.18
Cross-sectional area (mm)	IN1	4.61±0.97	9.50±1.38	19.20±3.34	7.21±1.12
	IN2	9.30±2.62	25.19±4.55	36.91±6.55	20.59±3.41
	IN3	13.09±3.36	33.26±7.12	46.25±7.77	31.4±5.99
	IN4	17.93±4.56	37.28±6.66	50.13±7.68	35.54±6.54

* The stem height was measured from a height of stem that growth on ground to start position of panicle. ** The numbers of after ± sign are standard deviation. IN1, IN2, IN3 and IN4 are first, second, third and fourth internodes, respectively.

Table 2. Regression equations representing relationship of cutting energy for second and third internodes with thickness of internode of paddy rice stem for tested variety

Internode	Variety			
Position	Tarom	Hybrid	Khazar	Dorfak
(IN_2)	E_c=180.90t- 98.07 R^2=0.815	E_c=323.30t- 251.40 R^2=0.893	E_c=305.70 t- 341.80 R^2=0.821	E_c=211.90t-136.90 R^2=0.887
(IN_3)	E_c=242.50t-170.10 R^2=0.902	E_c=343.00t-337.70 R^2=0.899	E_c=331.50t - 404.40 R^2=0.877	E_c=362.70t -373.70 R^2=0.884

IN2 and IN3 are the second and third internodes, respectively; t is the stem wall thickness in mm and E_c is the cutting energy in mJ.

and Huh (1984) investigated the cutting force of two varieties of rice stem. Their results showed that the cross-sectional area and moisture content of the crop had significant effect on cutting energy and maximum cutting force. Tabatabaee Koloor and Borgheie (2006) measured the static and dynamic cutting force of rice stems for different varieties including Binam, Khazar, Hashemi and Fajr. Their results showed that the highest shearing strength was related to Khazar variety and the lowest value in Tarom. Tabatabaee Koloor (2007) studied the effect of blade parameters on the cutting energy of rice stem (Sepidroud variety) by an impact shear test apparatus. He resulted that the specific cutting energy decreased with increasing in oblique angle and it is a minimum at 30º. He deduced that the specific cutting energy increased at a blade velocity less than 2.24 m s^{-1}. Majumdar and Dutta (1982) studied the required shearing energy for two varieties of rice and a variety of wheat in different cutting speeds and edge angles. Results showed that the effect of crop type and edge angles on shearing energy were significant. Yore et al. (2002) investigated the cutting properties of rice straw to aid development of novel header system for combines. Tavakoli et al. (2010) compared mechanical properties of two varieties of rice straw, namely Hashemi and Alikazemi. The results showed that the energy requirement for cutting of Hashemi straw is more than Alikazemi variety. Although many studies have been conducted to determine effective parameters on mechanical properties of other crops, little comparative study was reported on the stem cutting energy of high-yielding and local Iranian rice varieties. Therefore, the objective of this study was to determine the variations in cutting energy rice stem with respect to physical properties, such as internode positions, stem wall thickness, major and minor diameters and cross-sectional area of rice stem.

Material and methods

Sample preparation and measuring apparatus

This study was carried out in the Agricultural Engineering Department, Rice Research Institute of Iran (RRII), Rasht, Guilan, Iran. Four common Iranian rice varieties, namely Khazar, Hybrid, Dorfak (high-yielding and lodging tolerant varieties) and Tarom (local and lodging susceptible variety) were selected for the experiment. Samples of the rice stems were cut from the ground level, sealed in polyethylene bags and transferred to the laboratory of Agricultural Engineering

Table 3. Regression equations representing relationship of cutting energy for second and third internodes with major diameter and also minor diameter of rice stem for tested variety

Internode		Variety			
Position	Diameter	Tarom	Hybrid	Khazar	Dorfak
IN_2	Major	E_c=42.06D-112.90 R^2=0.866	E_c=56.61D-231.00 R^2=0.758	E_c=79.25D-403.30 R^2=0.700	E_c=36.35D-105.60 R^2=0.866
	Minor	E_c=39.49d-89.28 R^2=0.885	E_c=60.33d-182.30 R^2=0.82	E_c=64.10d-249.70 R^2=0.904	E_c=63.18d-181.9 R^2=0.903
IN_3	Major	E_c=45.18D-134.20 R^2=0.899	E_c=65.34D-305.80 R^2=0.845	E_c=99.38D-598.80 R^2=0.793	E_c=55.30D-230.50 R^2=0.840
	Minor	E_c=47.19d-122.60 R^2=0.905	E_c=94.54d-441.10 R^2=0.813	E_c=105.20d-556.60 R^2=0.913	E_c=81.78d-309.50 R^2=0.90

Ec is cutting energy in mJ, IN2 and IN3 are the second and third internodes, respectively, D and d are the major and minor diameters, respectively in mm.

Table 4. Regression equations representing relationship between the stem cross-sectional area (A) and variety on the cutting energy (E_c) in second and third internodes

	Internode position	
Variety	IN_2	IN_3
Tarom	E_c=10.14A – 26.28 R^2=0.901	E_c=10.14A – 43.42 R^2=0.921
Hybrid	E_c=9.45A – 56.51 R^2=0.935	E_c=9.28A – 102.4 R^2=0.944
Khazar	E_c=9.92A – 142.5 R^2=0.910	E_c=10.67A – 165.3 R^2=0.908
Dorfak	E_c=7.77A – 11.52 R^2=0.908	E_c=8.56A – 30.13 R^2=0.931

Ec is cutting energy in mJ, IN2 and IN3 are the second and third internodes, respectively, A is the stem cross-sectional area in mm2.

Department for cutting test. All the required measurements for each variety were performed on the same day of harvesting. A pendulum impact testing apparatus was fabricated and used to measuring the cutting energy (Fig. 1a). The apparatus consisted of a commercial serrated edge knife section, which was attached to the end of a pendulum arm and performed the cutting operation of rice stems in the lowest position of rotary movement. A pointer on a semicircle scale connected to the main rotary shaft recorded the final angle (the angle produced between pendulum and perpendicular line) of pendulum after cutting the rice stem.

Experimental methods

In order to determine the initial moisture content of rice stems, three samples of 15 g were weighed and dried in an oven of 103ºc for 24 h and then reweighed (ASAE 2006). The stem internodes were separated out according to their position down from the ear (Annoussamy et al., 2000). Four internodes of paddy stems were named first to fourth from the top (panicle neck node) toward the bottom (plant base), respectively (Fig. 1b). The stem cutting energy was measured in the second and third internodes positions, as most of rice variety is cut in these part of the stem by the harvesters like combines and reapers. In each internode position, the stem height, internode length, wall thickness, major and minor diameters were measured using a digital slide caliper (Mitutoya caliper, Japan) with the accuracy of 0.01 mm. The stem cross-sectional area, considering oval shape for rice stems was calculated through the following equation:

$$A = \frac{\pi . t}{2}\left[a + b - 2t\right] \quad (1)$$

Where A is the cross-sectional area of rice stem in mm^2, and *a*, *b* and *t* are the major diameter, minor diameter and thickness of the stems in mm, respectively. In order to calibrate the pendulum impact testing device, measuring system for eliminating of friction and air resistance was carried out and the value of final angle (θ_c) were amended according to the obtained calibration equation. The relation between peripheral velocity (V_c) and initial angle (dropping angle) of a pendulum arm (θ_d) at the impact moment was calculated from the following equation (Tabatabaee Koloor, 2007):

$$V_c = \sqrt{\frac{2WR(1-\cos\theta)}{I}}L \quad (2)$$

Where, W is the weight of pendulum in N, *R* is the distance between the rotational center and center of gravity in m, *I* is the moment of inertia in kg m^2 and *L* is the length of pendulum in m. It is obvious that when the value of θ is equal to 90º, the V_c will have the maximum value. Considering the maximum cutting velocity of 2.77 m s^{-1} by pendulum for single paddy stem (Chakraverty et al., 2003), the optimum dropping angle of pendulum (θ_d) was calculated by the following equation:

$$\theta_d = Arc\cos\left(1 - \left(\frac{2.77}{V_{c\max}}\right)^2\right) \quad (3)$$

Where, $V_{c\max}$ is the peripheral velocity of the pendulum in the angle of 90º calculated from the equation 2. At each test

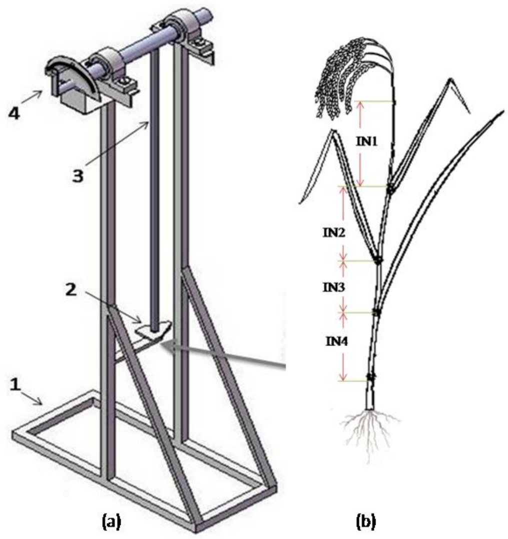


Fig 1. The Schematic representation of (a) Pendulum impact testing apparatus used in the experiments (1. Chassis, 2. Cutting blade and stationary ledger plate, 3. Pendulum arm, 4.pointer). (b) Rice stem (IN1, IN2, IN3 and IN4 are first, second, third and fourth internodes, respectively).

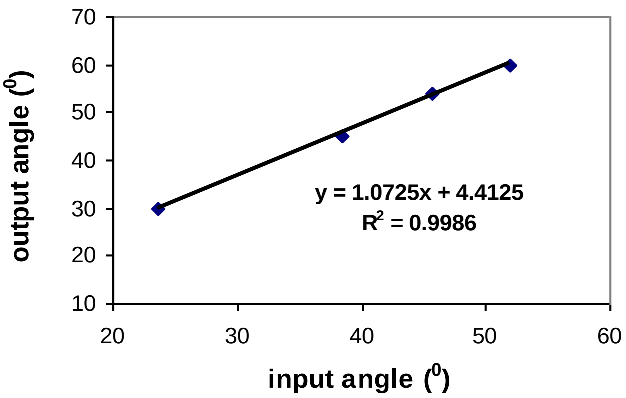


Fig 2. The relationship between the initial (input) and final (output) angles of the pendulum arm in cutting of rice stem

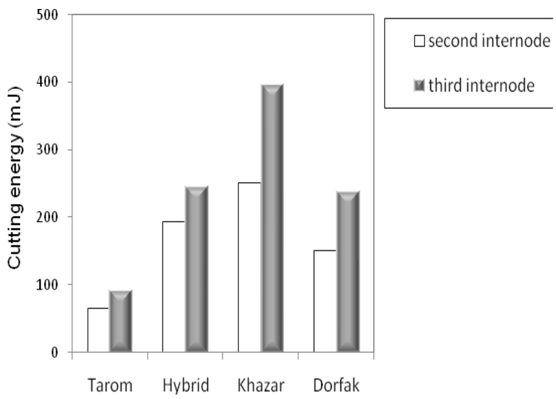


Fig 3. The effect of variety on cutting energy of rice stem

run, a rice stem was fixed in a special holder, which was located between the cutting blade and stationary ledger plate, and stem cutting action was performed by releasing the pendulum arm from the calculated dropping angle. The cutting angle (θ_c) was read from the pointer sign over semicircular scale in degree. Then the cutting energy of rice stem (E_c in mJ) was calculated by the following equation (Tabatabaee Koloor, 2007):

$$E_c = WR(\cos\theta_d - \cos\theta_c) \times 10^3 \qquad (4)$$

Experimental design and statistical analysis

This study was planned as a randomized complete block design (RCBD) with 20 replications in each treatment. Experimental data were analyzed using analysis of variance (ANOVA). Comparison between treatment means was made using Duncan's multiple range tests at 1% and 5% levels in SAS 9.0 software.

Result and discussions

Physical properties of rice stem

A summary of the results on some determined physical properties of at initial harvest moisture content are given in Table 1. The results indicated that among the tested varieties, the highest stem height (length between plant base and panicle neck node) and internode length (the length of two consecutive on rice stem) was measured in Tarom variety, while the greatest stem major and minor diameters, stem wall thickness and cross-sectional area was registered in Khazar followed by Hybrid variety. It can be seen that in all of the varieties, the internode length was decreased towards the forth internode position, while the stem major and minor diameters, stem wall thickness and cross-sectional area increased.

Relationship between initial and final angles of pendulum arm

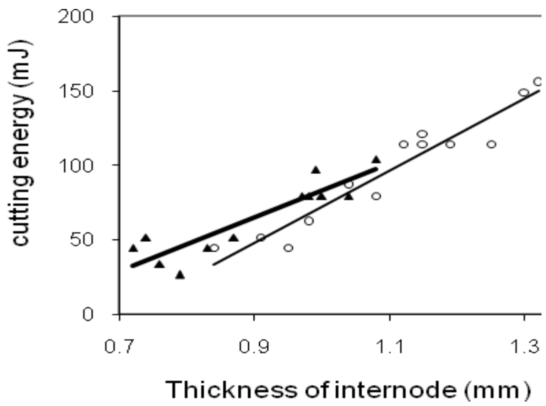
The obtained results on the relationship between the initial and final angles of pendulum arm in impact testing of rice stem are shown in Fig. 2. As shown in the figure, there was a linear and positive relationship between the initial and final angles of the pendulum arm with high coefficient of determination (R^2). The final angle of each experiment was amended with substituting of the following equation:

$$\theta_C = 1.0725\theta_d + 4.4125 \qquad R^2 = 0.998 \qquad (5)$$

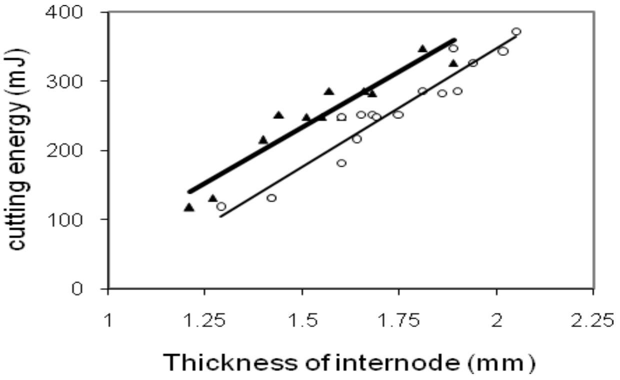
Where, θ_c and θ_d are the final and initial (dropping) angles of the pendulum arm in degrees, respectively.

Cutting energy of rice stem for the different varieties

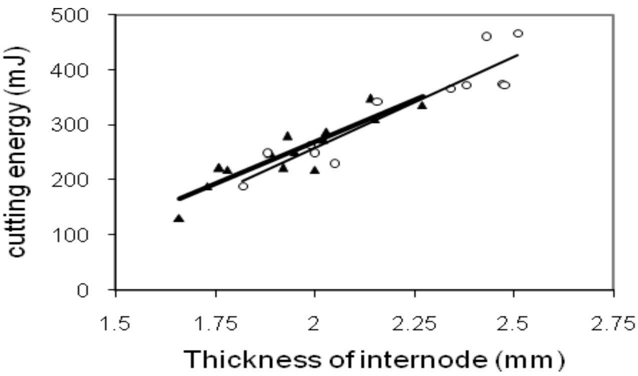
The comparison between the cutting energy of rice stem for the tested varieties at the second and third internode positions is illustrated in Fig. 3. The results indicated that among the varieties, Khazar was found to exhibit the most required cutting energy followed by Hybrid variety. This effect could be related to higher stem wall thickness and cross-sectional area of Khazar compared to the other examined varieties, which resulted in greater contact area and



(A)



(B)



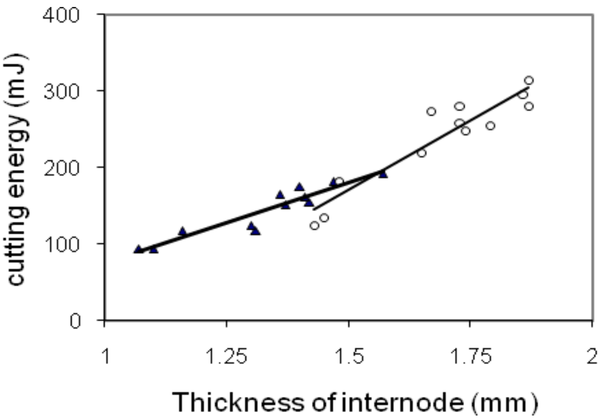
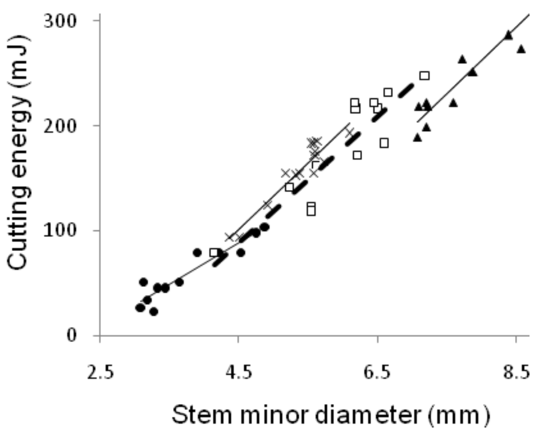


Fig 4. The interaction effect of internode position and stem wall thickness on cutting energy of rice stem. (▲) second and (○) third internodes, (a) Tarom, (b) Hybrid, (c) Khazar and (d) Dorfak

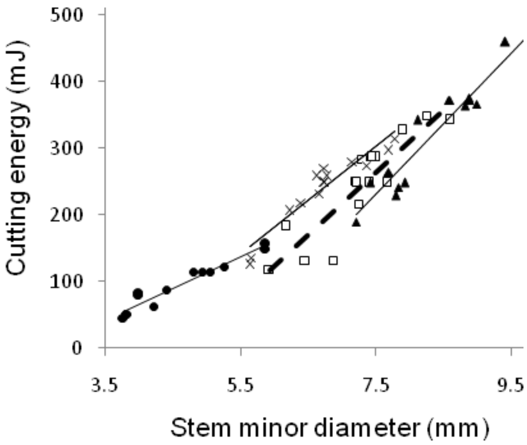
friction between the blade and the stem, leading to more cutting energy. Tabatabaee Koloor and Borgheie (2006) in their investigation on shearing strength of rice varieties reported that the cross-sectional area of Khazar (high-yielding variety) was about 2.0 times bigger than Hashemi (as a local variety). The cutting energy values in the second internode position for the varieties of Khazar, Hybrid, Dorfak and Tarom were 250.66, 192.48, 150.00 and 65.07 mJ, respectively. The corresponding values in the third internode were 397.45, 246.94, 238.84 and 93.13 mJ, respectively. This means that the cutting energy was increased with decreasing of cutting height. This may be possibly due to the accumulation of more mature fibers in lower parts of the stem. Similar trends were reported by Nazari Galedar et al. (2008) for alfalfa stem, Tavakoli et al. (2009) for barely stem, Ince et al. (2005) for sunflower stalk, Esehaghbeygi et al. (2009) for wheat, Zareiforoush et al. (2010) for rice straw and Chattopadhyay and Pandey (2001) for sorghum stalk. The cutting energy of two Iranian local rice varieties, namely Hashemi and Alikazemi was found to be 228.18 and 140.72 mJ in second internode position and the corresponding values in third internode was measured to be 236.06 and 191.31 mJ, respectively (Tavakoli et al., 2010). Yore et al. (2002) investigated the cutting properties of rice straw to aid development of novel header system for combines. Results showed that the cutting location and number of stem were significant factors on the cutting energy. Considering obtained results, with increasing the cutting height towards the second internode, the cutting energy will be decreased by the average of 32.5%. This reduction was 37% for Khazar and Dorfak varieties and also 22 and 30% for Hybrid and Tarom varieties, respectively. As the cutting energy indicated how much energy is needed to cut the stem, Therefore, the lesser is the stem strength, the more optimized will be energy consuming by the machine (Yiljeb and Mohammed, 2005; Hoseinzadeh et al., 2009).

Effect of stem wall thickness on the cutting energy

The effect of stem wall thickness on the cutting energy in the second and third internode positions is presented in Fig. 4. It can be observed that for each examined variety, the cutting energy increased as the stem wall thickness increased. The results also indicated that more cutting energy was required at the third internode compared to the second internode position. This may be due to greater stem wall thickness towards the lower height of the stem with maximum value for Khazar variety and with the minimum for Tarom. Similar trend was reported by Esehaghbeygi et al. (2009) for wheat stem and Skubisz et al. (2005) for pea stem. As well known, the resistance of plant to lodging is closely related to the physical and mechanical properties of their stems (Grundas and Skubisz, 2008; Ooawa et al., 1993). According to Chaturvedi et al. (1995), lodging tolerant rice varieties had more vascular bundles than susceptible varieties, which resulted in higher cutting energy as measured in this experiment. The regression equations describing the relationship between the stem wall thickness and cutting energy requirements of the four tested varieties at the second and third internode positions are given in Table 2. As shown, there are linear relationships between the cutting energy and stem wall thickness, however higher coefficient of determination (R^2) was obtained in third internode for all the varieties.

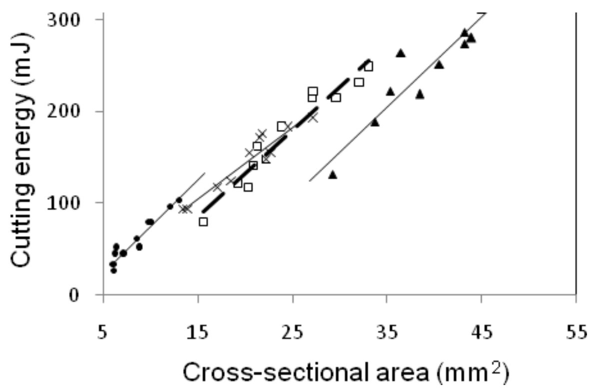


(a)

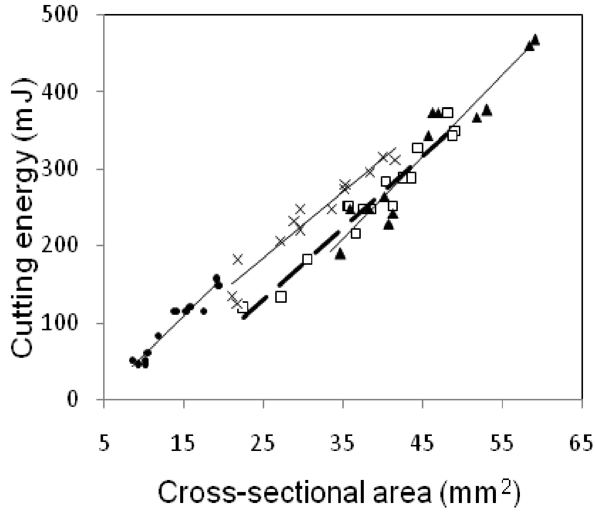


(b)

Fig 5. The interaction effects of the minor diameter of rice stem and variety on the cutting energy for (a) second and (b) third internodes (● Tarom, ☐ Hybrid, ▲ Khazar and × Dorfak)



(a)



(b)

Fig 6. The interaction effects between the cross-sectional area of stem and variety on the cutting energy for **(a)** second and **(b)** third internodes (● Tarom, ☐ Hybrid, ▲ Khazar and × Dorfak)

Effect of stem diameters and cross-sectional area on the cutting energy

The effects of stem minor diameters of the second and third internode on the cutting energy are presented in Fig. 5. An increasing trend was observed in cutting energy with increasing the stem minor diameters of the varieties in the two internode positions, with the maximum value for Khazar followed by Hybrid, Dorfak and Tarom varieties. Khazar is a relatively short and thick plant variety, while Tarom has a narrow and tall stem, which effectively influences on the stem cutting energy. Esehaghbeygi et al. (2009) reported that taller plants have lower stem diameter and shearing energy will be decreased. The regression equations describing the stem major and minor diameters and the cutting energy at the second and third internode positions of the four varieties are given in Table 3. As shown, there are a highly significant and positive correlation between the independent and dependent variables. The interaction effects of the stem cross-sectional area and variety on the cutting energy of the second and third internodes are presented in Fig. 6. The results revealed that for each type of variety, there was a significant correlation between the stem cross-sectional area and cutting energy. The regression equations describing the relationship between the stem cross-sectional area and cutting energy are given in Table 4. It can be expressed that the cross-sectional area played more effect on the cutting energy than the stem wall thickness and diameter.

Conclusion

The following conclusions were drawn from the result of this study: 1) For all the tested varieties, the internode length was decreased towards the forth internode position, while the stem major and minor diameters, stem wall thickness and cross-sectional area increased. 2) The cutting energy of rice stem at third internode was significantly higher than that of the second internode. The cutting energy of rice stem in the second internode was decreased by the average of 32.5% compared to third internode position. 3) It was concluded that increasing cutting height towards the second internode causes to more energy saving by harvesting machines.

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