Bending behavior investigation of plants with elliptical cross-section and tapered stalks (case study: privet stalk)

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Abstract: Unlike metals with elastic behavior, most agricultural products are viscoelastic and they behave differently under various loads. With knowledge of agricultural products behaviour, it is possible to fabricate the best operation machine. To design a new hedge trimmer machine, the bending behavior analysis of hedge plant stalks like privet were carried out. Given that the privet stalk is similar to a tapered rod and the cross-section of the stalk is oval, the stalk specimens were performed in a bending process at the rate of loading from 5 to 20mm/min, four internode positions of fifth, tenth, fifteenth and twentieth and two directions of applying the force of *x*-direction (major diameter of the stalk cross-section) and *y*-direction (minor diameter of the stalk cross-section). The variance analysis of the data indicated that the loading rate and internode position created a significant effect on the stalk Young's modulus and bending strength ($P<0.05$) in both force applying directions. Also, the moisture content created a significant effect on the stalk Young's modulus and bending strength ($P<0.01$) in both force applying directions. The results showed Young's modulus at *y*-direction of applying force had about 10-20% higher values than that of the *x*-direction for all loading rates, moisture contents and internode positions. Also, the bending strength at *y*-direction of applying force had about 5-10% lower values than the *x*-direction for all loading rates, moisture contents and internode positions. Results show the maximum value for the privet stalk Young's modulus was found to be 14.20GPa for the moisture content of 30% at bending speed 5mm/min and *y*-direction of applying force and the minimum value was found to be 5.06GPa for the moisture content of 75%, at bending speed 20mm/min and *x*-direction of applying force.

Keywords: Bending stress, Force, Major diameter, Minor diameter

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1 Introduction

A hedge is one of the most beautiful features in parks and streets which is made of evergreen shrubs such as privet, which are usually planted in dense rows. These plants play an important role in enhancing the beauty of parks and streets and also reducing air pollution of cities (Kamandar and Massah, 2017). Trimming the hedge is a manual operation and it's normally an unsafe, periodic and time-consuming operation that is performed by gasoline-powered hedge , trimmer (Fezyi et al., 2014). Knowing information of mechanical properties of the privet stalks is essential for selecting design and operational parameters of new equipment relating to pruning of the stalks (Kamandar et al., 2018). The morphology of crop stalks is an important criterion for the design of machinery, especially for the determination of mechanical structure and key components (Dongdong and Jun, 2016). The knowing of shearing and bending properties of plants stalks have an important role in the design and fabrication of new machines, because cutting materials is generally the result of combined deformation by shearing and bending (Sitkei, 1986). The mechanical properties are affected by numerous factors such as the species variety, stalk diameter, maturity, moisture content, and cellular structure (Bright and Kleis, 1964).

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Most studies on the mechanical properties of plants have been done during their development using failure criteria (force, stress and energy) or the young's modulus. The physical properties of the cellular material are important in cutting, compression, tension, bending, density and friction (Shaw and Tabil, 2007). The mechanical properties depend on species variety, stalk diameter, maturity, moisture content and cellular structure (Persson, 1987). The physical properties are also different at different heights of the plant stalk. Hence, it is necessary to determine the physic-mechanical properties such as the bending and shearing stress and energy requirements for suitable knife design and operational parameters (Ince et al., 2005). The section Young's modulus in bending varied with the third power of the diameter for the cotton stalks with the diameter ranging from 7 to 16mm. The Young's modulus of cotton stalks varied from 600 to 3500MPa (Curtis and Hendrick, 1969). The mechanical and an *X*-ray method were used to determine the mechanical properties of the stems of winter rape varieties and the result showed, the character of the changes in the rigidity, bending stress, static shear energy, and the dynamic shear energy properties over the length of the stem was best expressed by a quadratic polynomial equation (Skubisz, 2001). The mechanical properties are also different at different heights of the plant stalk. Hence, it is necessary to determine the mechanical properties of stalks such as the bending and shearing stresses and energy requirements for suitable knife design and operational parameters (Ince et al., 2005).

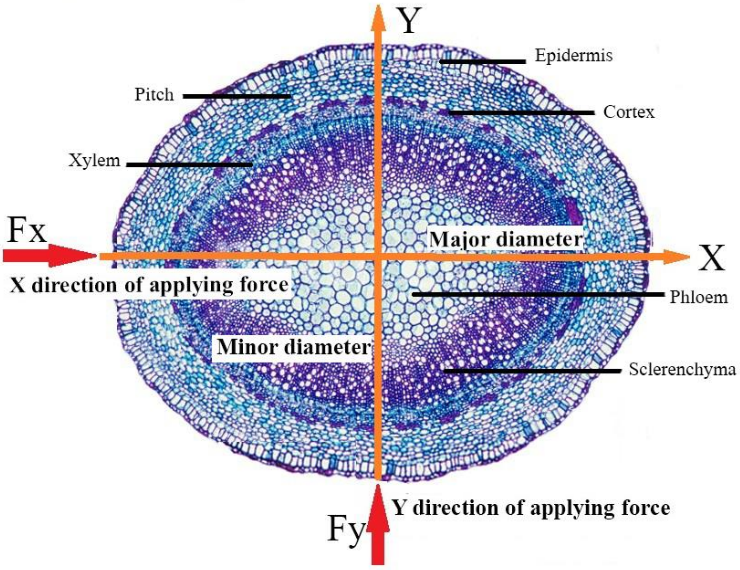
In the impact cutting by rotary cutting machine, there is no fixed blade to support the plant's stalks in bending. The moment of inertia of the stalk or the tendency of the stalk to stand is the main factor that keeps it standing at the time of cutting (Srivastava, 2005). The physical properties (major and minor diameter, thickness of stem, cross-section area of wall, second moment of area and mass per unit length) of barley straw increased with increasing moisture content. The physical properties also increased towards the stem third internode position (Tavakoli et al., 2009). The bending stress and Young's modulus of canola stem decreased as the moisture content increased while, the specific shear energy increased with increasing the stem moisture content (Eshaghbeygi et al., 2009). The bending tests on timothy and showed that the defection did not follow exactly the expected defection of a uniform cantilever beam but was close enough for the calculation of stiffness modulus, which is determined as the product of modulus of elasticity and sectional moment of inertia (Chancellor, 1958). The bending stiffness of meadow fescues decreased to approximately half, as the moisture content fell from 86 to 74% w.b (Schulze, 1953).

The young's modulus for wheat straw had a magnitude of 4.76 to 6.58GPa and the rigidity modulus was in the range from 267 to 547MPa (O' degherty et al., 1995). The bending stress for sorghum stalk as 40.53 and 45.65MPa at the seed stage and forage stage, respectively (Chattopadhyay and Pandey, 1999). The Young's modulus of alfalfa varies from 0.79 to 3.99GPa (Nazari Galedar et al., 2008). Mechanical properties of crops are influenced by the moisture content and the plant maturity of the stems, the internode position, the soil type and the temperature. An increase in moisture content results in a decrease in maximum bending stress, tensile stress, tensional stress, Young's modulus and rigidity modulus, while the shear stress increases (Bright and Kleis, 1964). Most researches in the area of mechanical and physical properties are focused on crops stalk and there are no studies on bending properties of privet stalk and lack of information about the stalk young's modulus, bending force and bending strength. The aim of this study was measure bending characteristics namely bending stress and Young's modulus of privet stalk and determine of the relationship between these properties with loading rates, moisture contents and height regions of the stalk as a function of applying bending force directions.

2 Materials and methods

Privet with the scientific name of *Ligustrum Ovalifolium* (*Oleaceae Sp*) was the experimental material in this study. It is one of the prevalent cultivars of privet in Iran and its stalk is similar to the tapered rod with an elliptical cross-section. The stalk samples were collected at the first month of the summer season in 2020 (Figure 1.a). The stalks material consists of nodes and filled internodes and also, the stalk diameter decreases towards to the top of the plant stalk which means it is similar to elliptical tapered cantilever beams (Figure 1.b). As shown in Figure 1.c, the cross-section of privet stalk with such parts as Epidermis, Cortex, Sclerenchyma, Phloem, Xylem and Pitch indicates the complexity of its structure and the morphological studies show, the stalk cross-section is perfectly elliptical with two different diameters (major and minor diameters). According to Figure 1.c, the major and minor diameters of the stalk cross section were aligned in the directions of the *x*-axis and *y*-axis of coordinate axis respectively. During the bending test, the forces *Fx* and *Fy* were applied in the direction of the *x* and *y* axes of the stalk cross section.

(a) Privet stalk (*Ligustrum Ovalifolium)* (b) Selected internode positions



(c) Cross-section of stalk of privet with main components and major and minor diameters

Figure 1 Picture of privet stalk, cross-section and selected internode positions

Before starting the tests the selected samples with defined height (the stalk with 400mm height) were equally marked into four regions (Figure 1.a): (a) fifth internode position (100mm downward from the terminal bud), (b) tenth internode position (200mm downward from the terminal bud), (c) fifteenth internode position (300mm downward from the terminal bud) and (d) twentieth internode position (400mm downward from the terminal bud). The major (*x*-direction) and minor (*y*-direction) diameters of each sample cross-section, were measured using an electronic digital caliper having a resolution of 0.01mm. Table 1 shows the cross-section minor and major diameters range of stalk samples at each selected internode position. To determine the moisture content of the privet stalks, the specimens were weighed and oven-dried at 103 ℃ for 24h and then reweighed.

Table 1 Diameter range of stalk samples

Minor diameter range (mm)	Major diameter range (mm)
4.27 - 5.49	5.18 - 6.88
5.05 - 6.65	6.02 - 7.85
7.14 - 7.50	7.47 - 8.62
7.33 - 8.78	8.22 - 9.50

The rewetted samples were then transferred to separate plastic bags and were kept at 5 ℃ in a refrigerator for a week. After that, the specimens were taken out of the refrigerator and allowed to warm up to room temperature for about 2h. The specimens were then reweighed to specify amounts of water absorbed by them and finally, the moisture content of the straw specimens was attained (ASAE Standards, 2005; Tavakoli et al., 2009). The experiments were conducted at moisture levels of 30, 45, 60 and 75% w.b. To determine the bending behavior of the stalks, an especial testing apparatus consisting of servo motor (ASD-B2-0121-B, Delta Electronics, Inc. Taiwan, China), load cell (Zemic H3-C3-25kg S Type Load cell), laptop (Asus K43S) and indicator (ADAK iBATCH Weight Controller) was created and used (Figure 2). In the laboratory, the twenty fifth internode position of the selected privet samples was clamped at the set point of the apparatus at which maximum bending moment occurs and the samples were tied from the tip in elastic rope connected horizontally with the load cell. Then the stalk was bent in *x* and *y* directions by pulling the rope by the servo motor at the constant selected speed. On reaching 300mm deflection at the tying point, the bending force versus sample tip displacement data was recorded by the laptop of the testing apparatus.

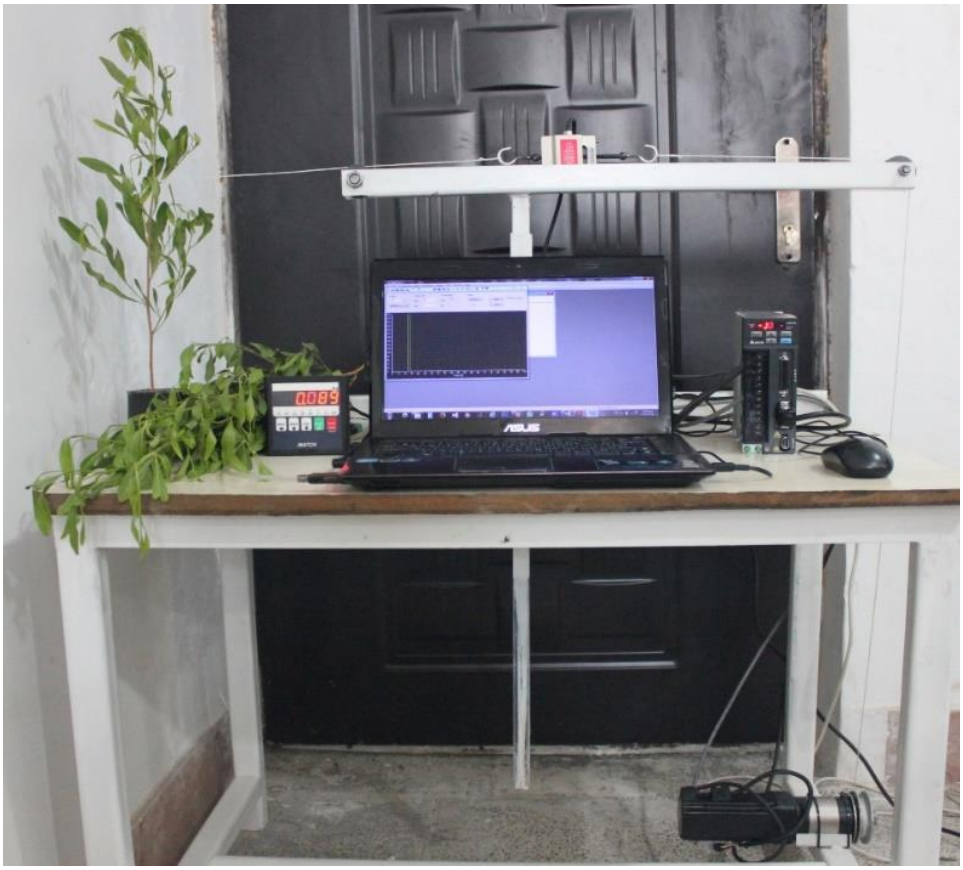


Figure 2 Bending test apparatus

The specimens were arranged with the major and minor axes of the cross-section in the horizontal plane and placed in the testing apparatus in two directions of major (*x*-direction) and minor (*y*-direction) diameters and the force was applied to the tip of the stalk specimen at the four loading rates of 5, 10, 15 and 20mm/min. An example of the bending force versus tip displacement curves for both directions of applying force (*x* and *y* directions) is shown in Figure 3 (bending speed: 5mm/min, moisture content: 75% and internode position:

twentieth). The maximum values for the bending force were found to be 125N and 97N for the twentieth internode position, moisture content 30% and bending speed 5mm/min at *x* and *y* directions of applying force respectively. The test results showed the bending force values at *y*-direction of applying force (F_y) had about 15-25% lower values for the bending force than the *x*-direction (F_x) for all loading rates, moisture levels and internode positions.

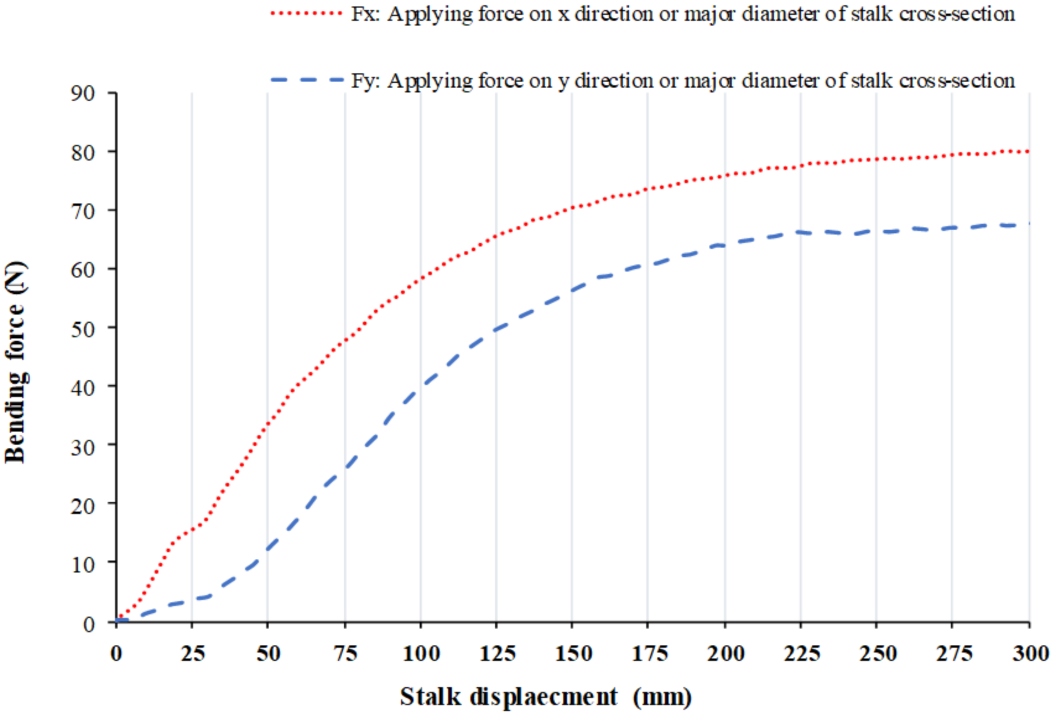


Figure 3 Real time bending force versus stalk displacement curve

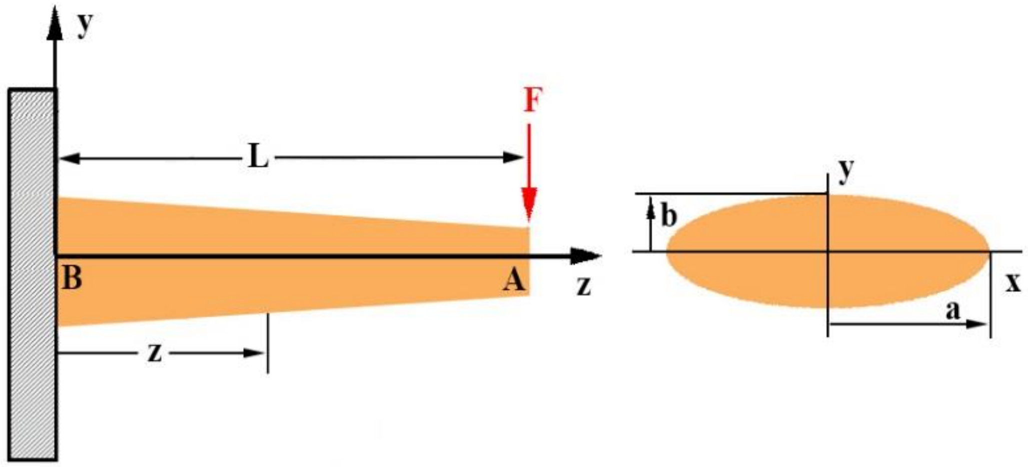


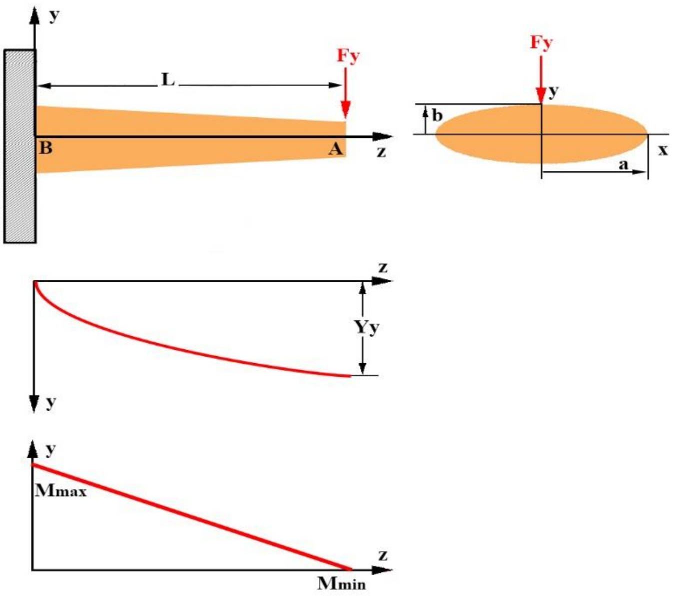
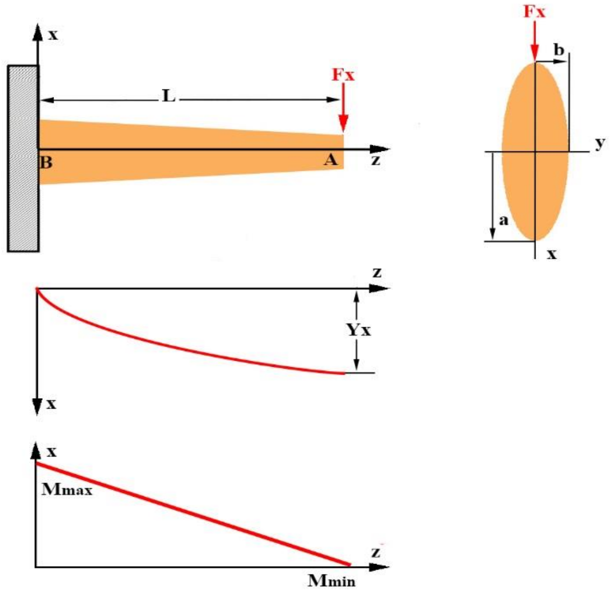
Figure 4 Concentrated bending force acting on elliptical tapered cantilever beam

The bending properties of privet stalk were calculated utilizing the principles and approximations of elliptical tapered cantilever beam bending theory. Given that the privet stalk is similar to the beam with a concentrated load *F* at the tip (Figure 4), the moment of inertia of cross-section area, *I*, Young's modulus of elasticity in bending, *E*, and the bending strength, *σ*, were calculated as equations 1 to 6 for twentieth, fifteenth, tenth and fifth internode positions (Kanafojski and Karwowski, 1976; McCutcheon, 1983).

$$I = I_A[1+(\mathrm{r}-1)\xi] \qquad (1)$$

Finally, two different values of the moments of inertia, bending strength and Young's modulus were calculated for each cross-section of the stalk (fifth, tenth, fifteenth and twentieth internode positions) in both directions of applying force by the equations as shown in Table 2 (McCutcheon, 1983).

Table 2 Bending properties determination of privet stalk in *x* and *y* applying force directions

Applying force in *y* direction (F_y)		$r=\frac{d_B}{d_A}$ $E_y=\frac{F_y \cdot L^3}{3 \cdot y_y \cdot I_x} \cdot \frac{1}{r^3}$ $I_A=\frac{\pi}{64}(a \cdot b^3)$ $I_x=r \cdot I_A$ $M_x=F_y \cdot Z$ $\sigma_{zy}=\frac{M_x \cdot b}{I_x} \cdot \frac{1}{r^3}$ $0 \le Z \le L$
Applying force in *x* direction (F_x)		$r=\frac{d_B}{d_A}$ $E_x=\frac{F_x \cdot L^3}{3 \cdot y_x \cdot I_y} \cdot \frac{1}{r^3}$ $I_A=\frac{\pi}{64}(b \cdot a^3)$ $I_y=r \cdot I_A$ $M_y=F_x \cdot Z$ $\sigma_{zx}=\frac{M_y \cdot a}{I_y} \cdot \frac{1}{r^3}$ $0 \le Z \le L$

Where

F: Maximum of applied load in each axis direction of cross-section area in N

I: Area moment of inertia in bending about a cross-section diameter in mm^4

L: Length of the beam between the load position and support in mm

Z: Length of the beam between the selected area and tip in mm

σ: Bending stress in each axis directions in MPa

a: Major radios of cross-section area in mm

b: Minor radios of cross-section area in mm

y: Deflection tip of the beam in mm

E: Young’s modulus in MPa

S: Section modulus in mm^3

d: Beam diameter in mm

3 Results and discussion

The study was undertaken to gather some basic information about the bending properties of privet stalk. The parameters Young's modulus and bending strength were determined in a quasi-static process at four rates of loading, four moisture contents, four internode positions and two directions of applying force. A factorial test with five replications based on a completely randomized experimental design was used and data were analyzed using analysis of variance (ANOVA). The means were compared by applying Duncan's multiple range tests SPSS software (version 22). The variance analysis of the data indicated that the loading rate and internode position created a significant effect on Young's modulus and bending strength ($P<0.05$) in both force applying directions. The moisture content created a significant effect on Young's modulus and bending strength ($P<0.01$) in both force applying directions. Based on the statistical analysis, the interaction effects of moisture content × loading rate and internode position × loading rate, on Young's modulus were significant at 5% probability level in both force applying directions. Also, internode position × moisture content and moisture content × internode position × loading rate on Young's modulus and bending strength were not significant ($P>0.05$). The results of Duncan's multiple range tests for comparing the mean values of the bending properties of the privet stalk at different loading rates, moisture contents and internode positions in both force applying directions are presented in Table 3. In the following, the effects of each factor on Young's modulus and bending strength in both force applying directions are comprehensively discussed.

Table 3 Means comparison of Young's modulus and bending strength of privet stalk

Independent variables	Dependent variables			
	Young's modulus (GPa)		Bending strength (MPa)	
	Direction (*y*)	Direction (*x*)	Direction (*y*)	Direction (*x*)
Loading rate (mm/min)				
5	14.26^{a}	9.28^{a}	362.77^{a}	387.21^{a}
10	11.96^{b}	8.84^{b}	334.29^{b}	346.60^{b}
15	10.82^{c}	7.10^{c}	305.43^{c}	320.55^{c}
20	9.11^{d}	6.99^{c}	271.93^{d}	294.35^{d}
Moisture content (%)				
30	13.54^{a}	10.64^{a}	355.58^{a}	374.43^{a}
45	11.90^{b}	8.93^{b}	336.87^{b}	354.97^{b}
60	10.68^{c}	7.09^{c}	319.35^{c}	332.11^{c}
75	9.45^{d}	6.88^{c}	261.76^{d}	289.15^{d}
Internode position				
Fifth	6.70^{c}	6.68^{c}	280.75^{d}	255.29^{d}
Tenth	8.25^{b}	6.97^{c}	290.99^{c}	287.25^{c}
Fifteenth	11.33^{a}	8.56^{b}	325.95^{b}	293.60^{b}
Twentieth	11.89^{a}	9.77^{a}	348.11^{a}	340.44^{a}

Mean values followed by different letters are significantly different from others in the same column ($P<0.01$)
Direction (*x*): These values have been calculated based on the force applied along the *x*-axis or major diameter of the stalk cross-section.
Direction (*y*): These values have been calculated based on the force applied along the *y*-axis or minor diameter of the stalk cross-section.

3.1 Loading rate effect

The mean values of Young's modulus and bending strength at different loading rates in both applying force directions were presented in Table 3. It is observed that Young's modulus and bending strength of the privet stalk decreased significantly with an increase in the loading rate and moisture level for both forces applying directions. Also, it is clear that Young's modulus and bending strength of the stalk increased towards the fifth to twentieth internode position for both applying force directions. Figure 5 shows the relationship between Young's modulus of privet stalk and loading rate at different moisture content as a function of applying force directions. As shown in Figure 5, Young's modulus of the privet stalk decreased from 14.2 to 10.2GPa, 13.6 to 9.8GPa, 13.2 to 8.5GPa and 12.5 to 8.1GPa for the 30, 45, 60 and 75% moisture levels, respectively, as the loading rate increased from 5 to 20mm/min in the *y*-direction of applying force. But in the *x*-direction of applying force, Young's modulus decreased from 11.0 to 7.4GPa, 10.0 to 6.6GPa, 9.6 to 6.6GPa and 8.7 to 5.0GPa for the 30, 45, 60 and 75% moisture levels, respectively, as the loading rate increased from 5 to 20mm/min. The results revealed in the *y* directions of applying force that the maximum and minimum values for the stalk Young's modulus were found to be 14.20GPa and 8.10GPa for the moisture content of 30% at bending speed 5mm/min and moisture content of 75% at bending speed 20mm/min respectively. While the maximum and minimum values for the stalk Young's modulus, in the *x* directions of applying force were found to be 11.09GPa and 5.06GPa for the moisture content of 30% at the bending speed 5mm/min and moisture content of 75% at bending speed 20mm/min respectively. Figure 5 shows, for all stalk moisture levels, Young's modulus of the stalk at a loading rate of 5mm/min had about 10-25% and 20-30% higher values than that of the 20mm/min in the *y* and *x* directions of applying force respectively.

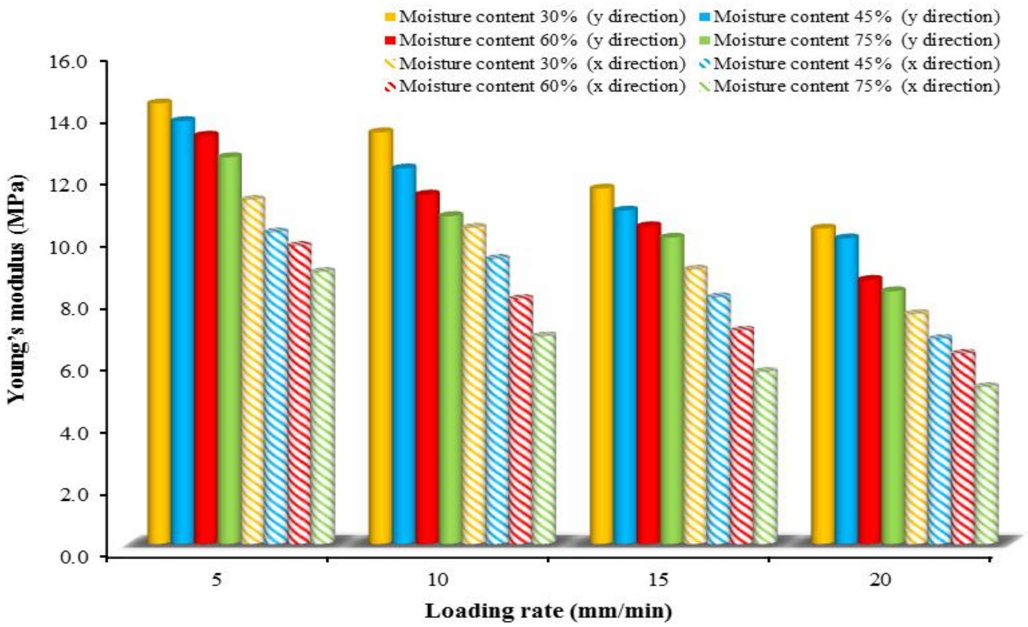


Figure 5 Relationship between Young's modulus of stalk and loading rate at different moisture content as function of applying force directions

(x direction: x direction of applying force - y direction: y direction of applying force)

Table 4 Comparison of Young's modulus of privet stalk considering interaction effect between loading rate and internode position as a function of force direction

Loading rate (mm/min)	Internode position							
	Young's modulus (GPa)							
	Direction (*y*)				Direction (*x*)			
	IN 5	IN 10	IN 15	IN 20	IN 5	IN 10	IN 15	IN 20
5	6.86^{a}	7.79^{d}	9.83^{fs}	12.53^{h}	6.19^{n}	6.67^{a}	8.99^{m}	10.28^{f}
10	5.99^{b}	7.36^{e}	8.18^{g}	12.10^{k}	5.70^{b}	6.22^{q}	7.54^{d}	9.67^{s}
15	5.33^{c}	6.80^{a}	7.68^{d}	10.08^{f}	5.00^{c}	5.13^{c}	6.33^{q}	8.88^{m}
20	5.01^{c}	5.89^{b}	6.98^{a}	8.99^{m}	4.77^{p}	5.08^{c}	6.08^{n}	7.55^{d}

Mean values followed by different letters are significantly different from others ($P<0.01$)

Direction (*x*): These values have been calculated based on the force applied along the *x*-axis or major diameter of the stalk cross-section.

Direction (*y*): These values have been calculated based on the force applied along the *y*-axis or minor diameter of the stalk cross-section.

IN: Internode position number

The interaction effect of loading rate × internode position on Young's modulus of privet stalk is presented in Table 4. The results reveal that Young's modulus was also decreased with increasing loading rate and increased from the top of the stalk to the bottom. Based on the analyzed results, with increasing bending speed from 5 to 20mm/min the value of Young's modulus decreased for all internode positions. For all stalk regions, Young's modulus of privet stalk at a loading rate of 5mm/min had about 25-30% and 20-25% higher values than that of the 20mm/min in the *y* and *x* directions of applying force respectively. Finally, the analyzed results of the effects of loading rate on Young's modulus of privet stalk showed, Young's modulus values in the *y*-direction of applying force had about 10-20% higher values than that of the *x*-direction for all loading rates from 5 to 20mm/min.

Figure 6 shows the relationship between bending strength of privet stalk and loading rate at different moisture content as a function of applying force directions. As shown in Figure 6, the bending strength of the stalk decreased from 394.49 to 365.56MPa, 373.25 to 325.25MPa, 346.82.2 to 248.54MPa and 326.81 to 278.17MPa for the 30, 45, 60 and 75% moisture level, respectively, as the loading rate increased from 5 to 20mm/min in the *y* direction of applying force. Also, the bending strength decreased from 441.16 to 354.78MPa, 395.39 to 301.78MPa, 358.90 to 279.98MPa and 338.78 to 257.89MPa for the 30, 45, 60 and 75% moisture level, respectively, as the loading rate increased from 5 to 20mm/min in the *x*-direction of applying force. The highest value of bending strength was obtained as 441.16MPa at the fifth internode position, the loading rate of 5mm/min and *x*-direction of applying force while the highest value of bending strength at *y*-direction of applying force was obtained as 394.49MPa at the fifth internode and loading rate of 5mm/min. Figure 6 shows, the increasing of bending speed from 5 to 20mm/min, decreases the values of the bending strength for all internode positions at both applying force directions and the loading rate of 20mm/min had about 15-20% lower value for the bending strength than that of the 5mm/min for all stalk regions in the both applying force directions. The results revealed that the bending strength values at *y*-direction of applying force had about 5-10% lower values for the bending force than the *x*-direction for all loading rates and internode positions.

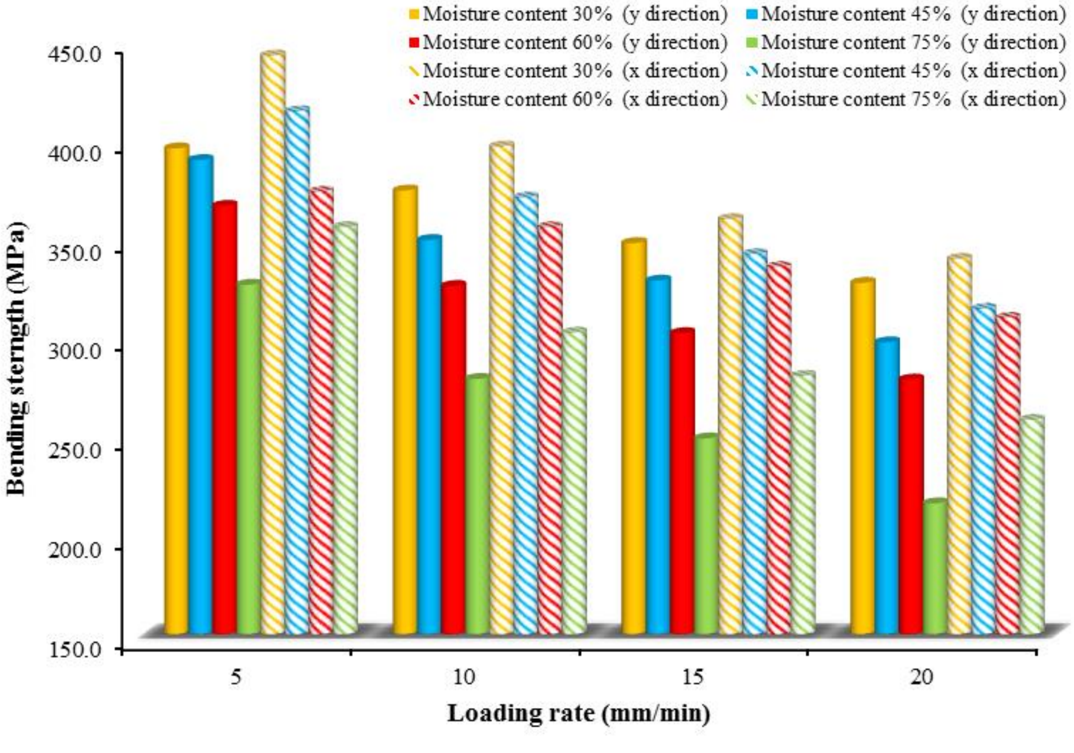


Figure 6 Relationship between bending strength and loading rate at different moisture content as function of applying force directions (*x* direction: *x* direction of applying force - *y* direction: *y* direction of applying force)

The interaction effect of loading rate × internode position on the bending strength of privet stalk is presented in Table 5. Based on the analyzed results, with increasing bending speed from 5 to 20mm/min the value of the bending strength decreased for all internode positions. For all stalk regions, the bending strength of privet stalk at a loading rate of 5mm/min had about 10-20% and 15-20% higher values than that of the 20mm/min in the *y* and *x* directions of applying force respectively. By considering Table 5, the difference between the values of the major and minor diameters cross-section area of the stalk is about 2mm, which can have a significant effect on the area moment of inertia. Similar results regarding the effect of loading rate on the modulus of elasticity and bending strength of plants were also reported by (Mohsenin, 1963; Prasad and Gupta, 1975; O' degherty et al., 1995; Skubisz, 2001; Nazari Galedar et al., 2008; Eshaghbeygi et al., 2009; Tavakoli et al., 2009; Mahmoodi et al., 2010; Leblicq et al., 2015; Tabatabaee and Hadie pour, 2016; Al-Zube et al., 2018).

Table 5 Means comparison of Bending strength of privet stalk in different moisture contents, loading rates and internode positions as a function of force directions

Loading rate (mm/min)	Internode position							
	Bending strength (MPa)							
	Direction (*y*)				Direction (*x*)			
	IN 5	IN 10	IN 15	IN20	IN 5	IN 10	IN 15	IN20
5	279.78^{a}	292.45^{d}	341.84^{e}	384.67^{gam}	304.56^{dj}	325.67^{i}	389.44^{m}	423.34^{n}
10	268.25^{bf}	281.09^{ag}	299.68^{dj}	351.33^{h}	300.77^{dj}	315.54^{k}	346.88^{e}	391.22^{o}
15	255.03^{b}	265.50^{bf}	277.66^{a}	321.44^{i}	275.40^{a}	289.70^{l}	305.28^{dj}	338.36^{p}
20	220.77^{c}	257.33^{b}	265.53^{fb}	301.93^{dj}	252.23^{b}	275.00^{a}	298.99^{dj}	319.04^{ik}

Mean values followed by different letters are significantly different from others ($P<0.01$)

Direction (*x*): These values have been calculated based on the force applied along the *x*-axis or major diameter of the stalk cross-section.

Direction (*y*): These values have been calculated based on the force applied along the *y*-axis or minor diameter of the stalk cross-section.

IN: Internode position number

3.2 Internode position effect

The mean values of the bending strength and Young's modulus at different internode position are presented in Table 3. It is clear that, the bending strength and Young's modulus of the privet stalk decreased significantly towards the fifth to twentieth internode position for both force applying directions. Figure 7 shows the relationship between Young's modulus and internode position at different moisture content as a function of applying force directions.

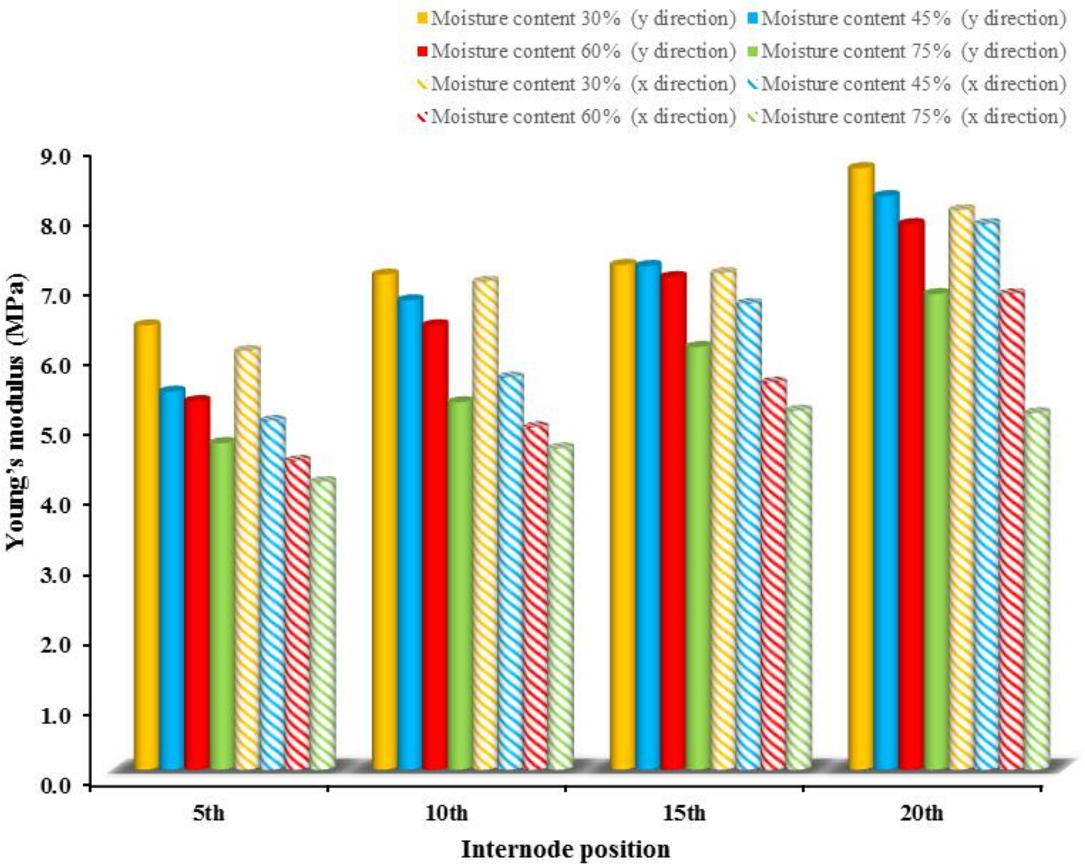


Figure7 Relationship between Young's modulus and internode position at different moisture content as function of applying force directions (*x* direction: *x* direction of applying force - *y* direction: *y* direction of applying force)

As shown in Figure 7, Young's modulus of the privet stalk decreased from 6.35 to 5.99GPa, 7.08 to 5.25GPa, 7.21 to 6.04GPa and 8.60 to 6.80GPa for the 30%, 45%, 60% and 70% moisture level, respectively, towards the fifth to twentieth internode position for *y*-direction of applying force. Also Young's modulus decreased from

5.99 to 4.11GPa, 6.97 to 4.59GPa, 7.10 to 5.13GPa and 8.00 to 5.10GPa for the 30%, 45%, 60% and 70% moisture level, respectively, towards the fifth to twentieth internode position for *x*-direction of applying force. Also, Young’s modulus increases towards the bottom region of the stalk. Young’s modulus at the twentieth internode position had about 15-25% and 30-35% higher values than that of the fifth internode position at y and x directions of applying force respectively for all stalk regions.

It is evident from Figure 7, the Young’s modulus increased towards to lower region of the privet stalk. The mentioned parameter was greater in the lower region than the upper in both applying force directions, because of more accumulation mature fibers in the stalk and more cross-section diameter (Mohsenin, 1963). The results showed Young’s modulus values at *x* direction of applying force had about 5-15% lower values for Young’s modulus than the *y*-direction for all internode positions. According to the values of the forces obtained in different loading directions of the stalk (the major and minor diameter of the stalk section), different values of the moment of inertia and displacement of the stalk center will be obtained. Eventually, these different values change the value of the Yang’s modulus in both directions of applying forces.

Figure 8 presents the interaction effects of internode position and moisture content on bending strength of privet stalk as a function of applying force direction. It is observed that the bending strength of the privet stalk decreased from 266.31 to 205.31MPa, 290.48 to 218.40MPa, 315.43 to 346.24MPa and 380.89 to 289.24MPa for the 30%, 45%, 60% and 75% moisture level, respectively, towards the twentieth internode position for *y* direction of applying force. Also, the Young’s modulus decreased from 297.57 to 219.74MPa, 337.57 to 246.74MPa, 346.24 to 277.02MPa and 427.57 to 347.63MPa for the 30%, 45%, 60% and 75% moisture level, respectively, towards the twentieth internode position for *x* direction of applying force. It was probably greater in the lower levels because of the accumulation of more mature fibers in the stalk. The highest value of bending strength was obtained as 427.57MPa at the twentieth internode position, the moisture level of 30% and *x* direction of applying force while the lowest value of bending strength was obtained as 297.57MPa at the fifth internode and moisture level of 75% and *y* direction of applying force.

Figure 8 shows, moving toward to twentieth internode position, increases the value of the bending strength for all moisture contents at both applying force directions and the internode position fifth had about 25-35% lower value for the bending strength than the internode position twentieth for all moisture contents and both applying force directions. Similar results regarding the effect of internode position on the modulus of elasticity and bending strength of plants were also reported by (Curtis and Hendrick, 1969; McRandal and McNulty, 1980; Chattopadhyay and Pandey, 1999; Ince et al., 2005; Skubizs et al., 2007; Eshaghbeygi et al., 2009; Yilmaz et al., 2009; Shahbazi and Nazari Galedar, 2012; Xue et al., 2015; Al-Zube et al., 2018).

3.3 Moisture content effect:

The moisture content had a significant effect on Young’s modulus and bending strength as shown in Table 3. Figures 5 and 7 show that Young’s modulus of the privet stalk decreased with an increase in the moisture content in each loading rate and internode position for both applying force directions. In fact, Young’s modulus at the 30% moisture level had about 10-25% and 25-35% higher values than that of the 75% moisture level at *y* and *x* directions of applying force respectively. Also, the results of Figures 6 and 8 indicate the bending strength of the privet stalk decreased with an increase in the moisture content in each loading rate and internode position for both applying force directions. The bending strength of the privet stalk at the 30% moisture level had about 15-30% and 10-20% higher values than that of the 75% moisture level at *y* and *x* directions of applying force respectively. The decrease of Young’s modulus and bending strength of the privet stalk with an increase in the moisture content for both applying force directions may be due to the drier stalk being more brittle. Similar results regarding the effect of moisture content on the modulus of elasticity and bending strength of plants have been reported by most previous researchers (McRandal and McNulty, 1980; Nazari Galedar et al., 2008; Ince et al., 2005; Shahbazi and Nazari Galedar, 2012; Al-Zube et al., 2018).

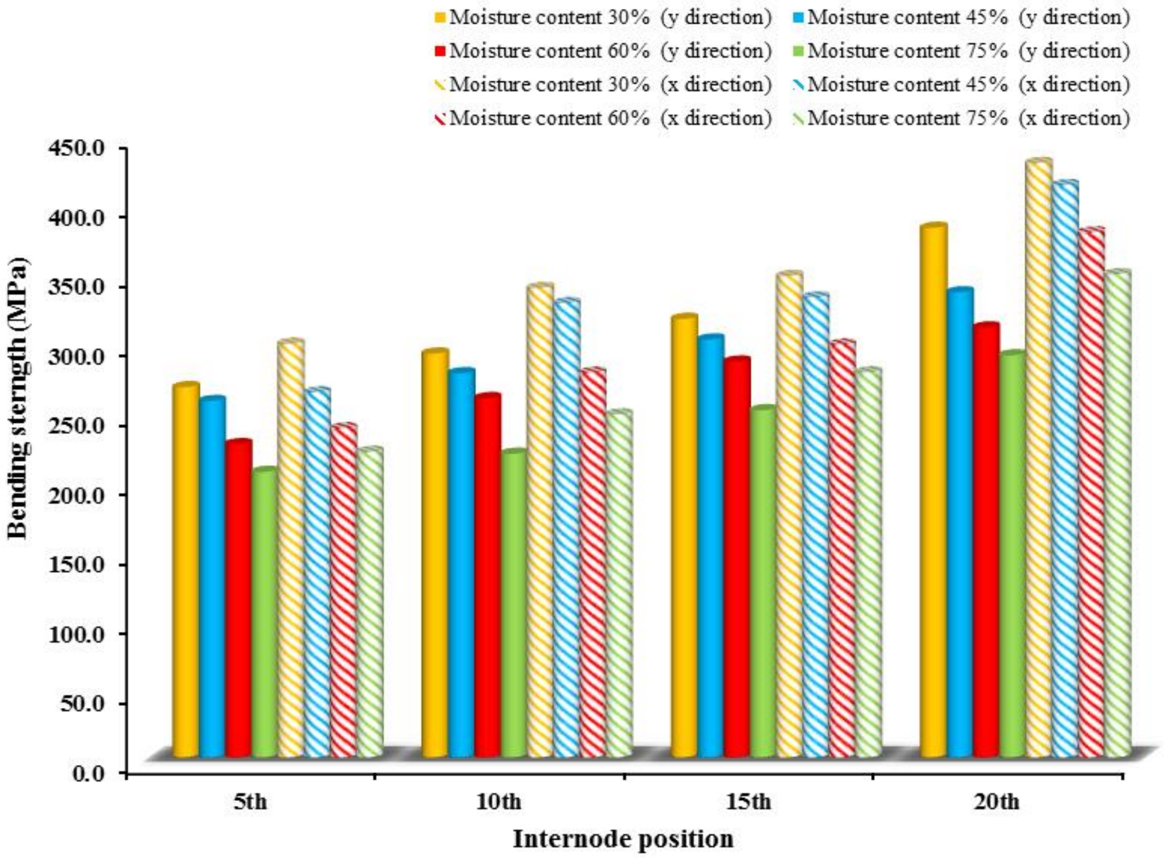


Figure 8 Relationship between bending strength and internode position at different moisture content as function of applying force directions (x direction: x direction of applying force - y direction: y direction of applying force)

4 Conclusions

In this study, the effect of lading rate, internode position and moisture level on bending strength and Young's modulus of plant with an oval cross-section and tapered stalk-like privet stalk were investigated according to the direction of applying force. From the results of this study, the following conclusions can be drawn:

The bending strength values at *y*-direction of applying force had about 5-10% lower values for the bending force than the *x*-direction for all loading rates and internode positions. The results show the maximum value for the stalk Young's modulus was found to be 18.57GPa for the moisture content of 30% at bending speed 5mm/min, at twentieth internode position and *y*-direction of applying force and the minimum value for the privet stalk Young's modulus were found to be 3.88GPa for the moisture content of 75%, at bending speed 20mm/min at fifth internode position and *x*-direction of applying force. The results showed that Young's modulus values at *y*-direction of applying force had about 10-20% higher values than that of the *x*-direction for all loading rates, moisture levels and internode positions. The highest value of bending strength was obtained as 485.33MPa for the moisture content of 30%, at the twentieth internode position, the loading rate of 5mm/min and *x*-direction of applying force while the minimum value of bending strength was found to be 145.58MPa for the moisture content of 75%, at bending speed 20mm/min at fifth internode position and *y*-direction of applying force. The results showed the bending strength values at *x*-direction of applying force had about 10-20% higher values than that of the *y*-direction for all loading rates, moisture levels, and internode positions. The difference in the stalk bending behavior in two directions of *x* and *y* can be due to the following reasons.

(1) The resistance of the stalk to failure is greater in the direction of the major diameter of the stalk cross-

section (*x*-direction).

(2) The differences in the structural and morphological characteristics of the stalk cross-section from two different directions of major (*x*-direction) and minor (*y*-direction) diameters is the important reason for the difference between the forces applied in *x* and *y* directions.

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