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Effects of Moisture Content and Stem Diameter on Mechanical Properties of Chickpea Plants for Harvester Development

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ABSTRACT

Background: Information on the mechanical properties of chickpea plants and their changes with moisture content and stem diameter is highly needed to design agricultural equipment such as harvesters, threshers, hoppers, chutes, etc.

Methods: The experiments were conducted at 17.44, 15.33 and 13.13% levels of moisture content and 5-6×10^{-3}, 7-8×10^{-3} and 9-10×10^{-2} m levels of stem diameter to measure properties such as cutting energy, cutting force, specific cutting energy and bending force of chickpea plant in *rabi* season during 2022-2023.

Results: The range of cutting energy of chickpea plants was found to be 0.39 to 7.48 J for 6×10^{-3} to 1×10^{-2} m stem diameter with blade velocity of 4.57 to 1.66 ms^{-1} at 13.33 to 17.44% moisture content. The cutting force of chickpea plants varied from 65 to 748 N for 6×10^{-3} to 1×10^{-2} m stem diameter with blade velocity of 4.57 to 1.66 ms^{-1} at 13.33% to 17.44% moisture content. On ther other side the specific energy was found to be 0.0106 to 0.1219 J mm^{-2} for 6×10^{-3} to 1×10^{-2} m stem diameter at 13.13 to 17.44% moisture content. The bending force of chickpea plants was found in the range 1.25 to 27.28 N for 6×10^{-3} to 1×10^{-2} m stem diameter at 17.44 to 13.13% moisture content.

Key words: Bending force, Cutting energy, Cutting force, Specific cutting energy.

INTRODUCTION

The chickpea plant (*Cicer arietnum L.*) an important food source, is grown in more than 50 countries (89.7% of the area is in Asia, 4.3% in Africa, 2.6% in Oceania, 2.9% in America and 0.4% in Europe) (Gaur *et al.* 2010). It is the third highest producing pulse crops in the world, producing 11.67 million tons per year with a global yield of about 1.8 tons per hectare. Production of chickpea in terms of harvested area has reached to a high of 14.56 M ha in 2017. As the world's largest producer of chickpeas, India accounts for over 65% (9.075 million tons) of all chickpea production and has stable mean yields of about 935 kg per ha (Merga and Haji, 2019). Due to a semi-spreading growth habit and a height of lower pods about 0.15-0.20 m from the ground, traditional varieties of chickpea are unsuitable for mechanical harvesting. In addition, they have a fruiting zone located about 30 cm above the ground (Jayalakshmi, 2016). Chickpeas are typically harvested with sickles after they have matured and dried. Traditionally, chickpeas have been harvested manually, a tedious and inefficient process. Using a hand-pulling and uprooting process of the entire plant has many disadvantages, including the loss of nitrogen-fixing bacteria, a salty taste in the plant residue for animal food and an increase in manpower costs as compared to other harvesting methods.

For manual harvesting, 64 man-h per ha were required, which makes the process time consuming (Golpira *et al.* 2013). Where as in the wide header of the combine excessive pod loss occurs due to uneven ground. The low height of the plant during chickpea harvesting is inappropriate for conventional headers. It is reported that some farmers used the multi-crop combine harvesters readily available on the market. However, they ended up losing 200-300 kilograms of seeds per hectare, which amounts to an approximate loss of Rs. 8000 to 13,000 per hectare (Jayalakshmi, 2016). Cellular materials have a variety of properties that contribute to their strength, including compression, tension, bending, shearing, density and friction. Multiple factors affect these properties; including variety, stem diameter, maturity, moisture content and cellular structure (Nazari *et al.,* 2008 and Tavakoli *et al.,* 2009). It is therefore important to determine the physical and mechanical properties of chickpea plants. The purpose of this is to determine the design and operational parameters of equipment for harvesting, threshing, handling and other phases of crop processing (Yiljep and Mohammed, 2005).

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Atul *et al.* (2011) investigated how moisture content, blade velocity and cross section area affected cutting energy and cutting force. The amount of cutting energy and cutting force required decreased as the cutting velocity decreased at different moisture contents, whereas these values increased when chickpea stalks had a larger cross-sectional area. Allameh and Alizadeh, (2016) examined variations in cutting energy according to the cultivar and blade parameters of rice stems. As decrease in the cross sectional area of the stem an increase in specific cutting energy was observed. Consequently, there is a reverse relationship between the cross sectional area and the cutting energy. Amirian *et al.* (2018) used a compression testing machine in order to assess bending properties of chickpea stems (Hashem) and found that the bending force of chickpea stems decreased with an increasing moisture content. In contrast, no detailed studies have been conducted on the mechanical properties of chickpea plants at varying levels of moisture content and stem diameter. Therefore the aim of this study was to examine how moisture content and stem diameter affect the cutting energy, cutting force, specific energy and bending force of chickpea plants.

MATERIALS AND METHODS

This study was conducted at ICAR-Central Institute of Agricultural Engineering, Bhopal, Madhya Pradesh. The chickpea plant variety JG-12 samples were taken from the field at maturity stage in summer season of April 2022. Plants were selected randomly (Latitude: 23.2599, Longitude: 77.4126). Firstly, the physical properties like diameter, length and weight of the plant parts were measured and noted. A digital Vernier caliper (Make: aerospace, Model: PLA250) with a resolution of 0.01 mm was used for measuring the stalk diameter. To calculate the moisture content of residue samples, the oven drying method was used. The plants were grouped in three categories, *i.e.* (1) 124 days after sowing date M1 (17.44%), (2) 129 days after sowing date M2 (15.33%) and 134 days after sowing date M3 (13.13%). The selected plant stalks were grouped based on the stalk diameter in the range of $5\text{-}6\times10^{-3}$ m (D1), $7\text{-}8\times10^{-3}$ m (D2) and $9\text{-}10\times10^{-3}$ m (D3) (Table 1). A pendulum operated impact cutter was used for measuring the cutting force of chickpea plants.

Cutting energy

The energy required to cut a chickpea stalk can be determined by following equation (Sushilendra *et al.* 2016).

$$CE = m \times g \times R\ (\cos\theta_1 - \cos\theta_2) \quad \text{......(1)}$$

CE= Cutting energy (J).
M= Mass of the pendulum (kg).
G= Gravitational acceleration (ms^{-1}).
R= Radial length to centre of gravity (m).
θ_1 = Angle of pendulum at initial position, degrees.
θ_2 = Angle of pendulum after cutting, degrees.

Cutting force

Cutting force of chickpea plants were calculated by dividing the cutting energy and stalk diameter (Sushilendra *et al.* 2016).

$$CF = \frac{CE}{d} \quad \text{......(2)}$$

CF=Cutting force (N).
CE=Cutting energy (j).
d= stalk diameter (mm).

Table 1: Plan of experiments for measuring mechanical properties of chickpea plants.

Independent variables	Levels	Dependent variables	Replications
	Cutting energy, cutting force and Specific energy		
Moisture content (%)	M1 (17.44)		
	M2 (15.33)		
	M3 (13.13)		
	V_1 (4.57)	1.Cutting energy	
Peripheral velocity of blade	V_2 (3.71)	2. Cutting force	5
(m/s) (serrated blade)	V_3 (2.74)	3. Specific cutting energy	
	V_4 (1.66)		
Cross sectional area/diameter of	D-1 (28)/(5-6)		
stalka (mm^2/mm)	D-2 (50)/(7-8)		
	D-3 (79)/(9-10)		
	Bending force of chickpea plants		
Moisture content (%)	M1 (17.44)		
	M2 (15.33)	1. Bending force	
	M3 (13.13)	a. Top	
	5-6	b. Middle	10
Stem diameter (mm)	7-8	c. Botton	
	9-10		

Specific cutting energy

In order to calculate specific cutting energy, cutting energy was divided by the cross-sectional area of the stem (Allameh and Alizadeh 2016).

$$SCE=\frac{CE}{D^2} \quad \text{Where} \quad D^2=\frac{\pi \times d^2}{4} \qquad ......(3)$$

SCE= Specific cutting energy (j mm^{-2}),
CE= Cutting energy (j).
D^2= Cross sectional of the stem (mm^2).

Bending force

Texture analyzer (make: stable micro system, UK) has a load cell of 50 kg capacity used for measuring bending force of chickpea stems. It uses three point bending probe which has pre-test speed 1 mms^{-1}, test speed 2 mms^{-1} and post-test speed 10 mms^{-1}, respectively (Fig 1a and b).

Experimental design and statistical analysis

An entirely randomized experimental design (CRD) was used in this study. In Design of experiment 13.0 software, ANOVA and a quadratic model was used to analyze experimental data. Comparison between treatment means was made at 1% and 5% levels of significance.

RESULTS AND DISCUSSION

Cutting energy

The maximum cutting energy of 7.48 J was observed at a blade velocity of 4.57 ms^{-1} for 1×10^{-2} m stalk diameter at 13.13% moisture content (Fig 2c). At 17.44% moisture content and a blade velocity of 1.66 ms^{-1} for 6×10^{-3} m stalk diameter minimum value of cutting energy of 0.39 J was obtained (Fig 2a). From the Fig 2, it is evident that the cutting energy decreased from 7.48 J to 0.39 J as the stem diameter decreased from 10 mm to 6 mm. Increasing the stem diameter causes the cutting energy to be gradually increased as a result of increasing stem thickness, since the blade has to cut more plant material as a result (Fig 2b). Similar results were reported by Sushilendra *et al.* (2016). Study also reveals that the cutting energy is increased as decrease in moisture content of stalks because surface hardness of the chickpea stem as cellulose became compact and hard at the maturity stage, offers more cutting resistance. Similar results were reported by Sushilendra *et al.* (2016).

The ANOVA (Table 2) for cutting energy showed that, the interaction effect of MC×SD, MC×BV and SD×BV affected the cutting energy for chickpea stalks significantly (P≤0,05).

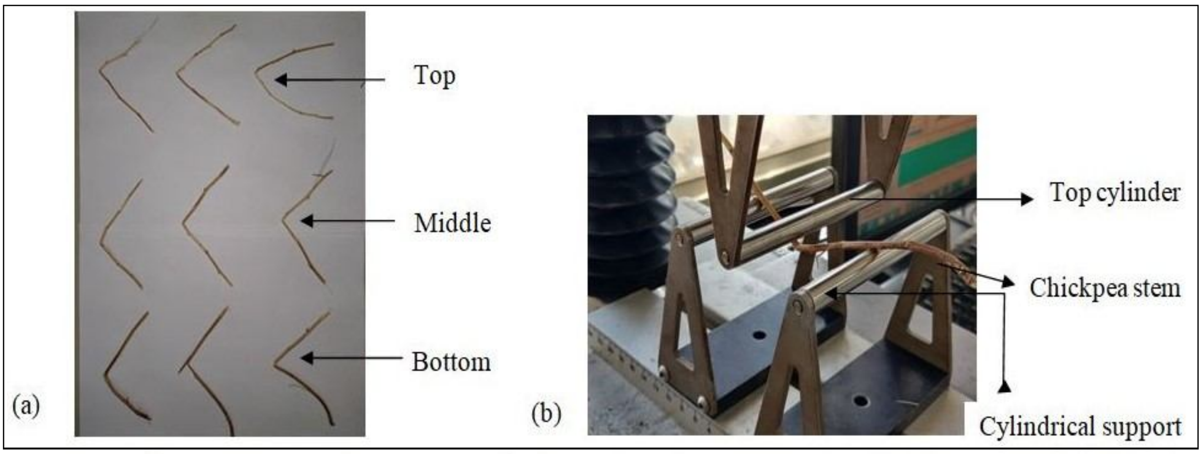

Fig 1: Measurement of bending force of chickpea plant at different stem region in texture analyzer.

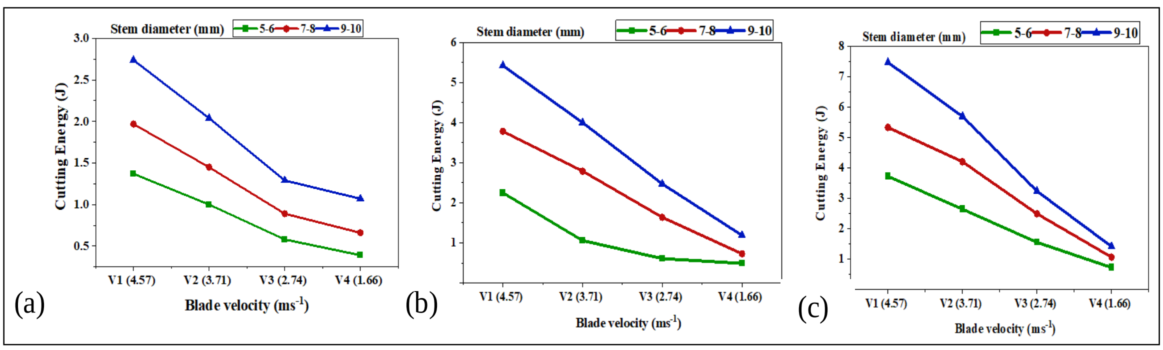

Fig 2: Effect of blade velocity and stem diameter on cutting energy of chick pea stalks at 17.44%, 15.33% and 13.13% moisture content.

A significant relationship was found between the independent variables, with moisture content of stalks being the most significant, followed by stem diameter and blade velocity. The actual equation was found between the cutting energy of chickpea stems and moisture content (%) stem diameter (mm) is described as below.

$$CE = -6.72 + 0.16\,MC + 0.95\,SD + 2.34\,BV - 0.086\,MC \times SD - 0.237\,MC \times BV + 0.168\,SD \times BV + 0.027\,MC^2 + 0.0174\,SD^2 + 0.157\,BV^2 \quad ......(4)$$

Cutting force

The maximum cutting force of 748.00 N has been recorded at a cutting velocity of 4.57 ms^{-1} for 1×10^{-2} m stalk diameter at 13.13% moisture content (Fig 3c). At 17.44% moisture content and a blade velocity of 1.66 ms^{-1} for 6×10^{-3} m stalk diameter minimum value of cutting force of 65 N was obtained (Fig 3a). From Fig 3b, it was observed that increasing moisture content has expressed a decreasing effect on cutting force, this might be due to the fact that chickpea plants with more moisture content have vascular bundles of the stem are collateral and arranged in a ring and force required to cut chickpea plants is decreased with increasing moisture content, similar results were reported by Atul *et al.* (2011). Results also showed that the force required for cutting chickpea stems increased gradually as the diameter of the stem increases from 6 mm to 10 mm. It may due to full maturity of plants, the cellulose has become compact and hard, resulting in a greater force being required to cut it with increasing diameters. Similar results were reported by Atul *et al.* (2011). The ANOVA (Table 2) for cutting

Table 2: Analysis of variance for cutting energy, cutting force and specific cutting energy of chickpea stalks.

Source	DF	Pr > F CE	Pr > F CF	Pr > F SCE
Model	9	<0.0001*	<0.0001*	<0.0001*
MC	1	<0.0001*	<0.0001*	<0.0001*
SD	1	<0.0001*	<0.0001*	<0.0001*
BV	1	<0.0001*	<0.0001*	<0.0001*
MC×SD	1	<0.0001*	0.8857	0.0020
MC×BV	1	<0.0001*	<0.0001*	<0.0001*
SD×BV	1	<0.0001*	<0.0001*	0.6606
MC^2	1	0.2133	0.2676	0.4781
SD^2	1	0.4890	0.4980	0.6016
BV^2	1	0.0023	0.0096	0.0002
Residual	170			
Lack of fit	26	0.2033 ns	0.0611 ns	0.1234 ns
Pure error	144			
Corrected total	179			

	Std. Dev	Mean	C.V.%	R^2	Adjusted R^2	Predicted R^2
CE	0.6385	2.27	28.08	0.8786	0.8722	0.8590
CF	68.14	266.83	0.8868	0.8868	0.8808	0.8773
SCE	0.0139	0.0436	31.92	0.8159	0.8062	0.7875

*Significant at 1% level, Ns-Not significant.

DF: Degree of freedom, CE: Cutting energy, CF: Cutting force, SCE: Spectic cutting energy, MC: Moisture content, SD: Stem diameter, BV: Blade velocity.

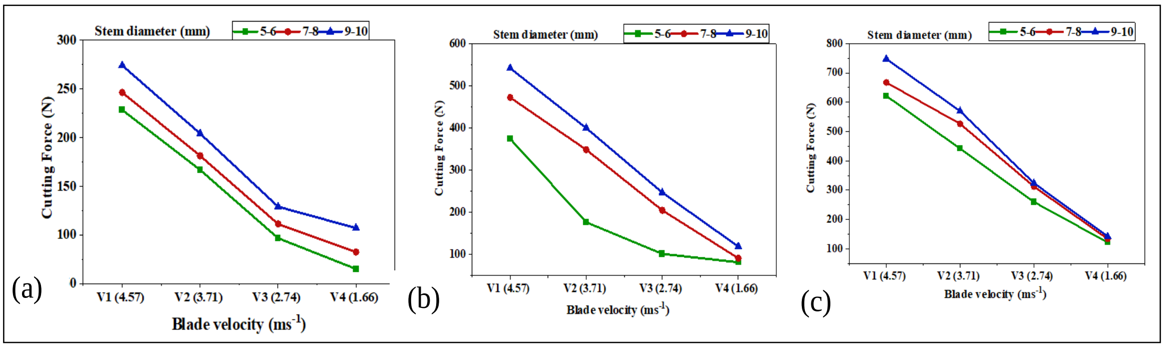

Fig 3: Effect of blade velocity and stem diameter on cutting force of chick pea stalks at 17.44%, 15.33% and 13.13% moisture content

force showed that, the interaction effect of MC×BV and SD×BV affected the cutting force for chick pea stalks significantly (P≤0,05) but the interaction effect of MC×SD was found to be insignificant. A significant relationship was found between the independent variables, with moisture content of stalks being the most significant, followed by stem diameter and blade velocity. The actual equation was found between the cutting force of chickpea stems and moisture content, stem diameter is described as below.

$$CF= -131.058-30.734\ MC+12.209\ SD+463.19\ BV+0.254\ MC\times SD -34.951\ MC\times BV +12.483\ SD\times BV +2.581\ MC^2 -1.830\ SD^2+14.180\ BV^2 \quad ......(5)$$

Specific cutting energy

The maximum specific cutting energy of 0.1219 Jmm^{-2} was observed at a cutting velocity of 4.57 ms^{-1} for 1×10^{-2} m stalk diameter at 13.13% moisture content (Fig 4c). At 17.44% moisture content and a blade velocity of 1.66 ms^{-1} for 6×10^{-3} stalk diameter a minimum specific cutting energy of 0.0106 J mm^{-2} was obtained (Fig 4 a). From Fig 4, it was observed the specific cutting energy decreased from 0.1219 to 0.0106 J mm^{-2} as the blade velocity decreased from 4.57 (V_1) to 1.66 (V_4) ms^{-1}. There is a possibility that this occurred because, at lower velocities, there is insufficient impact to sufficiently fail the stem, which leads to a high force requirement. It may be that at greater velocities, the specific cutting energy requirement increases as a result of the pendulum imparting kinetic energy to the separate parts even after they have been cut, *i.e*. a stem cut by this method would be accelerated and thrown much farther due to the extra energy that it would require (Fig 4 b). In other word, a reverse relationship exists between the stem cross sectional area and the specific cutting energy. This has been reported by the Allameh and Alizadeh, (2016).

The ANOVA (Table 2) for specific cutting energy showed that, the interaction effect of MC×SD and MC×BV affected the specific cutting energy for chick pea stalks significantly (P≤0,05) and interaction effect of SD×BV found to be insignificant. A significant relationship was found between the independent variables, with moisture content of stalks being the most significant, followed by stem diameter and blade velocity. The actual equation was found between the specific cutting energy of chickpea stems and moisture content, stem diameter is described as follows:

$$SCE=0.158-0.0139MC-0.0157SD+0.0641BV+0.001\ MC\times SD-0.004\ MC\times BV-0.00025SD\times BV+0.00034\ MC^2- 0.00028\ SD^2+0.00420\ BV^2 \quad ......(6)$$

Bending force

The maximum bending force of 27.28 N was found at bottom part of the stem having 1×10^{-2} m diameter at 17.44% moisture content (Fig 5 a) and minimum bending force of

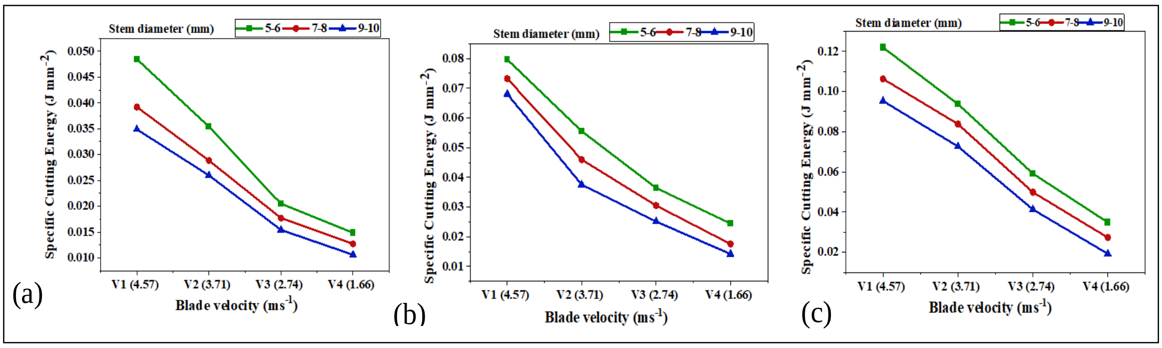

Fig 4: Effect of blade velocity and stem diameter on specific cutting energy of chick pea stalks at 17.44%, 15.33% and 13.13% moisture content.

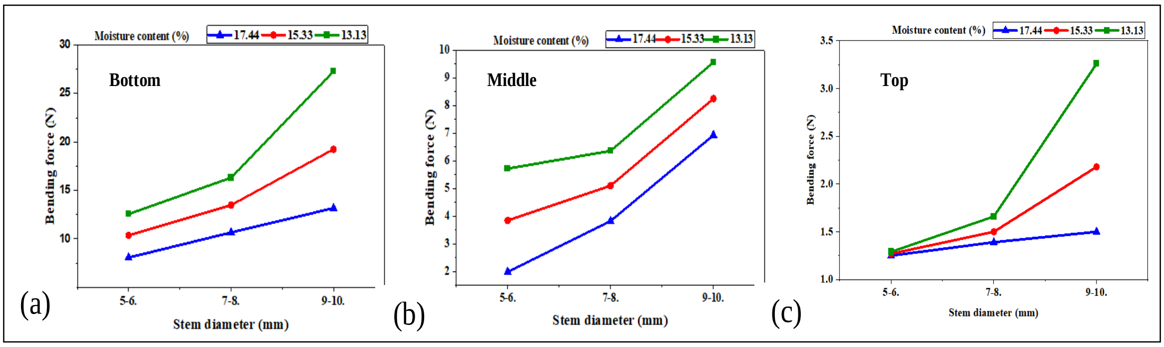

Fig 5: Chickpea stalk bending force at the bottom, middle and top region influenced by moisture content and stem diameter.

Table 3: Analysis of variance for bottom bending, middle bending and top bending force of chickpea stalk.

Source		DF		PR>F BBF		MBF	TBF
Model		5		<0.0001*		<0.0001*	<0.0001*
MC		1		<0.0001*		<0.0001*	<0.0001*
SD		1		<0.0001*		<0.0001*	<0.0001*
MC×SD		1		0.0174		0.2103	0.0016
MC^2		1		0.0437		0.5227	0.0004
SD^2		1		0.9678		0.0142	0.6516
Residual		39					
Lack of fit		3		0.4305ns		0.7219ns	0.507ns
Pure error		36					
Corrected		44					
	Std. Dev		Mean	C.V%	R^2	Adjusted R^2	Predicted R^2
BBF	2.13		14.31	14.85	0.8252	0.8028	0.7744
MBF	0.5787		5.65	10.25	0.9459	0.9389	0.9312
TBF	0.2062		1.62	12.39	0.8356	0.8146	0.7859

*Significant at 1% level, ns. Not significant.

BBF: Botton bending force, MBF: Middle bending force, TBF: Top bending force.

1.25 N was found at top part of the stem having 6×10^{-3} m diameter at 13.13% moisture content (Fig 5 c). In Fig 5 b, a decrease in brittleness can be observed when moisture content is increased, as evidenced by a decrease in the bending force of chickpea stems. Similar results were reported by Amirian *et al.* (2018). The maximum bending force at the bottom part of chickpea stem was presumably due to higher fiber content and thicker stem wall than at the top part. When the stalk matures, it becomes stiffer due to an increase in the thickness of the stem wall and the dry matter content of the stalk. Therefore, the maximum bending moment increases from top to bottom at the length of stalks similar results reported by Amer *et al*. (2008).

The ANOVA (Table 3) for bending force at different stem regions of chickpea stalks showed a significant (P≤0,05) relationship between the independent variables, with moisture content of stalks being the most significant, followed by stem diameter. The actual equation was found between the bending force of chickpea stems and moisture content, stem diameter are described as below.

$$BBF = -82.164+9.917\,MC+6.285\,SD-0.273\,MC\times SD-0.301\,MC^2-0.0068\,SD^2 \quad ......(7)$$

$$MBF = 43.486-2.534\,MC-4.627\,SD+0.064\,MC\times SD+0.0435\,MC^2+0.296\,SD^2 \quad ......(8)$$

$$TBF = -15.905+1.8617\,MC+0.846\,SD-0.036\,MC\times SD-0.0538\,MC^2-0.0074\,SD^2 \quad ......(9)$$

CONCLUSION

Chickpea stalks have a significant decrease in cutting energy, cutting force and specific cutting energy as blade velocity decreases. As the stem diameter of chickpea plants increases the cutting energy requirement increases about 19.2 times and specific cutting energy requirement decreases about 11.4 times at 13.13 to 17.44% moisture content. The cutting force of chickpea plants decreases about 11.5 times as stem diameter decreases. Minimizing cutting energy and cutting force during chickpea stem harvesting would be achieved by harvesting stems at lower moisture content. Because the lesser is the stem strength, the more optimized will be energy consuming by the machine for harvesting. In the experiment, blade velocities were above critical limits, so increasing velocity wasted energy as it carried the cut stem farther away. The bending force of chickpea stem increased about 21.82 times for 6×10^{-3} m to 1×10^{-2} m stem diameter as the moisture contents decreased from 17.44% to 13.33%. Results showed that the moisture content of the highest and lowest samples differed significantly, as well as bottom, middle and top regions in terms of bending force. The results indicate that harvesting time influences chickpea plants' response to agricultural activities. The mechanical properties of chickpea plants with respect to moisture content and stem diameter can be used for chickpea harvester development. In addition, they can be used as input parameter for modeling chickpea plants by using the discrete element method in simulation.

Conflict of interest: None.

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