Bending properties of green forage maize in field

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Abstract: Stalk lodging is prone to occur during the harvesting of green forage maize due to the header and root anchorage, resulting in loss of harvest. In particular, the fallen stalk wraps around the header, causing a blockage and increasing the energy cost. To address this problem, the deflection model was analyzed and established and a novel method to explore the field bend characteristics of green forage maize was proposed. The effects of stalk diameter, bending angle, and cutting height on bending stress and Young's modulus were explored by using the method of in-situ measurement. Additionally, the bending deflection, axial displacement and measuring point displacement were obtained. Experimental results indicate that the stalk diameter and bending angle have a significant influence on bending stress. The bending stress has a positive correlation with bending angle and cutting height, while there is a negative correlation with stalk diameter. On the other hand, the bending angle, stalk diameter, and cutting height are closely related to the Young's modulus. The mean values of the Young's modulus decrease as a quadratic function with the increasing diameter and bending angle, while the cutting height has the opposite effect on it. Besides, the average values of bending deflection, axial displacement, and measuring point displacement exhibit an increasing trend when the bending angle and cutting height increase. This study results can provide a reference for studying the failure mechanism of green forage maize stalk harvesting, and the design of green forage maize harvesting machinery.

Keywords: green forage maize, field measurement, bending stress, Young's modulus, deflection model, harvest
DOI: 10.25165/j.ijabe.20231604.8043

Citation: Fu J, Xue Z, Fu Q K, Chen Z, Ren L Q. Bending properties of green forage maize in field. Int J Agric & Biol Eng, 2023; 16(4): 51–57.

1 Introduction

Green forage maize (*Zea mays* L.) with high yield and rich nutrition is an important feed source in the developed countries of animal husbandry in the world. With the guidance of the 'Grain to feed' policy, China's green forage maize planting area has increased rapidly in recent years, with about 2.4 milliion hm^2 planted in 2020[1]. In order to ensure the yield and quality of maize harvesting, and reduce labor intensity, the use and development of forage harvesters has become an inevitable trend. However, green forage maize harvester has poor harvest quality and reliability, and has high harvest losses, at present in china. This is because most of the existing machines are designed by designers using empirical methods without considering crop characteristics. Thus, to optimize these processes, reduce losses and improve harvest quality, exploring the physical and mechanical properties of crops is requirement[2,3].

As with other plants, the physical and mechanical properties of green forage maize have a significant effect on the selection and design of machinery or equipment in the process of harvesting, shredding, processing and transportation. Most studies on the physical and mechanical properties of crops have been done during their development using failure criteria (force, stress and energy) and the Young's modulus[4-6] for the past few years. Among these properties, compression, tension, bending, density, friction and cutting are the main factors affecting crop harvesting and processing[7,8]. Francik et al.[9] conducted the compression and three-point bending test of Miscanthus×Giganteus stalk and analyzed the influence of the internode number and moisture content on modulus of elasticity and maximum stress in bending and compression. Zhang et al.[10] measured the tensile properties of maize stalk rind and found there is a significant effect between the moisture content and tensile stress, modulus of elasticity and tensile energy. Robertson et al.[11] analyzed the influence of loading position on bending characteristics through three-point bending test and pointed out that the node-loaded stalks' failure patterns were closer to the naturally occurring failure patterns and positions. Oduori et al.[12,13] derived a rice stem bending model based on formula derivation and empirical data. Liang et al.[14] analyzed the effects of moisture content variation, sampling location and loading rate on mechanical characteristics of shear and across compression of dwarf-dense-early mahor cotton variety stalks. Chattopadhyay and Pandey[15] determined bending stress for sorghum stalk as 40.53 MPa and 45.65 MPa at the seed stage and forage stage, respectively. İnce et al.[16] measured the bending stress and the Young's modulus for sunflower stalk as 37.7-62.09 MPa and 1251.28-2210.89 MPa, respectively. Among these researches, it can be noticed that varieties, stalk diameter, maturity, moisture content and other

Received date: 2022-11-19 **Accepted date:** 2023-05-12
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factors affect the physical and mechanical properties of plants. Moreover, the physical and mechanical characteristics of different regions of stalk are various. For example, Liu and Koc[17] found that compression strength, tensile strength, shear tensile, and the Young modulus of Switchgrass and Miscanthus changed with the region of stalk.

In fact, the study of mechanical properties is also important for understanding the interaction between crops and machinery. In harvesting process, stalks cannot be cut off instantaneously by a cutter, but becomes bending deformation with the action of a reel or cutter, which not only leads to stalk leakage and loss but also clogs up the header (Figures 1a-1c). Furthermore, the bending deformation also affects the stubble height (Figure 1d), which is one of the important indexes to evaluate the harvest performance of a harvester. Especially in the harvest of green forage maize, the stubble height directly affects the harvest yield and the economic benefit. Thus, it is necessary to study the bending characteristics of stalk in the process of harvesting. Du et al.[18] studied the relationship between mechanical properties (bending and shearing strength) of tea stem and their factors such as stem segment number, stem diameter, moisture content and so on to improve the harvest quality of tea plucking machine. Hiari et al. studied the reaction force of reel on a single wheat stalk[19], a bunch of wheat stalk[20], a single rice stalk[21], and a bunch of rice stalk[22] under quasi-static loading conditions based on the mechanical model of crops. And they also considered the initial crop posture[23]. To facilitate the calculation, Hang et al.[24] calculated the bending stiffness of the rice straw and fitted the deformation curve using the Simpson formula. However, most of the above studies focused on the mechanical properties of wheat and rice in the process of harvesting with grain combine harvester, while the harvest process of green forage maize is different from that of rice and wheat, and there have been no relevant researches in recent years. Especially, there is rarely study on the bending properties of green forage maize in fields.

a. Winding of stalk b. Block of header c. Loss of stalk d. Uneven stubble

Figure 1 Production problems in the process of harvesting green forage maize

To slove this issue, we analyzed and established the deflection model and proposed a novel method to explore the field bend characteristics of green forage maize. And the effects of bending angle, stalk diameter, and cutting height on bending stress and Young's modulus of green forage maize were studied. Furthermore, the variation rules of bending deflection, axial displacement and measuring point displacement of green forage maize were obtained through numerical calculation. The study can provide theoretical support and data reference for designing a harvester and a header of green forage maize that could reduce harvest loss and block and ensure uniform stubble retention.

2 Materials and methods

2.1 Materials

The variety of green forage maize used in this paper was Yayu silage No. 8, which was planted in the Agricultural Experimental Base of Jilin University (43°56'N, 125°14'E) in Changchun, Jilin province, China. The experiments were carried out in the suitable harvest period of green forage maize (October 2, 2021). The planting density was about 60 000 plants/hm^2, and the plant and row spacing were 0.26 m and 0.60 m, respectively. According to ASABE S358.2[25], the average moisture content during the trial was determined to be 68.5% by drying in the dryer at (103±2)°C for 24 h.

2.2 Analysis of bending during harvesting

The process of harvesting green forage maize includes cutting, feeding, chopping and throwing. This study focuses on analyzing the problems and phenomena in the cutting process as shown in Figure 2. As can be seen from the Figure 2, the stalk first enters the header along the divider and directly touches the cutter. The stalk is then subjected to cutting force, pushing force, and root anchoring force during the header advance, resulting in a certain deflection of the stalk. The stalk lodging can be seen from the third process in Figure 2. This is because when harvesting, the operator relies on his own experience to adjust the forward speed of the harvester and cannot ensure that the speed of the cutter matches the forward speed of the machine. Uncut stalks fall under the action of the header, resulting in stalk loss. It is important to note that uncut stalks are also easy to wind over the header, causing a blockage of the header. Meanwhile, the energy consumption increases and the harvesting efficiency decreases due to the blockage of the header. Therefore, it is necessary to investigate the bending properties of green forage maize in the field.

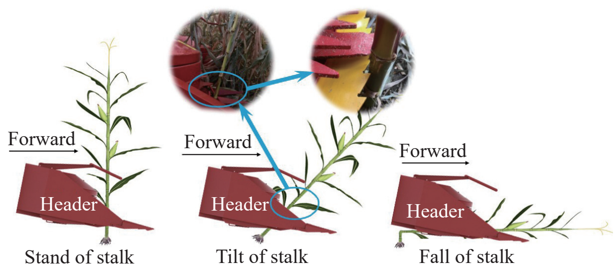


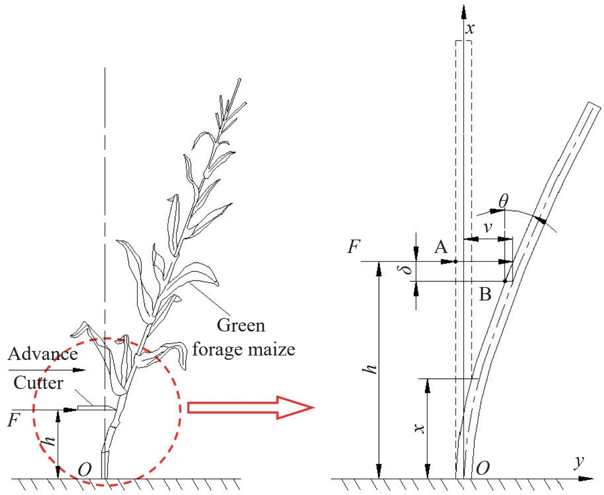
Figure 2 Stalk bending during harvesting green forgae maize

2.3 Establishment of deflection model

In order to determine the deformation characteristics of the stalk in this process, a deflection model shown in Figure 3 was established with green forage maize as the goal of this study. Since the force F applied by the machine is much larger than the weight of the maize stalk and ear, the dead weight of them was not taken into account. Meanwhile, in order to simplify the calculation, the stalk was regarded as a long pole with one end fixed and one end free. Then, the rectangular coordinate system shown in Figure 3 was established with the fixed end point O as the origin, the central axis of the stalk before deformation as the *x* axis and the vertical right axis as the *y* axis. Under the action of force *F*, the stalk deformed and the initial action point moved to *B*. And the abscissa of the deflection curve after deformation was the deflection at any section of the stalk, expressed by the letter *v*. In the process of green forage maize harvest, the bending angle generated by stalk bending cannot be ignored. Therefore, the exact differential equation of deflection line is used to analyze it, and the formula is shown as follows[24]:

$$\frac{\frac{d^2v}{dx^2}}{\left[1+\left(\frac{dv}{dx}\right)^2\right]^{\frac{3}{2}}}=-\frac{M}{EI} \tag{1}$$

where, M is the sum of bending moment at point A, N·mm; E is the Young's modulus, MPa; I is second moment of area, mm^4.



a. Bending phenomenon b. Deflection model of green forage maize stalk

Note: F is the force, N; h is the cutting height, mm; v is the bending deflection (deflection of point A), mm; δ is the axial displacement (vertical displacement of point A), mm; θ is the bending angle (angle of stalk section at point A), (°).

Figure 3 Diagram of bending phenomenon and deflection model of green forage maize stalk

In this model, the sum of bending moment in any section x is:

$$M(x)=-F(h-\delta-x) \tag{2}$$

In order to facilitate the solution, Equation (1) is converted and integrated, and the exact differential equation of the angle at point A can be obtained by using the boundary conditions:

$$\sin\theta_A=\frac{F(h-\delta)^2}{2EI} \tag{3}$$

where, θ_A is the bending angle at the point A, (°). Then, the axial displacement δ can be solved as follows:

$$\delta=h-\sqrt{\frac{2EI}{F}\sin\theta_A} \tag{4}$$

However, EI in the above formula is unknown and can be solved by numerical method[26]. Then, we can obtain the value of Young's modulus by calculating it. In addition, the bending stress can be calculated using Equation (5):

$$\sigma_b=\frac{FLd}{2I} \tag{5}$$

where: σ_b is the bending stress of stalk, MPa; d is the stalk diameter, mm.

2.4 Experimental Instruments and Methods

In order to ensure the authenticity and accuracy of the measurement, an experimental method for measuring the field bending properties of green forage maize is proposed, as shown in Figure 4. The force of stalk bending to different angles was measured and recorded by tensile meter (type: HP-1000, capacity: 1000 N, resolution: 1 N, Yueqing Handpi Instruments Co., Ltd, Yueqing city, China) and digital goniometer. Further, the influence of the stalk diameter, bending angle and cutting height on bending stress and Young's modulus of stalk was investigated.

According to field investigation, the stubble height of green forage maize during harvesting is generally 100-200 mm, so the cutting height was set to 100 mm, 150 mm, and 200 mm in the study. The diameter of the stalk at the measuring point was measured and ranged from 22 to 30 mm. The target diameters of the stalk set in this study were 22 mm, 24 mm, 26 mm, 28 mm, and 30 mm. But in fact, the actual diameter of the stalk and the target value are somewhat deviation. Therefore, stalks as close as possible to the target diameter were selected for testing, and the average diameter of the stalks used in the three tests was taken to be the actual value, which was 22.1 mm, 23.9 mm, 26.2 mm, 28.2 mm, and 30.1 mm, respectively. The bending angles were set at 5°, 10°, 15°, 20°, and 25°.

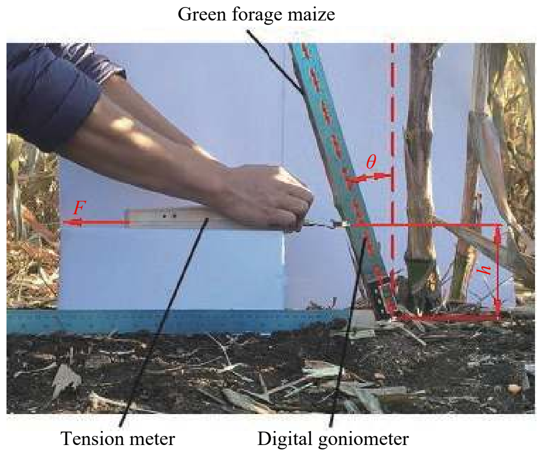


Figure 4 Instruments and methods for bending tests

Prior to the start of the experiment, the positions of 100 mm, 150 mm, and 200 mm, respectively, in the stalk heights were marked, that is, at the point of measurement. At the same time, the stalk diameter with different cutting heights was measured and marked. The leaves near the measuring point were removed for the convenience of measurement. During the test, a non-elastic rope was used for bundling at the measurement point, and the other end was connected to a tensile meter horizontally. Then, move the tensile meter horizontally to bend the stalk. Afterwards, according to the instrument's indicator, the force at this point was recorded when the stalk reached a predetermined bending angle (determined by the digital goniometer). Finally, adjust the digital goniometer and re-measure the force at different angles. Each group of experiments was repeated three times to eliminate errors. Then, the bending stress was calculated by Equation (5) and the Young's modulus was obtained by using the exact differential equation of deflection line[24]. And the value of the bending deflection and axial displacement can be obtained by numerical calculation. The bending deformation of the stalk can lead to the change of the stalk stubble height, which is main index to evaluate harvest quality and the performance of a harvester. Therefore, the change of stubble height can be expressed as measuring point displacement, which could be calculated by bending deflection and axial displacement. The research of these three parameters is of great significance to the design and development of forage harvester.

3 Results and discussion

To further understand and explain the influence of stalk diameter and bending angle on bending stress, the Young's modulus, the bending deflection, axial displacement and measuring point displacement, nonlinear regression fitting and variance analysis were carried out. Meanwhile, the data was separated from 5% level using the Duncan's multiple comparison tests. We discussed the results in detail below.

3.1 Effects of various factors on bending stress

3.1.1 Effects of stalk diameter and bending angle on bending stress

The effects of different diameters and bending angles on the bending stress of green forage maize stalks is listed in Table 1. During the test, the cutting height was 200 mm. The bending stress values varied in 22.13-15.88 MPa, 34.02-21.95 MPa, 42.79-27.09 MPa, 51.90-29.05 MPa, and 46.76-30.77 MPa for bending angles ranged from 5° to 25°, respectively, at the different stalk diameters. The bending stress of the stalk with a diameter of 22 mm first increases and then declines with a growing bending angle, and reaches maximum value at 20°. The reason for the reduced bending stress may be that the anchoring effect of soil loosening on the roots is diminished when the bending is too large. However, the bending stress of the stalk with a diameter of 24 to 30 mm gradually increases with the bending angle. This may be attributed to the stronger anchorage of the soil to the coarse stalks. The diameter and bending angle have a significant effect on the bending stress (p<0.05). In addition, the results of Duncan's multiple range test indicate that the bending stresses are statistically different from each other.

Table 1 Effects of stalk diameter and bending angle on bending stress of green forage maize

Stalk diameter/mm		Bending stress/MPa				
		Bending angle/(°)				
Target value	Actual value	5	10	15	20	25
22	22.1	22.13a	34.02a	42.79a	51.90a	46.76a
24	23.9	21.84ab	31.72b	35.47b	40.57b	45.92a
26	26.2	20.71bc	26.83c	30.71c	34.49c	40.09b
28	28.2	20.00c	24.59d	28.94cd	32.52c	35.81c
30	30.1	15.88d	21.95e	27.09d	29.05d	30.77d

Note: Values followed by the different letters in each column are significantly different (p<0.05).

In addition, the bending stress of green forage maize can be evaluated as a function of stalk diameter and bending angle, as shown in Figure 5. It is noticed that the bending stress of the stalk gradually decreases with the increasing diameters when the bending angle is fixed. This may be due to that denser internal structure and stronger bending resistance of the larger diameter stalks. Shi et al.[27] found that the bending mechanical properties of large-diameter stalks are superior to those of small-diameter stalks in the study of the mechanical properties of Artemisia selengensis stalk. Wen et al.[28] obtained similar results when studying the influence of Glycyrrhiza glabra stem diameter on bending stress. The quadratic regression equations obtained by regression analysis of stem diameter and bending stress at different bending angles are listed in Table 2. The regression coefficients of all fitting equations are greater than 0.94 (Table 2), which means that the regression equations are well fitted and the models are reliable.

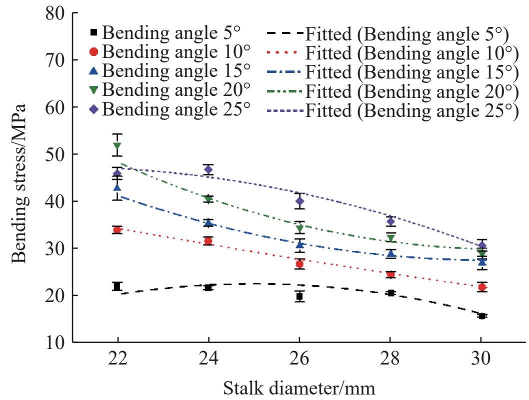


Figure 5 Relationship between bending stress and stalk diameter for different bending angles. Error bars indicate standard deviations

Table 2 Equations representing the relationships between bending stress of green forage maize and stalk diameter, bending angle, and cutting height

Factors		Bending stress/MPa	R^2
Bending angle/(°)	5	$-0.253d^2+12.660d-135.508$	0.9422
	10	$0.022d^2-2.708d+83.196$	0.9935
	15	$0.204d^2-12.331d+213.709$	0.9838
	20	$0.253d^2-15.461d+265.997$	0.9601
	25	$-0.193d^2+7.953d-34.745$	0.9726
Cutting height/mm	100	$-0.012\theta^2+0.834\theta+15.212$	0.9767
	150	$-0.006\theta^2-1.227\theta+15.953$	0.9999
	200	$-0.022\theta^2+1.826\theta+13.500$	0.9839

3.1.2 Effect of cutting height and bending angle on bending stress

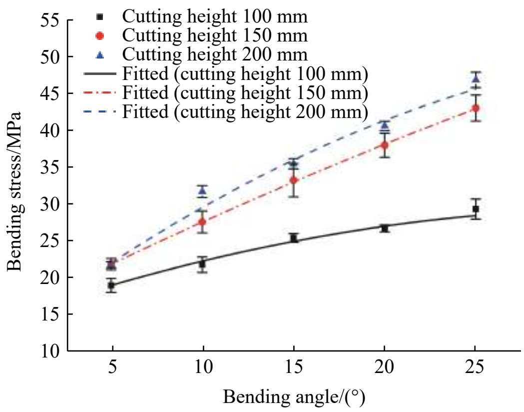
With the varying cutting heights and bending angles, the value of bending stress of green forage maize changes significantly (p<0.05), when the diameter is 22 mm, as listed in Table 3. From Table 3, it follows that the bending stress at the cutting height ranges from 100 to 200 mm increases for all bending angles. Moreover, the bending stress of green forage maize at the cutting height of 100 mm, 150 mm, and 200 mm increased by 55.5%, 45.7% and 106.2%, respectively, as bending angles were raised from 5° to 25°. It can be seen that the bending angle has a more significant effect on the bending stress at higher cutting height. This is because at higher cutting height, the deflection of the bent stalk at the same bending angle is larger. In addition, the maximum bending stress is 44.93 MPa, which was obtained at a cutting height of 200 mm at a bending angle of 25°, while the minimum one is 16.38 MPa occurred at 100 mm cutting height at the bending angle of 5°. The difference between the maximum and the minimum bending stress is about 274.3%. This is because the required force is minimized when the bending angle is small. The values of bending stress obtained in this study are larger than that of barley straw[29] (6.32-12.41 MPa) and wheat straw[30] (6.4-10.5 MPa), and close to that of sorghum stalk[15] (45.65 MPa) and alfalfa stems[31] (9.71-47.49 MPa), which indicates that green forage maize has poor flexibility. According to the results of Duncan's multiple range test, there is a statistical difference between the mean values of the bending stress at different bending angles for various cutting heights (Table 3).

Figure 6 shows a trend of increasing bending stress with increasing bending angle for all cutting heights. This means that the larger the bending angle, the more likely the stalk is to bend and

Table 3 Effects of bending angle and cutting height on bending stress of green forage maize

Bending angle/(°)	Bending stress/MPa		
	Cutting height/mm		
	100	150	200
5	16.38d	24.68d	21.79e
10	19.07c	28.61c	31.21d
15	21.87b	32.42b	34.50c
20	24.84a	34.99a	38.06b
25	25.48a	35.95a	44.93a

Note: Values followed by the different letters in each column are significantly different (p<0.05).



Note: Error bars indicate standard deviations.

Figure 6 Relationship between bending stress and bending angle at different cutting heights

break off. For the same bending angle, the bending stress increases as the cutting height increases. A similar effect of the stalk region on bending stress was also pointed out by Shahbazi et al.[32] for safflower stalk, and Galedar et al.[31] for alfalfa stem. The most suitable fitting model of data was obtained by regression analysis. The relationship between bending stress and bending angle for each cutting height is expressed by the equation and it was listed in Table 2. Similarly, these models also fit very well (R^2>0.97).

3.2 Effect of various factors on the Young's modulus

3.2.1 Effect of stalk diameter and bending angle on Young's modulus

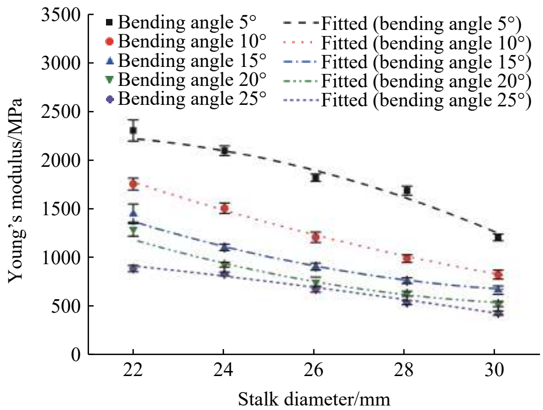
The effect of the stalk diameter and bending angle on the Young's modulus in bending was studied and the results are listed in Table 4. From the results, it is observed that the stalk diameter and bending angle have a significant effect on Young's modulus (p<0.05). The results related to the Young's modulus decrease with increasing stalk diameter for all bending angles. In the past studies have had similar results, for example, Shahabazi et al.[33] and Özbek et al.[34] reported that the value of the Young's modulus gradually grows toward the top region of stalk. Specifically, when the diameter of stalk varies from 30 to 22 mm, the average value of Young's modulus for the bending angle of 5°, 10°, 15°, 20°, and 25° ranged in 1204.47-2292.07 MPa, 826.76-1747.57 MPa, 669.81-1444.79 MPa, 528.09-1288.33 MPa, and 435.87-888.06 MPa, respectively. However, it can be found that Young's modulus decreases slowly with increasing stalk diameters for the bending angle of 5°. Based on the results of Duncan's multiple range test, it follows that for all bending angles, there is essentially no statistical difference between the mean values of the Young's modulus for different diameters. But, the difference between the mean values of Young's modulus of 28 mm and 30 mm stalk is not significant for the bending angle of 15°. This is probably because the forces required to bend a stalk of 28 mm and 30 mm diameter by 15 degrees are similar. On the other hand, Young's modulus of stalk with same diameter decreases as the bending angle increased from 5° to 25°, which means that the larger the bending angle is, the easier the stalk is to break. Therefore, in harvesting green forage maize stalks, the stalks should be cut off smoothly within a safe bending angle range.

Table 4 Effects of stalk diameter and bending angle on Young's modulus of green forage maize

Stalk diameter/mm		Young's modulus				
		Bending angle/(°)				
Target value	Actual value	5	10	15	20	25
22	22.1	2292.07a	1747.57a	1444.79a	1288.33a	888.06a
24	23.9	2085.96b	1502.14b	1104.12b	928.27b	833.54b
26	26.2	1812.71c	1207.25c	907.90c	750.57c	679.18c
28	28.2	1680.41d	989.57d	765.23d	632.29d	542.55d
30	30.1	1204.47e	825.76e	669.81d	528.09e	435.87e

Values followed by the different letters in each column are significantly different (p<0.05).

In order to clearly characterize the trend of the Young's modulus variation for green forage maize with various stalk diameters and bending angles, the quadratic curves shown in Figure 7 are plotted. From Figure 7, the Young's modulus decreases with an increase in stalk diameter for fixed bending angle. Similar results were reported by Shahbazi[31]. İnce et al.[16] studied the bending characteristics of sunflower straw and also obtained similar results. Furthermore, the best-fit equations of Young's modulus and different diameters of green forage maize for different bending angles were determined by the regression analysis, and the coefficients of the equations are all greater than 0.96, indicating that the fittings are good and the models are reliable (Table 5).



Note: Error bars indicate standard deviations.

Figure 7 Relationship between the Young's modulus and stalk diameter for different bending angles

3.2.2 Effect of cutting height and bending angle on Young's modulus

The effect of bending angle and cutting height on Young's modulus of green forage maize in bending were also acquired. Both the bending angle and cutting height significantly affect the Young's modulus at 5% level of probability (p<0.05). The average value of Young's modulus of green forage maize ranges in 258.93-900.84 MPa, 573.04-1566.68 MPa and 833.55-2085.96 MPa at the cutting height of 100 mm, 150 mm, and 200 mm, respectively, when the bending angle changes from the largest to smallest. For

Table 5 Equations representing the relationships between Young's modulus of green forage maize and stalk diameter, bending angle, and cutting height

Factors		Young's modulus/MPa	R^2
Bending angle/(°)	5	$-9.727d^2+385.398d-1560.011$	0.9730
	10	$4.324d^2-341.919d+7196.853$	0.9999
	15	$6.876d^2-443.152d+7788.063$	0.9882
	20	$6.876d^2-437.509d+7481.581$	0.9765
	25	$-1.373d^2+11.121d+1335.606$	0.9926
Cutting height/mm	100	$1.396\theta^2-68.645\theta+1111.352$	0.9644
	150	$2.689\theta^2-127.200\theta+2084.407$	0.9806
	200	$3.215\theta^2-157.830\theta+2776.214$	0.9969

Explanation as in Figure 3.

the three cutting heights, the Young's modulus in distinct bending angles has a statistical difference between each other (Table 6). Moreover, the mean values of Young's modulus of green forage maize determined in three heights for each bending angle have significant differences. In addition, the difference between the values of the Young's modulus at the lowest and highest cutting height for the bending angle increased from 5° to 25° is 131.6%, 193.3%, 181.5%, 206.7%, and 221.9%, respectively. It can be seen that the smaller the bending angle, the more significant the influence of the cutting height on the Young's modulus.

Table 6 Effects of bending angle and cutting height on Young's modulus of green forage maize

Bending angle/(°)	Young's modulus/MPa Cutting height/mm 100	 150	 200
5	900.84a	1566.68a	2085.96a
10	512.11b	978.19b	1502.14b
15	392.22c	774.31c	1104.12c
20	302.69d	649.53d	928.27d
25	258.93d	573.04d	833.55e

Values followed by the different letters in each column are significantly different (p<0.05).

The relationship between the Young's modulus and bending angle under three cutting heights were drawn in Figure 8. As described in this figure, the Young's modulus decreases significantly with the bending angle increased for all heights. Furthermore, the curve of the bending angle-Young's modulus decreases as a polynomial at three cutting heights. Regression analysis shows that there is a strong correlation between Young's modulus and bending angle (R^2>0.96), as listed in Table 5.

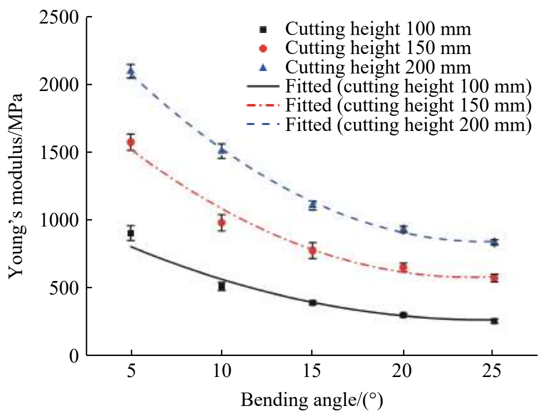


Figure 8 Relationship between the Young's modulus and bending angle at different cutting heights. Error bars indicate standard deviations

3.3 Effect of various factors on other indicators

Table 7 lists the values of the bending deflection, axial displacement and measuring point displacement for the bending angle varied from 5° to 25° at different cutting heights. As follows from Table 7, both the bending angle and the cutting height have an impact on these parameters. When the bending angle is fixed, all three parameters increase significantly with increasing the cutting height. On the other hand, the bending deflection, the axial displacement, and the measuring point displacement change with the varying bending angle for each height. According to the previous analysis, the larger the cutting height and bending angle, the smaller the Young's modulus, implying weaker resistance of the stalk to elastic deformation. Therefore, the cutting height and bending angle have a significant effect on these three parameters. The maximum bending deflection, axial displacement and measuring point displacement occurred at the bending angle of 25° for 200 mm height are 40.93 mm, 10.10 mm, and 11.15 mm, respectively, while the minimum values obtained at the bending angle of 5° for 100 mm height are 4.93 mm, 0.20 mm, and 0.20 mm, respectively. As can be seen from Table 7, the measuring point displacements changes to a large extent with the varied of cutting height and bending angle. This is because the higher the cutting height and bending angle, the more serious the deformation of the stalk. The varied measuring point displacements during the bending process are the main reason for the inconsistency in the stubble height during the harvest of green forage maize. Therefore, it is necessary to study the bending characteristics and related parameters of green forage maize during harvesting in order to ensure consistent stubble height and address issues such as loss reduction.

Table 7 Effects of bending angle and cutting height on bending deflection, axial displacement and measuring point displacement

Bending angle/(°)	Cutting height/mm Bending deflection/mm 100	 150	 200	 Axial displacement/mm 100	 150	 200	 Measuring point displacement/mm 100	 150	 200
5	4.93	7.40	9.87	0.20	0.30	0.41	0.20	0.31	0.41
10	9.49	14.23	18.97	0.81	1.22	1.62	0.82	1.24	1.65
15	14.01	21.01	27.99	1.82	2.74	3.65	1.89	2.83	3.78
20	18.47	27.70	36.86	3.24	4.86	6.48	3.45	5.17	6.89
25	20.58	30.87	40.93	5.05	7.58	10.10	5.57	8.36	11.15

4 Conclusions

The bending stress increased with the increase of bending angle and cutting height, but decreases with an increase in stalk diameter. And as the stalk diameter and bending angle increase, the mean value of young's modulus of green forage maize decreases as a quadratic function. But the Young's modulus of stalk gradually grows with the increase of the cutting height. Additionally, the bending deflection, axial displacement and measuring point displacement are only related to bending angle and cutting height. The mean values of the three parameters show an upward trend when the bending angle and cutting height increased.

The values of bending stress, Young's modulus, bending deflection, axial displacement and measuring point displacement ranged in 15.88-51.90 MPa, 258.93-2292.07 MPa, 4.93-40.9 3 mm, 0.20-10.10 mm and 0.20-11.15 mm, respectively, with the bending angles of 5°-25° and the cutting heights of 100-200 mm.

In this study, it was assumed that the stalk could not be cut off instantaneously but bent to a certain extent during harvest. However, in the actual harvesting process, the bending angle of stalk is uncertain. Therefore, in future work, it is necessary to conduct in-depth research on its cutting characteristics in combination with bending characteristics.

Acknowledgements

The authors appreciate the careful and precise reviews by anonymous reviewers and editors. This work was financially supported by the National Key R&D Program of China (2022YFD2002102) and the National Natural Science Foundation of China (52105257).

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