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MECHANICAL PROPERTIES OF WATERCRESS STALKS AT DIFFERENT POSITIONS

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KEYWORDS

mechanical properties, physical properties, watercress stalks.

ABSTRACT

Mechanised watercress harvesting involves clamping and cutting its stalks, which can result in their incomplete breaking and crushing. The harvest quality is directly affected by the force used to clamp and cut the watercress stalks. Therefore, studying the physical and mechanical properties of the stalks is important to accurately calculate the force that needs to be applied. Herein, the microstructure of watercress stalk sections with and without nodes was observed using scanning electron microscopy. Moreover, the basic physical properties, such as the total length, internode outer diameter, internode inner diameter and water content, of watercress stalks were measured. Additionally, the mechanical properties of watercress stalks at different positions were measured using four modes: tension, compression, shear and bending. Results revealed that watercress stalks with nodes exhibited a more pronounced medullary cavity and a greater number of internal vascular bundles. The lower section of the watercress stalks was considerably more resistant to mechanical stress than the rest of the stalk. Further, in terms of resisting load, the stalks with nodes were stronger than those without nodes. This study provides useful information for efficient watercress harvesting.

INTRODUCTION

Watercress, a member of the Umbelliferae family, is a well-recognised healthy vegetable that is popular among consumers, and its extracts exhibit cardiovascular- and liver-protecting effects (Liu et al., 2010; Nian et al., 2008). Additionally, watercress is susceptible to few pests and diseases, is highly adaptable and productive and is grown in an area of ~17,000 hm^2 per year in China. The expanding area of watercress cultivation signifies a potential market for watercress harvesting. However, presently, watercress harvesting in China primarily relies on manual labour and has low economic benefits, thus restricting the development of the watercress industry (Wang, 2019; Chen, 2017). To improve watercress harvesting efficiency and reduce its production cost, the mechanisation of watercress harvesting should be urgently promoted. The mechanical and biomechanical properties of watercress stalks are important influencing factors for the mechanised harvesting of watercress, and studying the mechanical properties of crop stalks can help reduce research and development costs, shorten research and development cycles and aid in the development of reasonable harvesting methods to save costs and reduce energy consumption (Jia et al., 2022; Wan et al., 2022; Li et al., 2019). Therefore, to calculate the clamping and cutting forces during the mechanised harvesting of watercress, experimental studies regarding the physical and biomechanical properties of watercress stalks are necessary.

The mechanised device used for harvesting watercress stalks comprises a clamping stem support part and a cutting part. Ensuring that the clamping force is not too large is important as this can squeeze and bend the stalks, resulting in deformation. Similarly, a small cutting force may not completely cut the stems. Therefore, the mechanical properties of watercress stalks play a crucial role in this process. Presently, research on watercress remains limited to appearance and nutritional value and there is a lack of research regarding the physical and biomechanical properties of watercress stalks. This study refers to the research methods of wheat, onion and radish crops to determine the biomechanical properties of watercress stalks

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using Handpi tensile pressure testers (Feng et al., 2022; Fang et al., 2014; Sun et al., 2022). The aim is to measure the different mechanical properties of watercress stalks under different mechanical treatments to provide a theoretical basis for reducing damage to watercress during harvesting and designing efficient watercress harvesting equipment.

MATERIAL AND METHODS

Nantong small-leaf watercress was obtained from the Jiangsu province for this study. The specimens were selected from watercress with a growth cycle of 50 days, free of pests and diseases and without visible damage. The watercress was removed from the test field along with roots every morning and immediately followed by experiments to determine its mechanical properties to ensure experiment completion within 24 h. After 24 h, resampling was conducted for further experiments (Ali et al., 2022). The upper, middle and lower portions with and without nodes of each stalk were selected as study samples. The length of the sampled stalks was not controlled during sampling to ensure the sufficient representativeness of the specimens and reduce systematic errors arising from human selection.

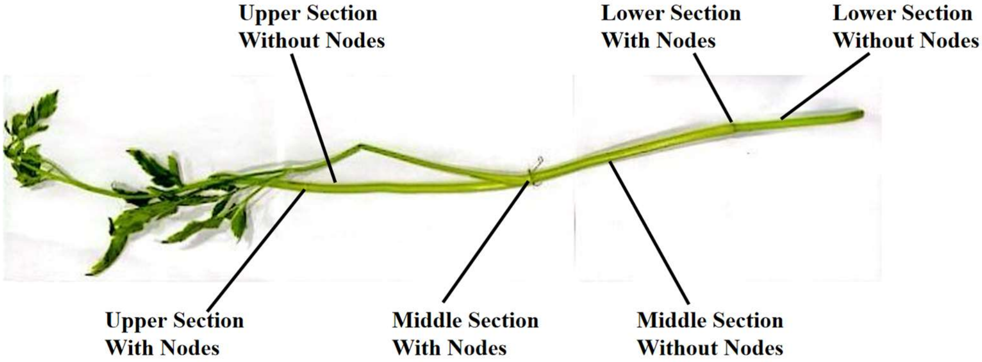


FIGURE 1. Names of structures and parts of Nantong small-leaf watercress.

Sample preparation

The mechanised harvesting of watercress stalks requires clamping the stalks before cutting them to ensure efficient harvesting. For clamping, any part of the stalk may be gripped. Herein, the watercress stalks were divided into upper, middle and lower portions for analysis. Each specimen was selected from the three different portions of the watercress stalks with and without nodes, and the six specimen groups were tested individually. The watercress specimens were cut to a length of ~50 mm, and a layer of medical tape was wrapped around the ends of the specimens to prevent slippage and protect the clamping area. Additionally, the tensile load and displacement and the compressive, shear and bending loads were tested. All tests were conducted in a laboratory for agricultural machinery equipment at a temperature of 22°C.

Scanning electron microscope

First, the watercress stalk samples were naturally dried. Then, gold powder was sprayed onto the sample surface. The microstructure of the watercress stalks with and without nodes was observed in cross and longitudinal sections, respectively, using a scanning electron microscope.

Handpi tensile pressure tester

The Handpi tensile pressure tester can apply different sizes of force to the sample as well as the test speed, which must be calibrated before each test.

Tensile mechanical properties

Tensile mechanical properties are an important biomechanical property of watercress stalks (Gomes et al., 2021; Fan et al., 2023). In the tensile mechanical properties test, a constant tensile speed of 10 mm/min was applied to the three portions of the watercress with and without nodes, and the tensile force was measured as a function of time. To reduce the random error of the experiment, the test was repeated five times at the same level. The test procedure is shown in Figure 2.

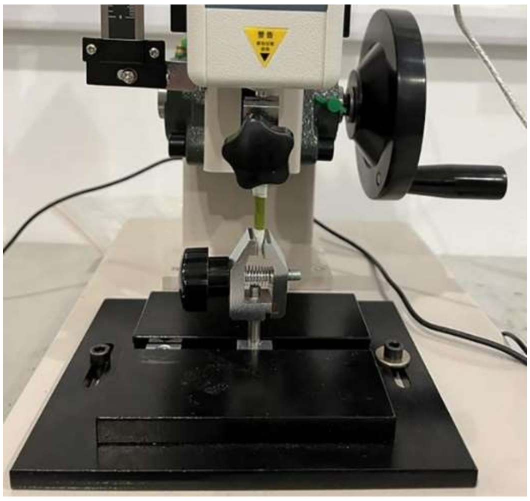


FIGURE 2. Watercress tensile test process.

Compression mechanical properties

In the compression mechanical properties tests (Dong et al., 2019), the compression speed was 10 mm/min, compression depth was 2 mm and the compression load of the watercress stalks was evaluated using the upper and lower parallel compression jigs (Peng et al., 2017; Pham & Liou, 2017). Further, each experiment was repeated five times. The process of the watercress compression test is shown in Figure 3. On the left is the process of the radial compression test of the watercress stalk, and on the right is the process of the axial compression test of the watercress stalk.

FIGURE 3. Watercress compression test process.

Shear mechanical properties

Three different portions of non-nodal and nodal watercress specimens were selected and six groups of specimens were tested individually. The shear speed was 10 mm/min and the test was repeated five times at the same level. The watercress shearing test process is shown in Figure 4.

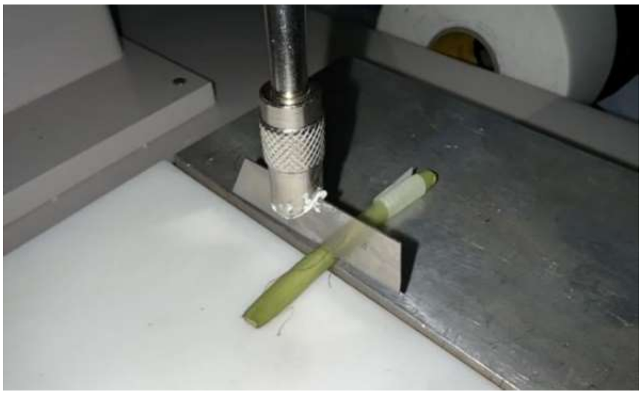


FIGURE 4. Watercress shearing test process.

Bending mechanical properties

The bending test was performed using the three-point bending method (Ma et al., 2022; Yang et al., 2020), and the test was set at a scale of 60 mm. The watercress stalks were placed horizontally on the two pivot points of the lower bending support to ensure that the upper pivot indenter of the test machine acted on the midpoint of the watercress stalks. To reduce the random error of the experiment, the test was repeated five times at the same level. The watercress bending test process is shown in Figure 5.

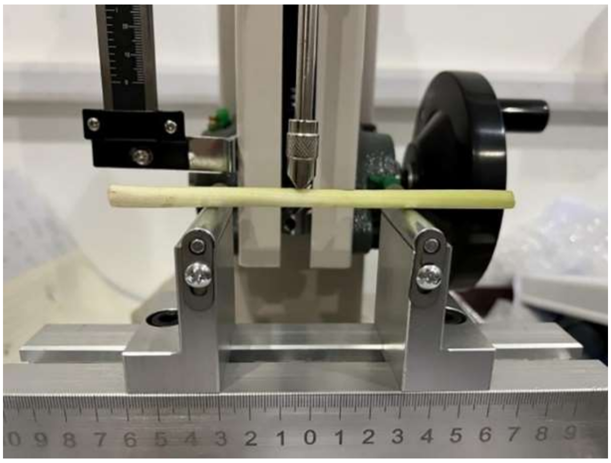


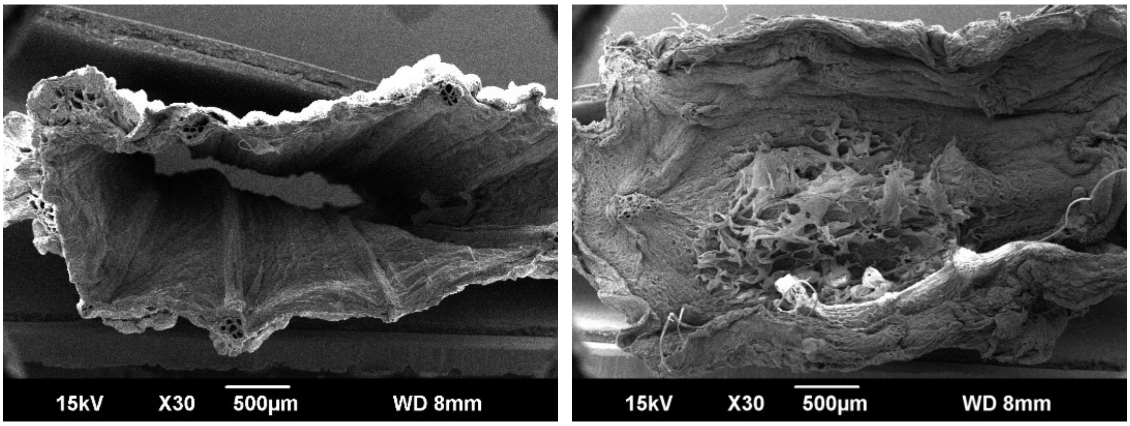
FIGURE 5. Watercress bending test process

Data analysis

The raw test data obtained from the tensile, compression, shear and bending mechanical property tests were analysed using the data analysis software that came with the Handpi tensile pressure tester. The data were tabulated and analysed graphically. Values were shown as mean ± standard deviation.

RESULTS AND DISCUSSIONS

Microstructure of watercress stalks



(a) Transverse Section Without Node (b) Transverse Section With Node

FIGURE 6. Microstructure of the watercress stalks.

Figure 6 shows the scanning electron microscopy patterns of the cross sections of the watercress stalks. The outermost layer of the watercress culm comprises thick-walled mechanical tissues with vascular bundles, while the middle contains thin-walled tissues and the medullary cavity. Figure 6(a) shows the thick-walled tissues all around with a hollow structure, and Figure 6(b) shows the vascular bundles and thick-walled tissues with the medullary cavity in the middle. The greater the proportion of the thick-walled tissues and the number of vascular bundles in the stalk, the stronger its ability to resist external loads. Therefore, stalks with nodes exhibit greater biomechanical strength than stalks without nodes.

Basic physical properties and moisture content of stalks

From the watercress test plots, 50 watercress plants were randomly selected, and the basic biological physical properties, such as the total length of the watercress stalks; intersegmental outer diameters at the upper, middle and lower portions; intersegmental inner diameters and length of the stem nodes and moisture contents, were measured (Ren et al., 2014; Nadian & Abbaspour-Fard, 2016). Owing to the need to leave stubble during harvest, a portion of the stem 3 cm above the root was selected for measuring the parameters of the lower portions. The measuring tools were as follows: tape measure and vernier caliper. The parameters obtained for each species are shown in Table 1.

TABLE 1. Basic physical properties of the watercress stalks of different varieties.

Total length (cm)	Sampling site	Intersegmental outer diameter (mm)	Intersegmental inner diameter (mm)	Stem node diameter (mm)	Moisture content (%)
	Upper section	3.50 ± 0.48	2.61 ± 0.02	4.98 ± 0.34	
83.03 ± 3.39	Middle section	7.29 ± 0.66	4.91 ± 0.42	8.50 ± 0.59	95.08 ± 1.14
	Lower section	7.83 ± 0.88	4.55 ± 0.51	9.61 ± 0.76	

Tensile mechanical properties

Figure 7 showed that the tensile load of the watercress could be considered a function of time. The load increased with increasing displacement, and when the maximum tensile load was reached, it continued to stretch, consequently breaking. Additionally, the tensile load sharply decreased until it became zero.

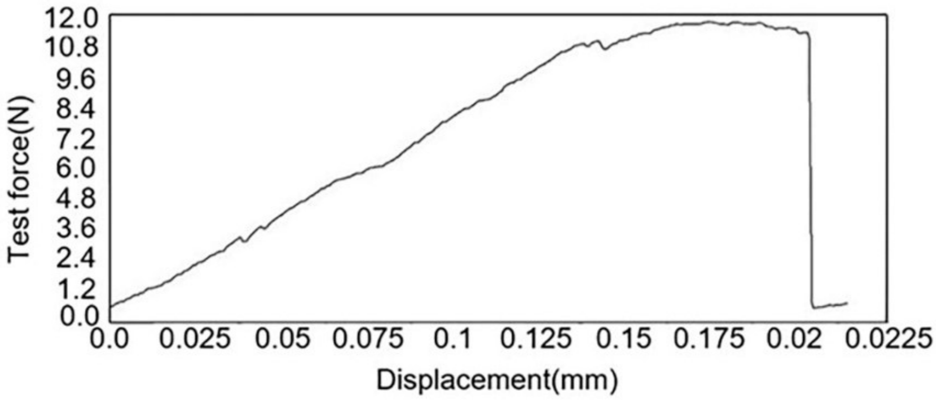


FIGURE 7. Tensile load profile of watercress stalks

The tensile properties of watercress stalks were calculated by reviewing the relevant literature (Zhao et al., 2020). The results of tensile strength of watercress stalks were shown in Table 2.

TABLE 2. Results of the tensile test of the watercress stalks.

Watercress stalks	Upper section		Middle section		Lower section	
	With node	Without node	With node	Without node	With node	Without node
Cross-sectional area (mm^2)	8.71 ± 1.83	7.85 ± 1.53	57.00 ± 2.11	31.34 ± 2.36	60.64 ± 2.09	32.94 ± 2.63
Critical tension (N)	8.62 ± 1.37	6.99 ± 0.65	87.36 ± 2.40	45.87 ± 2.82	102.62 ± 1.31	46.75 ± 1.01
Tensile strength (MPa)	1.02 ± 0.21	0.91 ± 0.12	1.55 ± 0.17	1.49 ± 0.18	1.71 ± 0.07	1.52 ± 0.09

The curves of the tensile process were obtained, and the results of the tensile tests on watercress were evaluated to obtain a model between the test factors such as sampling site and stalk diameter and the tensile strength of the watercress stalks. Further, the relation between the tensile properties and test factors is presented in Figure 8 below.

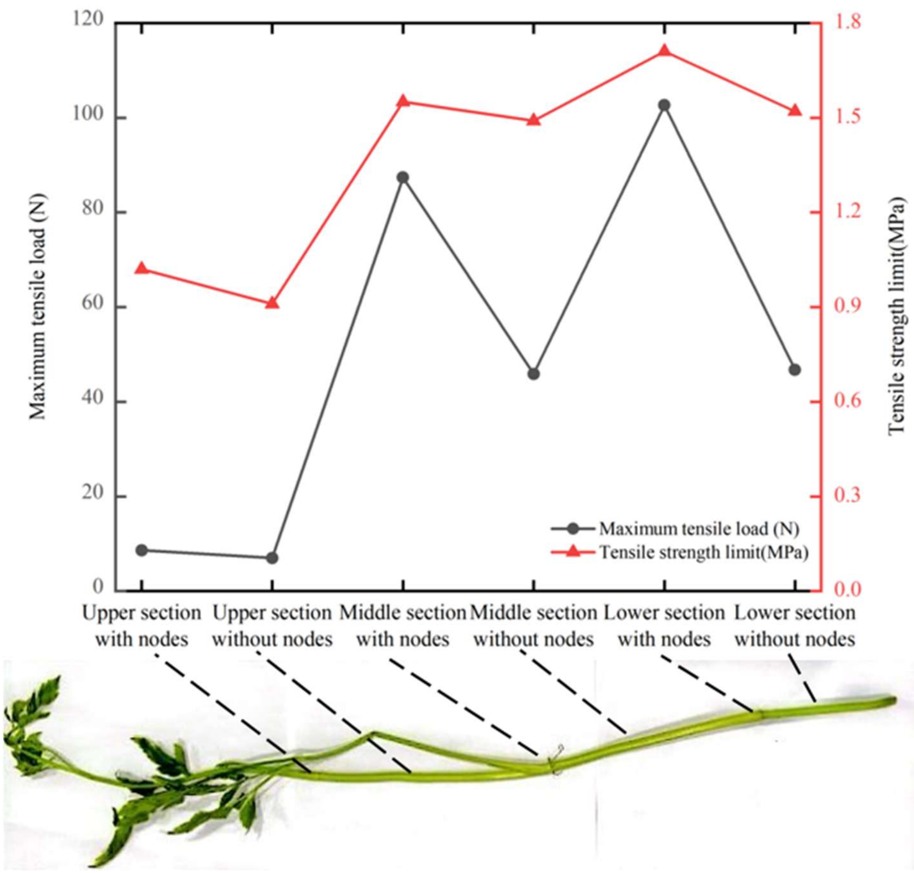


FIGURE 8. Curves of maximum tensile load and strength of the watercress stalks as a function of the sampling portion.

Figure 8 shows that the maximum tensile load of the watercress stalk was 102.62 ± 1.31N and the maximum tensile stress was 1.71 ± 0.07 MPa and that they all occurred at the lower portions of the stalk with nodes. Compared with the middle and upper portions of the stalk, the lower portion of the stalk was more resistant to tensile deformation. The tensile capacity of the stalk with nodes was stronger than that of the stalk without nodes. From a microscopic perspective, this occurs because the watercress stalks with nodes are more tightly organised than those without nodes. The dense vascular bundles inside the stalks with nodes are intrinsic to their greater resistance to tensile forces.

Compression mechanical properties

Radial compression mechanical properties

Figure 9 shows that at the beginning of the test, the press was in contact with the specimen and that the displacement gradually increased; however, the load was almost constant owing to the hollow inside of the stalk. Additionally, as the displacement continued to increase, the load gradually increased. When increasing to the maximum load, the watercress stalk ruptured and the experiment ended.

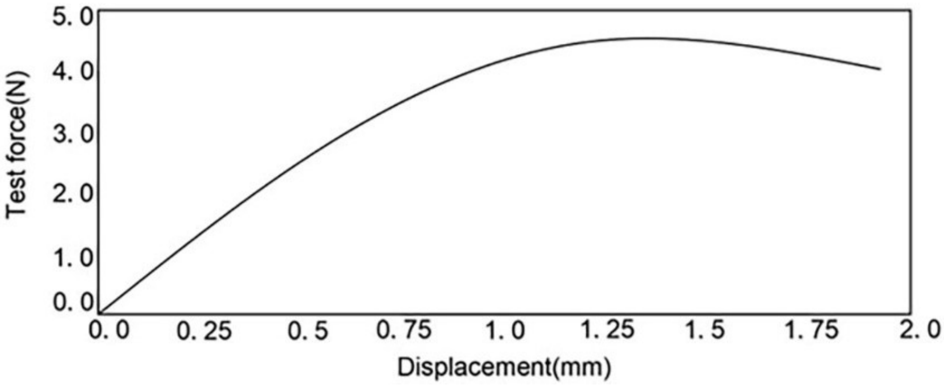


FIGURE 9. Radial compression load curve.

The radial compression process of the watercress stalks was approximated as a contact problem between a flexible cylinder and two rigid planes. The compression contact surface was a rectangle of length l_{jx} and width $2a$. According to the physical geometry shown in Figure 10, the width $2a$ was calculated using the following formula:

$$\boldsymbol{2a = 2\sqrt{\left(\frac{R}{2}\right)^2 - \left(\frac{R-\Delta D}{2}\right)^2} = \sqrt{2R\Delta D - \Delta D^2}} \tag{1}$$

Where:

$\boldsymbol{2a}$ = compressed contact surface width (mm);

$\boldsymbol{R}$ = diameter of the flat-topped cylindrical press (mm),

$\Delta\boldsymbol{D}$ = deformation of watercress along the load direction (mm).

The area of the radially compressed contact surface of the watercress stalks was calculated using the following equation:

$$\boldsymbol{S_{jx} = 2a \cdot l_{jx}} \tag{2}$$

Where:

$\boldsymbol{S_{jx}}$ = radial compression contact area of the watercress stalks (mm^2);

$\boldsymbol{2a}$ = compressed contact surface width (mm),

$\boldsymbol{l_{jx}}$ = compressed contact surface length (mm).

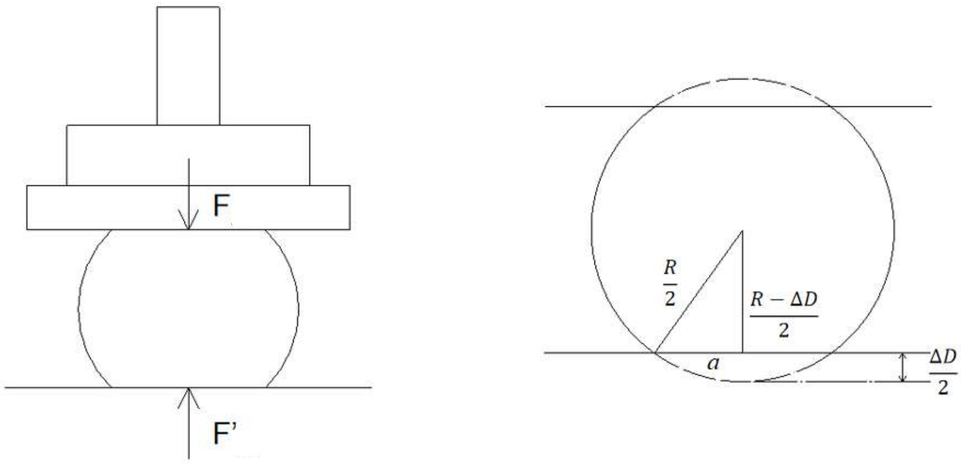


FIGURE 10. Experimental diagram of radial compression of the watercress stalks.

The radial compression properties of the watercress stalks were calculated by reviewing the relevant literature (Zhao et al., 2020). Results of the radial compressive strength of the watercress stalks were shown in Table 3.

TABLE 3. Results of the radial compression test of the watercress stalks.

Watercress stalks	Upper section		Middle section		Lower section	
	With node	Without node	With node	Without node	With node	Without node
Maximum radial compression load (N)	7.74 ± 0.42	6.11 ± 0.57	11.09 ± 0.48	6.50 ± 0.53	12.00 ± 0.37	6.93 ± 0.52
Radial compressive strength (kPa)	100.21 ± 20.01	80.14 ± 30.12	120.23 ± 40.12	80.26 ± 20.04	130.44 ± 10.16	90.15 ± 10.28
Radial compressive modulus of elasticity (kPa)	250.44 ± 30.56	180.48 ± 30.56	390.23 ± 41.59	221.26 ± 30.59	434.15 ± 24.26	283.18 ± 22.16

Results of the compression tests performed on the watercress stalks were processed. A model between the test factors such as sampling site and stalk diameter and the elastic modulus of the watercress stalk was obtained. Their relation is shown in Figure 11 below.

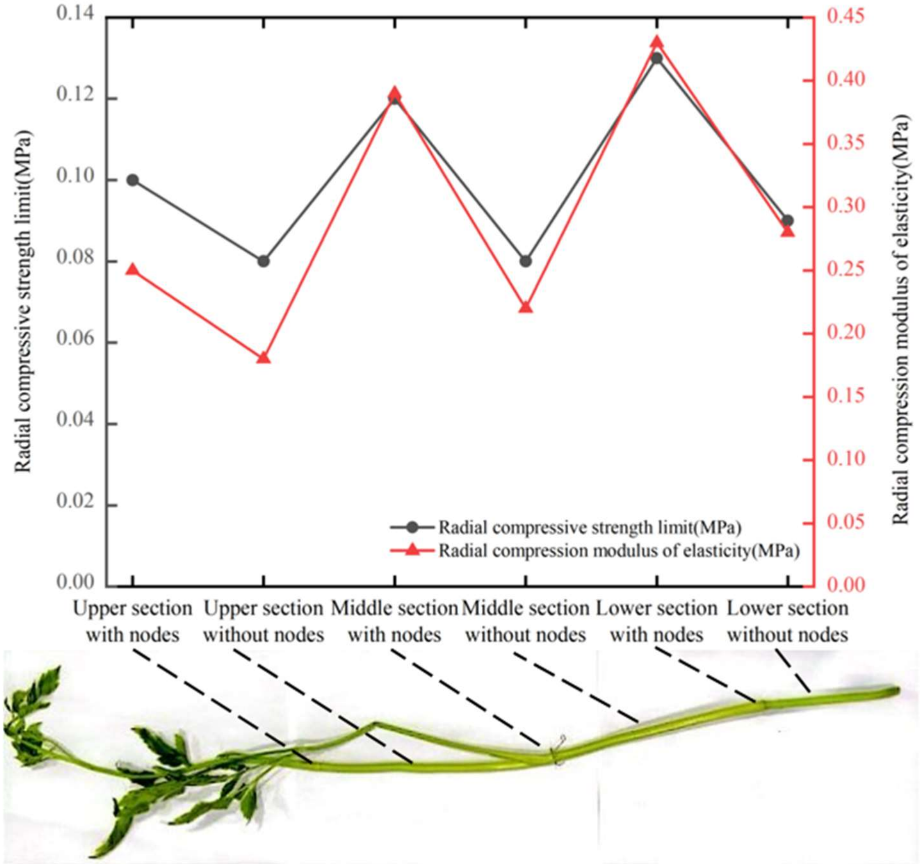


FIGURE 11. Curves of radial compressive strength and modulus of the elasticity of the watercress stalks as a function of the sampling portion.

Figure 11 shows that the maximum radial compressive strength of the watercress stalk was 130.44 ± 10.16 kPa and the maximum radial compressive modulus of elasticity was 434.15 ± 24.26 kPa. Further, they all occurred at the lower portions of the watercress stalk with nodes. The lower portions of the watercress stalk resisted radial compression deformation better than the middle and upper portions. The radial tensile capacity of the watercress stalks with nodes was stronger than that of the watercress stalks without nodes. Microscopically, the vascular bundles and thick-walled tissues inside the watercress stems were mainly concentrated at the nodes. The thick-walled tissues of the stems play an important supporting role. Additionally, the proportion of thick-walled tissues increases at lower portions. Therefore, the lower nodes of the watercress stalks are more resistant to loads.

Axial compression mechanical properties

The axial compression load curve is presented in Figure 12. At the beginning of the test, the press was in contact with the specimen. The load increased with increasing displacement and increased to a certain extreme value when the specimen was suddenly damaged. The damaged watercress stalk can still accept a certain load owing to the axial distribution of lignocellulose, which demonstrated a certain ability to resist external forces.

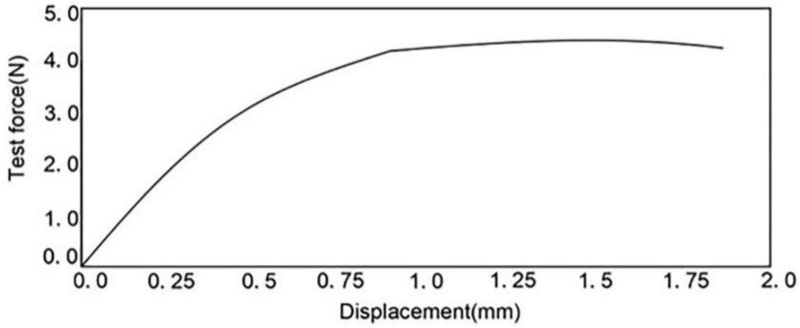


FIGURE 12. Axial compression load curve.

The axial compression properties of the watercress stalks were calculated by reviewing the relevant literature (Zhao et al., 2020). The results of the axial compressive strength of the watercress stalks were shown in Table 4.

TABLE 4. Results of the axial compression test of the watercress stalks.

Watercress stalks	Upper section		Middle section		Lower section	
	With node	Without node	With node	Without node	With node	Without node
Axial compressive maximum load (N)	3.84 ± 0.86	1.77 ± 0.72	11.89 ± 0.98	9.53 ± 0.88	18.91 ± 0.51	12.61 ± 0.58
Axial compressive strength (kPa)	292.56 ± 70.88	234.22 ± 31.25	312.26 ± 44.45	282.26 ± 21.57	390.14 ± 21.11	351.22 ± 22.15
Axial compressive modulus of elasticity (kPa)	731.25 ± 111.12	572.56 ± 94.23	771.48 ± 190.22	701.15 ± 102.16	980.22 ± 81.55	864.66 ± 75.14

Results of the compression tests performed on the watercress stalks were processed. A model between the test factors such as sampling site and stalk diameter and the elastic modulus of the watercress stalks was obtained, and the relation between the elastic modulus and the factors were shown in Figure 13 below.

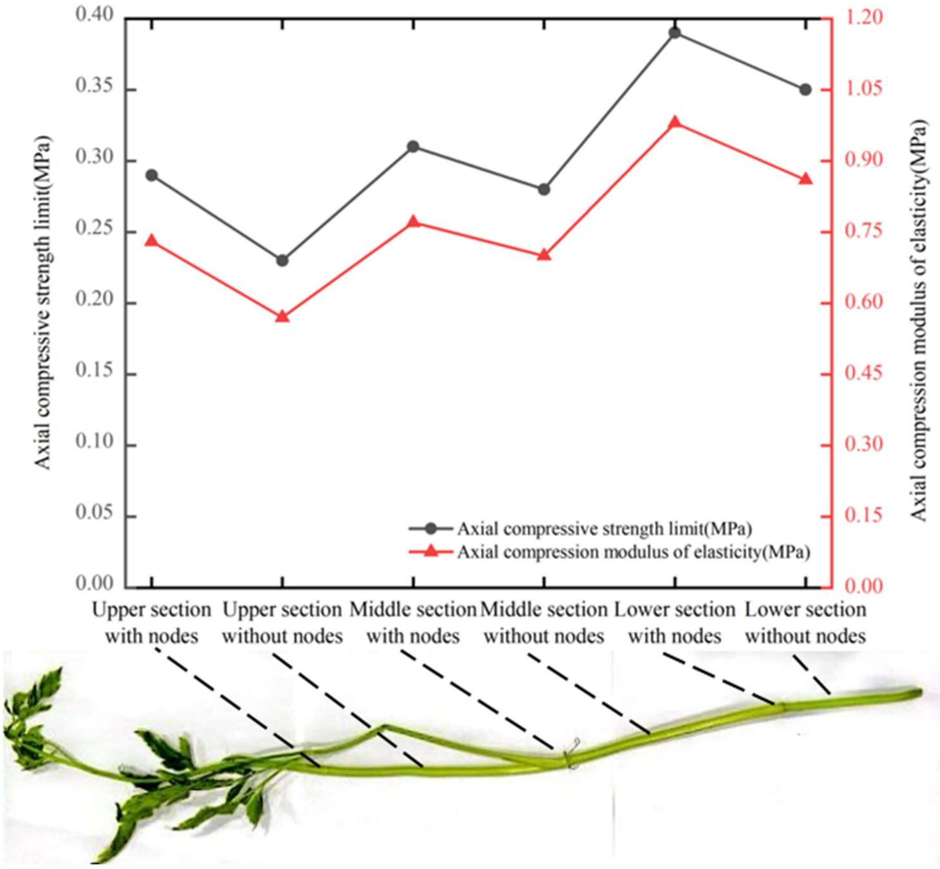


FIGURE 13. Curves of the axial compressive strength and modulus of the elasticity of the watercress stalks as a function of the sampling portion.

Figure 13 showed that the maximum axial compressive strength of the watercress stalk was 390.14 ± 21.11 kPa and the maximum axial compressive modulus of elasticity was 980.22 ± 81.55 kPa. Further, they all occurred at the lower portions of the watercress stalk with nodes. The lower portions of the stalk resisted axial compression deformation better than the middle and upper portions. Additionally, the axial tensile capacity of the stalks with nodes was stronger than that of the stalks without nodes.

The above results showed that the axial compression strength of the watercress stalks was greater than radial compression strength because of the difference in the proportion of the lignocellulose and medullary tissue (Feng et al., 2012). In addition, the axial stiffness is greater than the radial stiffness in watercress stalks.

Shear mechanical properties

The shear load curve is shown in Figure 14. At first, the force on the upper position of the watercress stalks increased with increasing displacement increased. Subsequently, the displacement continued to increase until the curve reached the first peak and then fell rapidly, which indicates that the upper portion of the stalk was damaged via shear force. Next, as the displacement continued to increase, the lower portion of the stalk began to be stressed. At this time, the curve began to rise twice until it reached the second peak and then fell again, indicating that the stalk was destroyed. The damaged stalks lost their compressive capacity instantaneously. The first peak force was considered the maximum shear force in the calculation (Wang et al., 2022; Dong et al., 2017).

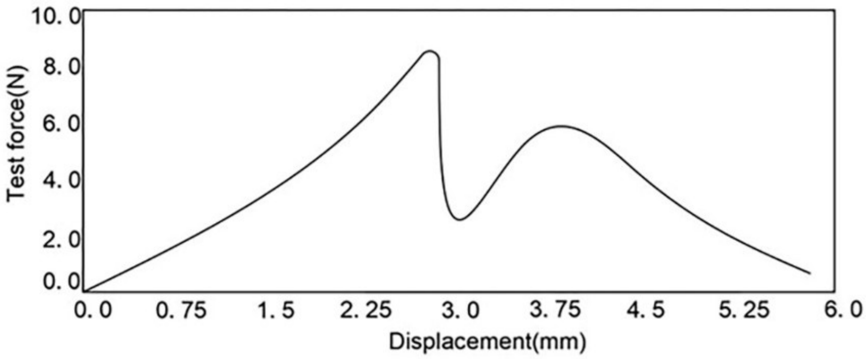


FIGURE 14. Shear load curve of watercress stem.

The shear properties of the watercress stalks were calculated by reviewing relevant literature (Zhao et al., 2020). Results of the shear strength of the watercress stalks are shown in Table 5.

TABLE 5. Results of the shear test of the watercress stalks.

Watercress stalks	Upper section		Middle section		Lower section	
	With node	Without node	With node	Without node	With node	Without node
Cross-sectional area (mm^2)	11.45 ± 1.67	9.42 ± 1.90	20.15 ± 1.41	31.00 ± 1.50	26.28 ± 1.52	33.53 ± 1.22
Maximum shear load (N)	3.35 ± 0.54	3.06 ± 0.51	10.55 ± 0.51	9.86 ± 0.81	12.61 ± 0.38	12.26 ± 0.43
Shear strength (kPa)	452.59 ± 54.54	354.41 ± 121.13	480.02 ± 90.03	331.33 ± 141.14	491.11 ± 61.19	401.29 ± 32.22

Results of the shear tests performed on the watercress stalks were processed. The relation between the test factors such as sampling site, shear load and shear strength of the watercress stalk were obtained, as shown in Figure 15.

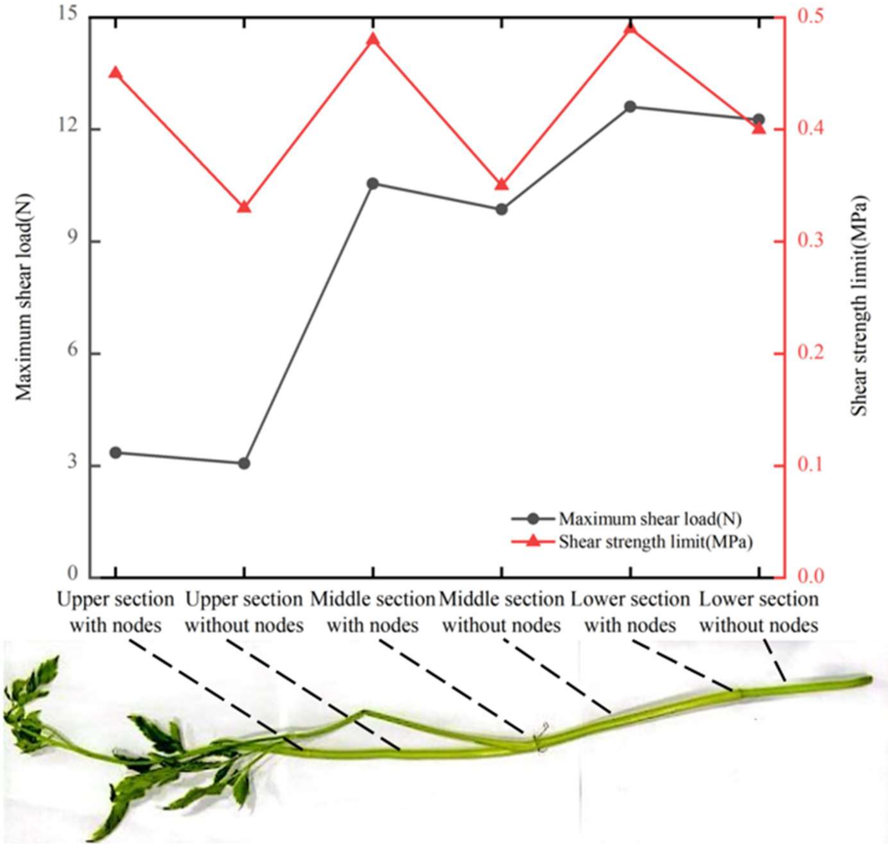


FIGURE 15. Curves of the shear load and modulus of the watercress stalks as a function of sampling location.

Figure 15 shows that the maximum tensile load of the watercress stalk was 12.61 ± 0.38 N and the maximum shear strength was 491.11 ± 61.19 kPa, both of which were observed at the lower portions of the stalks with nodes. The lower potions of the stalk was more resistant to shear deformation than the middle and upper portions. Additionally, shear resistance was stronger at the node than at the non-node of the stalks. The root component of the stalks was denser, allowing it to withstand more shear load when it was closer to the root. Moreover, stalks without nodes exhibited only a small portion of the thick-walled tissues, while those with nodes not only exhibited more thick-walled tissues but were also dotted with vascular bundles to resist mechanical forces.

Bending mechanical properties

The bending properties of the watercress stalks were calculated by reviewing relevant literature (Zhao et al., 2020). Results of the flexural strength of the watercress stalks are shown in Table 6.

TABLE 6. Results of the bending test of the watercress stalks.

Watercress stalks	Upper section		Middle section		Lower section	
	With node	Without node	With node	Without node	With node	Without node
Bending deflection (mm)	7.887 ± 0.72	7.307 ± 0.69	10.982 ± 0.59	9.820 ± 0.60	12.098 ± 0.45	11.873 ± 0.54
Ultimate load (N)	0.720 ± 0.33	0.680 ± 0.38	1.532 ± 0.29	1.380 ± 0.34	2.288 ± 0.22	2.197 ± 0.19
Flexural strength (KPa)	176.09 ± 42.22	151.36 ± 43.34	265.05 ± 60.01	229.04 ± 60.05	334.21 ± 21.47	302.11 ± 31.33
Modulus of elasticity (KPa)	33.33 ± 13.41	31.02 ± 14.51	39.39 ± 13.15	32.19 ± 12.12	48.32 ± 11.33	44.41 ± 12.09

Results of the bending tests performed on the watercress stalks were processed (Xin et al., 2016). The relation obtained between the test factors such as the sampling site and bending strength of the watercress stalks are shown in Figure 16.

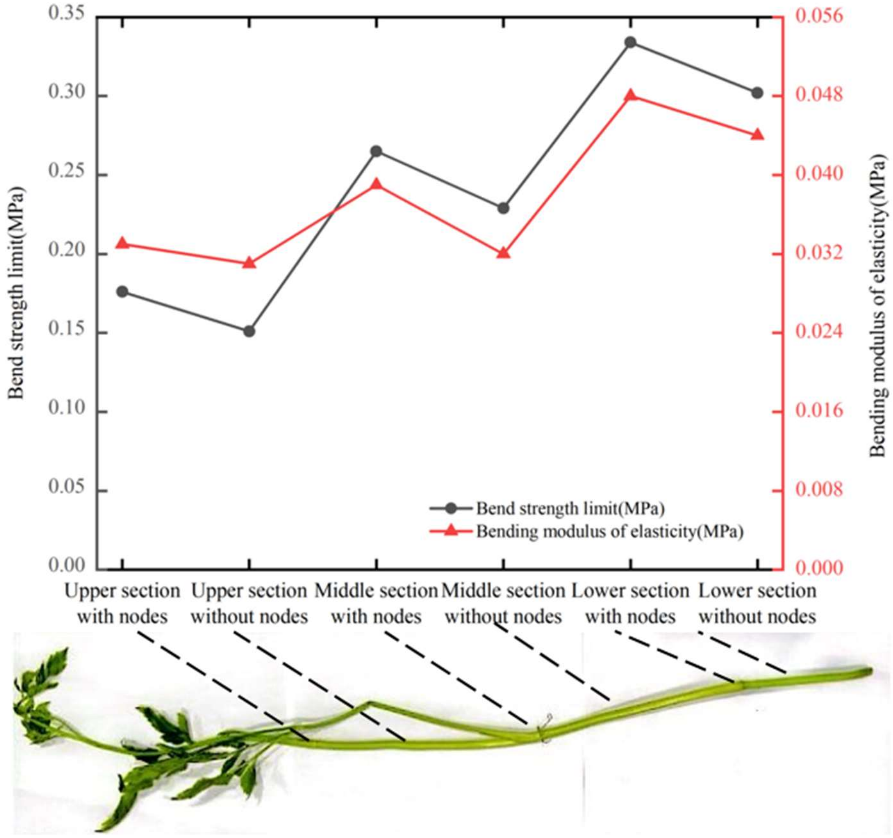


FIGURE 16. Curves of the flexural strength and modulus of the watercress stalks as a function of sampling location.

Figure 16 shows that the modulus of elasticity was 48.32 ± 11.33 kPa, and the flexural strength was 334.21 ± 21.47 kPa. Additionally, they all occurred at the lower portions of the watercress stalks with nodes. The bending resistance of the watercress stalks decreased with increasing sampling portion, and the bending resistance of the watercress stalks with nodes was stronger than that of the stalks without nodes. At the microscopic level, the ability of the stalks to resist external loads increases with the increasing proportion of thick-walled tissue and vascular bundles. This intrinsic feature results in better resistance to deformation in the lower node of the stalks that contain more vascular bundles.

CONCLUSIONS

The physical and biomechanical properties of the watercress stalks under different portions were studied, including the determination of basic physical, tensile, compression, shear and bending properties. The microstructural reasons for changes in the watercress stalk resistance to loads were briefly discussed. The proportion of thick-walled tissues in the watercress stalks with nodes was greater than that in the watercress stalks without nodes. Additionally, the stalks with nodes demonstrated vascular bundles capable of resisting external loads, resulting in a considerably greater mechanical strength compared with stalks without nodes. The tensile mechanical property tests revealed that the tensile capacity of the watercress stalks decreases with the gradual increase in the sampling portion of the watercress stalks. Next, the tensile capacity of the watercress stalks with nodes was significantly greater than that without nodes. The maximum tensile stress of the watercress stalk was 1.71 ± 0.07 MPa. Further, the compressive mechanical property tests revealed that the compressive strength and elastic modulus of the stalks showed a decreasing trend along the stalk growth direction, and the compressive strength and elastic modulus of the stalks with nodes were greater than those of the stalks without nodes. The compressive strength of the stalk in the axial direction was greater than that in the radial direction. The maximum radial compression compressive strength of the watercress stalk was 130.44 ± 10.16 kPa, and the maximum radial compression modulus of elasticity was 434.15 ± 24.26 kPa. The maximum axial compression compressive strength of the watercress stalk was 390.14 ± 21.11 kPa, and the maximum axial compression modulus of elasticity was 980.22 ± 81.55 kPa. Next, the shear mechanical property tests showed that, the maximum shear force and shear strength of the lower portion of the stalk were higher than those of the middle and upper portions. Additionally, the shear force and shear strength at the nodes were higher than those at the non-nodes. The maximum shear strength of the watercress stalk was 491.11 ± 61.19 kPa. Then, the bending mechanical property test showed that the bending limit load of the stalk decreased with increasing sampling portion. The maximum bending strength of the watercress stalk was 334.21 ± 21.47 kPa, and the maximum bending modulus of elasticity was 48.32 ± 11.33 kPa. Therefore, the strength of resistance to deformation obtained is larger than that of this paper. The mechanical properties of rice stalks and the trends of the mechanical property curves obtained previously (Zhao et al., 2020) were similar to those reported in this study. However, the water content of rice stalks was considerably lesser than that of the watercress stalks owing to the different types of crop stalks. Thus, the comprehensive strength index of the lower portion of the celery stalk with nodes was higher and relatively less prone to deformation. This study provides a theoretical basis for reducing watercress harvesting damage and designing watercress harvesting equipment.

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