Experiment and analysis on mechanical properties of *Artemisia selengensis* stalk

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Abstract: The technology used for the storage and transportation of *Artemisia selengensis* is becoming increasingly important with its increasing consumption and demand; moreover, the amounts of artificial planting contribute to the challenges in *Artemisia selengensis* harvesting. Therefore, the mechanical property parameters of the *Artemisia selengensis* stalks were determined and researched to reduce the mechanical damage during harvesting, transportation, processing and storage. The *Artemisia selengensis* stalks were taken as the test object and a physical test method was adopted to study the impact of different positions, diameters, and directions on the mechanical properties by using the TMS-Pro texture analyzer; then, the relevant changing trends of the characteristic mechanical parameters were analyzed using statistical software. In the compression test, the compression load-deformation curve was observed and the breaking force and deformation were obtained; then, the compressive strength, elastic modulus and compression energy were computed. Next, the curve-fitting of the compressive strength and compression energy was carried out. In the shear test, the shear stress-deformation curve was obtained and the shear force, deformation, shear strength, and shear work were calculated. Then, the regression fitting of the section area, peak shearing stress and shearing work was conducted. Finally, in the last bending test, the bending stress-deformation curve, bending peak force, deformation, and bending work were obtained. Then the bending forces of other plants were tested, the results were compared and analyzed with the theoretical values, and finally the regression fittings were implemented. All the analysis results showed that *Artemisia selengensis* stalks can be considered to be anisotropic materials. The results also showed that the compressive strength and elastic modulus decreased with the height of stalk position, while the deformation increased. In addition, with the increase in the stalk diameter, the bending strength and fracture mechanical work increased, while the deformation decreased. The research results can provide a theoretical basis and reference for the design of the harvest equipment of *Artemisia selengensis* while minimizing its mechanical damage.

Keywords: *Artemisia selengensis*, stalks, texture analyzer, mechanical properties
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1 Introduction

Artemisia selengensis Turcz. (known as water artemisia) is rich in a variety of essential mineral elements and has high medicinal value[1-3]. Suitable planting temperature can lead to its yearly growth[4], and it is now becoming one of the distinctive wild vegetables in winter and spring markets[5]. The enormous increase in the planting area is causing a huge problem in the

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harvesting of *Artemisia selengensis*, considering labor shortages, low level of mechanization, and so on. When realizing mechanized harvesting of *Artemisia selengensis*, the effect of harvest is not only related to the driving force of the machinery equipment and the technical parameters of the parts but also to the mechanical properties of the harvest object crop[6,7]. As an indispensable reference index in the quality analysis of agricultural products and in the mechanical equipment design, the mechanical properties of crops have been widely researched by many scholars[8-10]. Chen et al.[11,12] studied the mechanical properties of lychee and litchi tree branches, analyzed the compression, performed the shear characteristic test by the universal testing machine, and obtained its parallel and cross grain compression strength, and other mechanical characteristic parameters. Ding et al.[13] performed compression and shear characteristic tests on different maturities of the Gordon euryale seeds under different loading directions and analyzed the relationships among the breaking strength, strain energy, strain energy density, and other mechanical characteristic parameters. Li et al.[14,15] studied the reciprocating cutting mechanical characteristics of corn stalks and a pendulum-type stem cutting test-bed was developed and designed for the corresponding measurements and control system.

Throughout the research results in the literature, correlational research on the mechanical properties of crops has made some progress; however, theoretical research on the material and mechanical properties of *Artemisia selengensis* stalks has not been studied to a great extent[16-23]. With the rapid development of the *Artemisia selengensis* industry, the *Artemisia selengensis* storage technology is becoming a key topic and the mechanical characteristics of the stalks are important parameters for the mechanized harvesting of the *Artemisia selengensis*; these parameters are used for the material analysis and development of *Artemisia selengensis* harvesting machinery. Therefore, by utilizing the research methods to study the mechanical properties of stem crops such as cabbage, cassava, cotton and other melons as a reference, based on the independent development of self-propelled selengensis harvester, the mechanical performance for *Artemisia selengensis* stalks were studied to optimize the working parameters of cutting parts, determine the optimal cutting movement parameters combination, improve the quality of stubble and performance of harvesting machine.

Taking into consideration the mechanical damage of *Artemisia selengensis* during the harvesting, processing, transportation and storage, as well as the mechanization harvester is very useful to replace the manual selengensis harvesting in China. Therefore *Artemisia selengensis* stalks were took as the test object and a physical test method was adopted to study the impact of different positions, diameters, and directions on the mechanical properties by performing compression tests, shear tests, and bending tests using the TMS-Pro texture analyzer; The corresponding mechanical characteristic parameters were obtained and the relevant changing trends of these parameters for stalks were analyzed using statistical software to reduce the mechanical damage of *Artemisia selengensis* during harvesting, transportation, processing, and storage and also provide a theoretical basis for the development of a new orderly harvester, which combines agricultural machinery and agronomy for the *Artemisia selengensis*.

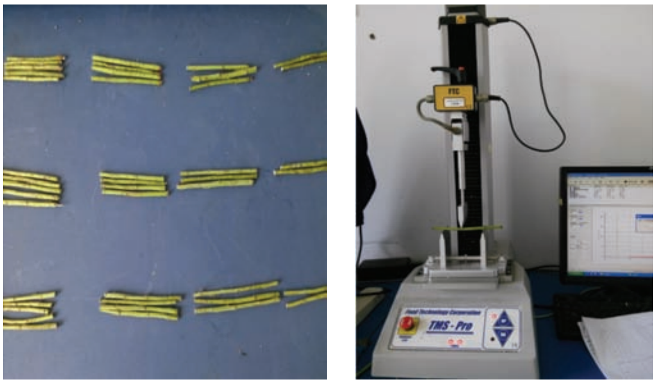
2 Materials and methods

2.1 Materials and equipment

The *Artemisia selengensis* stem samples were collected from the production base in the Bagua Continent, Nanjing city, Jiangsu Province, in April 2015 and the sample varieties were Qingbai *Artemisia selengensis*; the random sampling made the selected stems as straight as possible and there were no plant diseases and insect pests, and branchless, after picking a packed sample, as shown in Figure 1a.

The selected experimental apparatus for testing the mechanical performance parameters of the stalk was the TMS-Pro texture analyzer manufactured by the Food Technology Corporation, as shown in Figure 1b. Its technical characteristics are as follows: maximum detection force: 2500 N, detection precision: >0.015%, detecting stroke: 30 cm, detection speed: 0.1-500 mm/min, accuracy of the decrease of the 32 cm long distance:

2.5 μm, speed precision: >0.1%. The compression test device includes a cylindrical flat steel compressed head, the bottom diameter of which is 65 mm and thickness is 10 mm. The shear test apparatus has a cuboid steel blade of length 60 mm, width of 40 mm, and thickness of 0.5 mm. The bending test device consists of two support plates, which are machined in the triangle groove in the middle and can be easily fixed; their width is 100 mm and all the pressure surfaces are steel framework cubed with a side length of 130 mm.



a. Materials b. Equipment

Figure 1 Materials and the equipment

2.2 Sample preparation

Randomly selected, roughly similar *Artemisia selengensis* stems, were divided into two groups A_1 and A_2 based on the stem root diameter, i.e., (4±0.5) mm and (8±0.5) mm. Moreover, the loading direction was divided into axial C_1 and radial C_2. The internode of the stalks from the land was defined as root B_3, central B_2, and top B_1. The three-section samples should meet the requirements that the root sampled is at a distance of 10 mm to 15 mm from the stubble, the central has a deviation of 5 mm from the plant center, and the top is sampled at 100-150 mm above the central sample.

The stems were made into cylinders with diameters A_1 and A_2 and the lengths were (10±0.5) mm as that of the compressed sample. The shear specimens were made into cylinders, which were (20±0.5) mm long and the midpoint of each internode was chosen as the shear point. In addition, the bending specimens were cylinders, which were (110±1) mm long, made using the three-point bending fixture that matched the selected test-bench with the adjustable pivot distance of 100 mm.

2.3 Test method

The quasi-static loading method was used in our study; the loading rate was set as 10 mm/min and the return rate was set as 100 mm/min in the TMS-Pro texture analyzer. Flat-plate compression test was used to complete the test for different diameters and different radial and axial growth areas. The cutter surface was made perpendicular to the samples and the mid-point was selected as the shear point for the stalks with different diameters in different axial and radial positions. The stalk bending experiment was carried out for different diameters and different growth areas and the theoretical and practical mechanical characteristic parameters were comparatively analyzed. The test was repeated 5 times and the applied load and deformation parameters were automatically collected and recorded by the TMS-Pro texture analyzer; the average of the performance parameters was recorded for each group.

The puncture test of TMS-Pro texture analyzer and ASAE (American Society of Agricultural Engineers) Standards S352.2 were used to measure the hardness and moisture content of the *Artemisia selengensis* stem, respectively[24].

3 Results and analysis

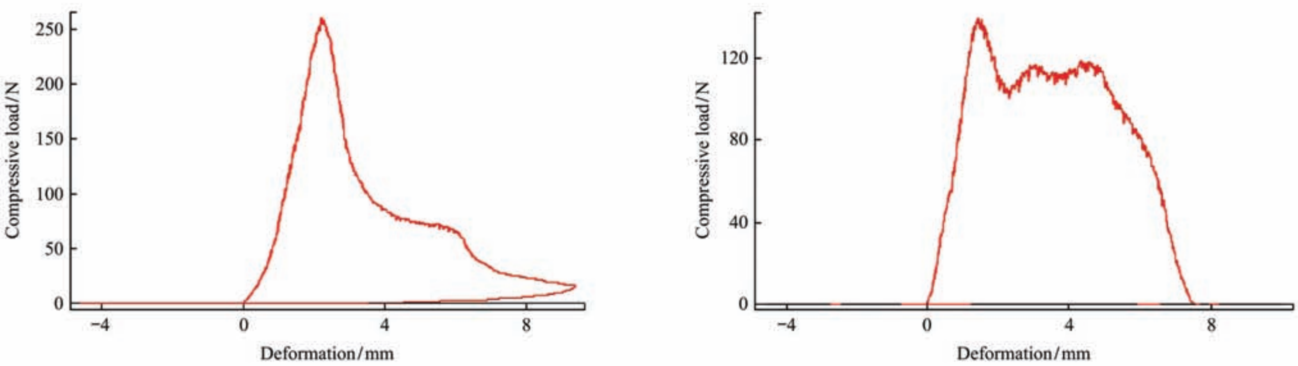
3.1 Compression mechanical properties

Two typical compressive load-deformation curves of *Artemisia selengensis* stems in different loading directions (axial and radial) are shown in Figure 2.

This study showed that, for the same loading rate along different directions of the applied compression force, the compression load-deformation curves are different. Figure 2a shows that at the beginning of the axial compression test, the stem deformation increased with the increase in the compression load, which is an approximate linear relationship. As the test load increases until a limit value, which is the breaking point, the stem will suddenly be destroyed and the corresponding applied load is the breaking force; the macroscopic structure of the material under axial compression load will be destroyed and the deformation will continue to increase with reducing load. Because the stem lignocellulose is axially distributed, the stem perpendicular to the axially cut production sample can still carry a certain load after being damaged. Figure 2b shows that at the beginning of the radial compression test, the deformation increased linearly with the increase in the compression load. When the test load reached a certain limit, after reached crop proportional limit, its microstructure began to degrade and the resistance decreased by a small amount. However, the resistance slightly increased when the stem sample was compressed until it was crushed and then the compression force was quickly changed to be equal to zero. This is due to the internal special structure of the *Artemisia selengensis* stems and the lignocellulose that surrounds the stem (skin); when the compressed load reaches a certain value, the skin is crushed and the internal core organization cannot bear the large compression load.

As can be seen from Figure 2, the stem compression resistance possesses anisotropic characteristics and the compressive mechanical characteristic curves are different under different loading directions, which are determined by the microstructure mechanism of stalks. The strength, quantity, and connection form of the fiber, which is mainly arranged inside along the axial direction, determine the transverse mechanical properties, and the strength, quantity, and connection form of the substrate between the fiber determine the radial mechanical properties of the stem. Therefore, the orthogonal anisotropic characteristics, i.e., the axial compression mechanical properties of the stem are far more than radial on the macroscopic mechanical behavior, are decided.

According to the value of the force deformation recorded by the TMS-Pro texture analyzer, the parameters of axial compression mechanical properties for *Artemisia selengensis* stem with different diameters (A_1, A_2) and different growth areas (B_1, B_2, B_3) are shown in Table 1.



a. Axial compression   b. Radial compression

Figure 2 Compression force-deformation curve of Selengensis stem in different loading directions

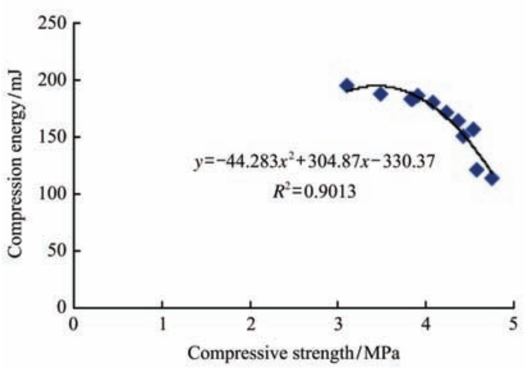
Table 1 Compression mechanical performance parameters of selengensis stem

Position	Diameter	Moisture Content/%	Rigidity /N·mm^{-2}	Compression test			
				Breaking force /N	Deformation/mm	Compressive strength/MPa	Elasticity modulus/MPa
B_1	A_1	68.22	11.52	39.05^a±0.32	9.98^a±0.23	3.11	6.23
	A_2	62.17	19.61	183.8^b±0.52	3.34^b±0.13	3.67	21.99
B_2	A_1	61.81	15.57	51.38^a±0.48	6.98^a±0.17	4.09	11.72
	A_2	55.94	27.45	276.97^b±0.59	2.18^b±0.19	5.51	50.55
B_3	A_1	56.36	21.33	59.77^a±0.52	3.79^a±0.14	4.76	25.12
	A_2	51.72	32.26	372.6^b±0.67	1.8^b±0.03	7.42	82.44

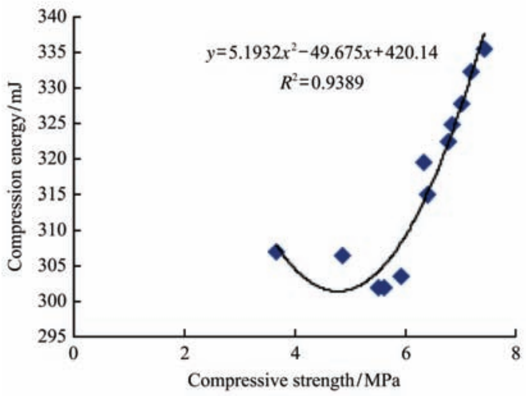
Note: The force and deformation values are AVG ± standard deviation. In each row different superscript letters indicate significant differences (p<0.05). Each point is the average of three replicates.

As can be seen from Table 1, when the stalk diameter was A_1, in B_3, B_2, B_1 positions, the average compression crushed forces were 59.77 N, 51.38 N, 39.05 N, respectively; the crushed force, compressive strength, compressive elastic modulus decreased from B_3 to B_1, but the deformation increased gradually and the difference was not significant. When the stalk diameter was A_2, the average compression crushed forces were 372.6 N, 276.97 N, 183.8 N, respectively. The changing tendency of the compressive mechanical characteristic parameters from B_3 to B_1 was similar to A_1, but the parameters were generally higher than A_1, which shows that the compression mechanical properties were better than A_1.

According to the test values, the stem compressive energy of A_1 and A_2 were computed, which were a maximum of 194.86 mJ and 335.34 mJ, respectively, and a minimum of 113.26 mJ and 301.89 mJ, respectively; the mean values were 165.70 mJ and 316.42 mJ, respectively, standard deviations were 26.26 mJ and 12.15 mJ, respectively, and the variation coefficients were 15.85% and 3.84% respectively. We performed regression (curve-fitting) for the compressive strength and compression energy for diameters A_1 and A_2. The fitting results showed that the quadratic polynomial function relation has a high fitting degree and the fitting equation is used to determine the coefficient, as shown in Figure 3 (p<0.05). The results showed that there exists a quadratic polynomial function relationship between the stem axial compressive strength and compression strain energy.



a. Diameter A_1

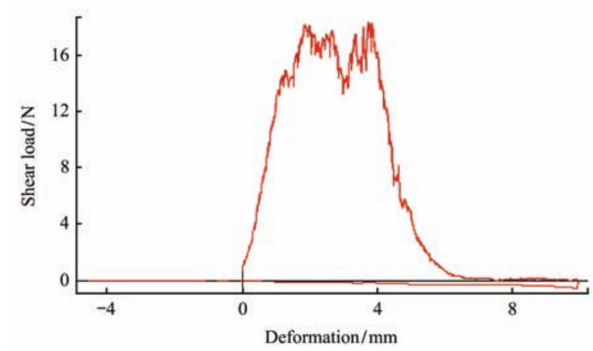


b. Diameter A_2

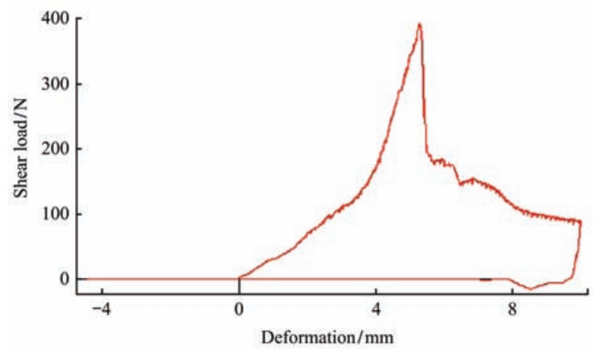
Figure 3 Relationship between stress resistance intensity and compression energy of selengensis stem

3.2 Shearing mechanical properties

We first completed the no-load test to limit the frictional resistance within the permitted error range for the moving cutter cutting process, and then began the shear test. The typical shear loading-deformation curves of the stem in different directions are shown in Figure 4.



a. Axial shearing



b. Radial shearing

Figure 4 Shear force-deformation curve of Selengensis stem in different loading directions

In Figure 4a, a linear relationship between the shear force and deformation can be observed in the initial stage of axial shear load. With the passage of time, because of the presence of some bifurcation nodes of the stem, a tiny shift of shear force occurred. When the load was increased to a certain limit, the stalk capacity of withstanding shearing load sharply reduced to zero, and was observed to split into two parts under the action of axial shearing. Moreover, in Figure 4b, the entirety of radial shearing process can be divided into three stages; at the preliminary stage of shearing, the relationship between the shearing force and deformation was similar to that in the initial stage of axial shear load. With the gradual increase in deformation, the shear force was observed to increase rapidly. This could be attributed to the stalk's axial fiber structure susceptibility to be squashed; both sides of the stem bulged to the center after being crushed, and the incision began to squeeze the stem. Therefore, the required shear force became increasingly large during shearing. In the intermediary stage, when the testing shear force increased to a certain value, the stem cortex experienced sheared failure, and the carrying capacity of internal core organization was reduced, which is indicated by the slowing down of the curve. In the final stage, the cutter cut to the bottom layer, leading to the stem subcortex being subject to stress. Correspondingly, the curve rose marginally, and reached a certain value subsequent to which, the stem was suddenly destroyed, thereby leading to an instantaneous reduction in the compressive capacity (reduced to zero).

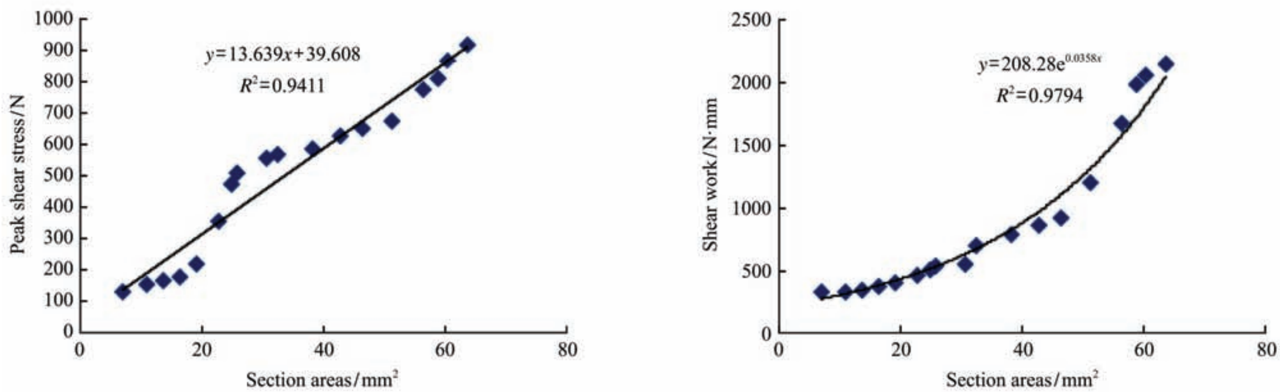
The shearing test results in different loading directions (C_1, C_2) for stem with different diameters (A_1, A_2) and different growth areas (B_1, B_2, B_3) are shown in Table 2. It can be seen that for stem with A_1 diameter, the shearing force in the root was the largest, and the mid and top section of the stem exhibited reduction in shearing force. The radial, axial shear force and radial, axial shear strength were 175.9 N, 17.7 N, 14 MPa and 0.44 MPa, respectively. The largest deformation was observed in the top section, where the radial, axial deformation mean values were 5.15 mm and 5.5 mm, respectively. However, the deformation in the mid-section and the root decreased. For stem with diameter A_2, all the change trends were identical to those for stem with diameter A_1.

Based on the stalks' shearing test parameters, we made regression fittings between the stem section areas and the peak shear stress, shear work respectively. The fitting equations and the corresponding determined coefficients are shown in Figure 5 (p<0.01). The results showed that when the area of the samples was within the range of 7.07-63.62 mm^2 (corresponding diameter of the homolographic circle was 3-9 mm), a linear function relationship between the stem peak shearing force and the section areas was observed. Moreover, there was an exponential function relationship between the shearing work and the section areas, and both of them exhibited positive correlation.

Table 2 Shear mechanical performance parameters of Selengensis stem

Position	Diameter	Direction	Shearing test			
			Shear force/N	Deformation/mm	Shear strength/MPa	Shear work/N·mm
B_1	A_1	C_1	129.8^a±0.54	5.13^a±0.12	10.33	320.91
		C_2	11.2^b±0.21	5.5^b±0.27	0.28	19.54
	A_2	C_1	554.9^b±0.72	5.03^a±0.23	11.04	542.87
		C_2	23.4^b±0.27	6.96^b±0.30	0.30	138.1
B_2	A_1	C_1	153.0^a±0.55	5.2^a±0.15	12.18	327.98
		C_2	13.6^c±0.23	4.38^b±0.22	0.34	30.78
	A_2	C_1	675^b±0.84	6.76^b±0.28	13.44	1196.57
		C_2	52.4^a±0.32	5.91^a±0.27	0.66	159.87
B_3	A_1	C_1	175.9^a±0.63	5.65^b±0.20	14.00	368.38
		C_2	17.7^a±0.29	3.57^b±0.14	0.44	33.37
	A_2	C_1	915.8^c±0.89	7.25^c±0.34	18.23	2140.46
		C_2	74.63^a±0.44	5.76^a±0.21	0.93	238.84

Note: The force and deformation values are AVG ± standard deviation. In each row different superscript letters indicate significant differences (p<0.05). Each point is the average of three replicates.

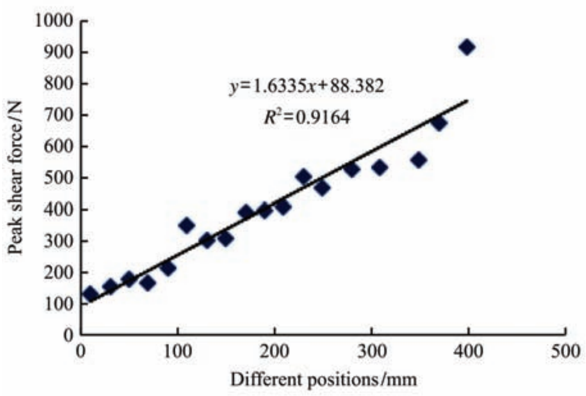


a. Relationship between sectional area and shear force

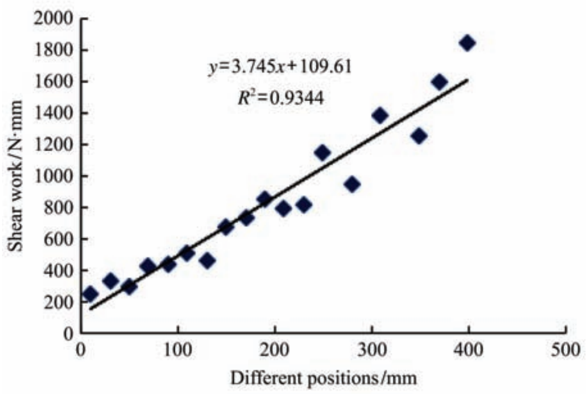
b. Relationship between sectional area and shear work

Figure 5 Relationship between cross-sectional area and shear force, shear work

We also completed the regression fittings for different positions and the peak shear force, shear work respectively, the fitting equations and determine coefficients as shown in Figure 6 (p<0.01). The results showed that for stem positions in B_1, B_2, and B_3 (10-400 mm), a positive linear correlation relationship exists between the peak shear force and the positions; a similar relationship was observed between the shear work and the above-said positions.



a. Relationship between position and shear force



b. Relationship between position and shear work

Figure 6 Relationship between position and shear force, shear work

3.3 Bending mechanical properties

The three-point bending test was adopted to measure the *Artemisia selengensis* stem bending mechanical property parameters; Figure 7 shows load-deformation curve in the radial bending test. The bending load exhibits a non-linear relationship with deformation. With the passage of time, when the load was increased to a certain value, the fibrous tissue structure was damaged, thereby leading to a reduction in the load bearing; however, because the stem had certain elasticity and brittleness, the curve shows an upward trend. While the stem distortion reached a certain degree, which was the yield limit, the load curve reduced to 0, causing the stem to snap.

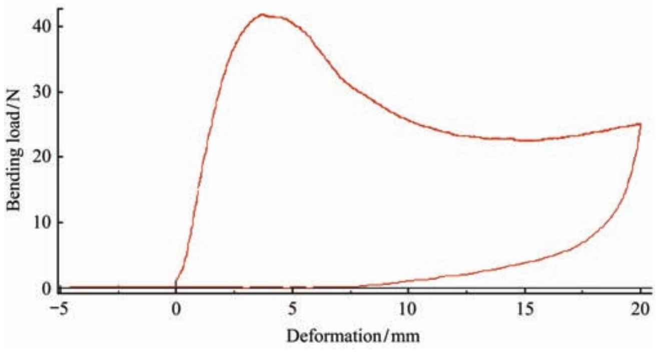


Figure 7 Bending force-deformation curve of Selengensis stem

The bending test results in different loading directions for stems with different diameters and different growth areas are shown in Table 3. The bending mechanical performance for stem with diameter A_2 was better than that of stem with diameter A_1. However, a reduction in the bending mechanical performance was observed in positions B_3, B_2, B_1. The bending mechanical performance parameters were maximum for stem diameter A_2 in position B_3; the mean peak force, bending breaking work, and deformation were 60.37 N, 153.6 N·mm, 3.7 mm, respectively. In addition, the stem with diameter A_1 in position B_1 exhibited the lowest bending mechanical performance parameters.

Table 3 Bending mechanical performance parameters of Selengensis stem

Position	Diameter	Bending test		
		Peak force/N	Deformation/mm	Break work/N·mm
B_1	A_1	$6.6^{a}\pm0.15$	$11.17^{a}\pm0.27$	45.96
	A_2	$34.8^{a}\pm0.33$	$5.86^{b}\pm0.19$	106.23
B_2	A_1	$8.4^{a}\pm0.17$	$8.98^{a}\pm0.18$	57.93
	A_2	$46.07^{b}\pm0.41$	$4.14^{b}\pm0.16$	130.13
B_3	A_1	$9.1^{a}\pm0.28$	$5.93^{a}\pm0.13$	65.54
	A_2	$60.37^{b}\pm0.57$	$3.7^{b}\pm0.08$	153.68

Note: The force and deformation values are AVG ± standard deviation. In each row different superscript letters indicate significant differences (p<0.05). Each point is the average of three replicates.

The *Artemisia selengensis* are generally bundled to many plants during storage transportation; therefore, we researched the bending mechanical parameters for multiple stems. The bending force of the stems diameter A_2 at different positions (B_3, B_2, and B_1) for 7 plants were measured, strapped along the circumferential. The three-point bending load test was adopted; each test was repeated 5 times, and the average value was obtained and compared with the theoretical value. The test results are shown in Table 4; the theoretical value in the table is the breaking force of the individual test multiplied by the amounts.

According to the data and the results of the analysis in Table 4, it can be observed that the stalks' composite bending strength increased with increasing number; however, the increase was not proportional to the individual breaking strength, and the difference between the theoretical value and experimental value increased with increasing number of stems. A fluctuation in the broken force was also observed in the bending experiments, and showed many peaks. This was attributed to the fact that the stem bending stress was not distributed equally; the stress applied was not uniform.

Table 4 Results of test on bending force of breaking Selengensis stems

Position	Bending test-Break force/N													
	1		2		3		4		5		6		7	
	E	T	E	T	E	T	E	T	E	T	E	T	E	T
B_1	34.8	34.8	45.8	69.6	106.1	104.4	129.5	139.2	138.7	174	155.0	208.8	190.4	243.6
B_2	45	45	63.2	90	136.8	135	159.4	180	185.1	225	218.4	270	250.2	315
B_3	54	54	80.8	108	158.8	162	192.8	216	234.5	270	265.2	324	283.6	378

Note: The T means theoretical value and the E means experimental value.

The regression fittings between the bending force and stem numbers were acquired based on the number of stalks' bending mechanical parameters. The fitting equations and the determined coefficients are shown in Figure 8 (p<0.01). The results showed that there was a strong positive linear relationship between the bending force and stem numbers; however, it was not a straight line.

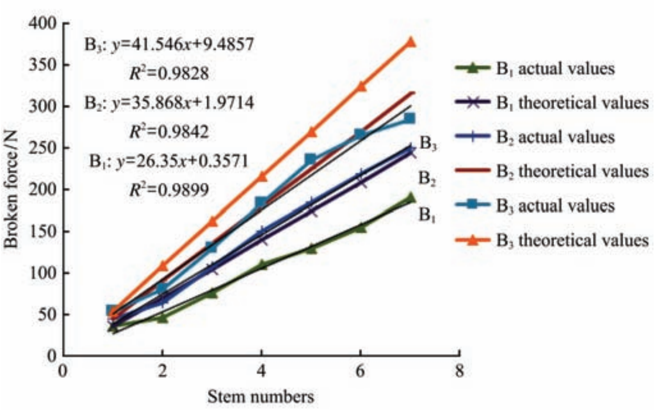


Figure 8 Relationship between amounts and bending breaking force

4 Discussion

Mechanical property of crop material is one of the most important bases to decrease the mechanical damage, explore the latest controlling method, improve processing quality and design agricultural mechanical equipment. As external force is usually under natural conditions, it is valuable to study mechanical properties under natural conditions. Phytomechanics is a branch of materials science, which deals with tensile compression and shear. Parameters such as breaking strength under tensile, could reduce the loss during harvest, transportation and processing, decide type of load and calculate it and provide basis and reference for designing, improving the precise and efficiency of modern agricultural mechanized equipment.

In this research, the mechanical properties and change rules of the *Artemisia selengensis* stem were analyzed. And according to the previous works on agricultural materials mechanical properties, in the future, the study emphasis will be moved from macro performance to microcosmic performance, especially with the advent of nano mechanical testing technology, which will be increasingly popular. Therefore, such as applying advanced finite element method to simulate the mechanical properties of grain stem under the condition of different load or shear change course could be carried out to help study the relationship among physical properties, chemical properties and mechanical properties, providing important reference for micro mechanics characteristics research of grain stem.

5 Conclusions

This research tested different mechanics properties of *Artemisia selengensis* under different test conditions and the change rule and analyzed the significance of each factor by using the TMS-Pro texture analyzer, which would provide reference and basis for designing and reduce research cost and period. Hence, the following conclusions can be made:

1) *Artemisia selengensis* stem has anisotropic characteristics for compressive capacity. The crushed forces of the stem with diameter A_1 and A_2 in position B_3 to B_1 were 59.77 N, 51.38 N, 39.05 N, 372.6 N, 276.97 N and 183.8 N respectively. The maximum compression energy of the stems was 335.34 mJ, minimum value was 113.26 mJ, variation coefficients were 15.85% and 3.84%, and there was quadratic polynomial function relationship between the axial compressive strength and compression strain energy.

2) The radial shearing force was much greater than the axial shearing force of the stem. The shearing mechanical performance of the stems in the root, the mean radial, axial shear force, and shear strength were 175.9 N, 17.7 N, 14 MPa, and 0.44 MPa, respectively, and it increased with the raise of diameter. When the areas of the stems were within 7.07-63.62 mm^2, there was a linear function positive correlation between the peak shear force and the section areas, and an exponential function positive correlation between the shear work and the sample's section areas. In addition, when the position was 10-400 mm, a linear positive correlation relationship existed between the peak shear force and the stem positions, and also between the shear work and the stem positions.

3) There was a nonlinear relationship between the bending load of the compressed stem and the deformation. The bending mechanical performance parameters were the maximum when the stem diameter was A_2 in B_3 period, and the mean of the peak force, the bending work, and the deformation were 60.37 N, 153.68 N·mm, and 3.7 mm respectively. The comprehensive bending breaking force of the stems increased linearly with the number stems but it was not a straight line and the difference between the theoretical value and experimental value was increased.

This can be used to achieve more efficient and low consumption of harvesting approach for *Artemisia selengensis*, as well as for optimizing the researched and developed harvester machine products according to the mechanical parameters of the stalks and the requirement of agronomy.

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