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Effects of Airflow Disturbance on the Content of Biochemical Components and Mechanical Properties of Cucumber Seedling Stems

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Abstract: In order to explore the changes in biochemical components and mechanical properties of cucumber seedlings with dwarfing characteristics under airflow disturbance treatment, 'Jinyou No. 1' cucumber seedlings were used as experimental materials and the split-plot design was used. The cucumber seedlings were treated with airflow disturbance with two airflow temperatures of 25 ± 5 °C and 35 ± 5 °C as the main factors and four airflow velocities of 1, 3, 6 and 9 m/s as the secondary factors. At the same time, cucumber seedlings without airflow disturbance were used as controls to study the effects of airflow temperature and velocity on the biochemical components and mechanical properties of cucumber seedling stems. The results showed that with the increase in airflow velocity, the content of the stems' biochemical components increased to varying degrees, and the bending load, shear load, elastic modulus, bending strength and shear strength of the seedling stems also increased. Under the same airflow velocity, the biochemical component content and the accepted load of seedlings under the 25 ± 5 °C airflow temperature treatment were larger than those under the 35 ± 5 °C airflow greenhouse treatment, but the elastic modulus, bending strength and shear strength of seedlings under the 25 ± 5 °C airflow temperature treatment were lesser than those under the 35 ± 5 °C airflow temperature treatment. Using the grey relational analysis method, the correlation degree between the biochemical components of the stem and the mechanical properties of the stem was different. The correlation degree between the biochemical components of the seedling stem and the mechanical properties under different airflow temperature treatments was significant. The correlation degree between the biochemical components of the seedling stem and the mechanical properties under different airflow velocity treatments was greater than 0.60, indicating that the biochemical components of the seedling stem under airflow velocity treatments had a greater influence on the mechanical properties. In summary, airflow disturbance significantly affected the biochemical components and mechanical properties of cucumber seedlings. The biochemical components and mechanical properties of seedlings were negatively correlated with airflow temperature and positively correlated with airflow velocity. With a decrease in airflow temperature and an increase in airflow velocity, the biochemical components and mechanical properties of seedlings increased.

Keywords: cucumber seedling stem; airflow disturbance; biochemical components; mechanical properties; grey relational analysis

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1. Introduction

In 1962, Shah (1962) studied the monsoon flora of Mumbai and the Salset Islands and found that the phenotypic characteristics of the same species were different in the strong and weak airflow regions [1]. The influence of airflow on plants has begun to enter the field of vision of domestic and foreign researchers. Studies have shown that airflow disturbance has the effect of inhibiting seedling growth, reducing plant height and improving seedling quality. Ma (2019) studied the effect of airflow disturbance on tomato seedlings [2]. The results showed that applying appropriate airflow disturbance in summer reduced plant height, increased stem diameter and seedling index. The study found that different airflow disturbance positions lead to uneven distribution of air flow in the greenhouse, affecting tomato growth rate, plant height, stem and leaf material accumulation [3]. Galedar et al. (2008) showed that the accumulation of fiber in the stem increased the bending stress [4]. Chen et al. (2021) found that the light environment changed the morphology of plant stems, and the bending properties, tissue structure strength and compressive strength of stems also changed with the mechanical properties test of the stems of Commelinaceae plants [5]. In the study of lodging resistance of oats, Nan (2021) pointed out that lignin and cellulose were beneficial to enhance the hardness of stems and had an important impact on stem quality [6]. Hussain et al. (2019) studied the effects of different environments on soybean, and the results showed that shading stress reduced the increase of lignin and cellulose, and the effect of lignin on stem strength was greater than that of cellulose [7]. Wang et al. (2022) measured the maximum shear force, shear strength and shear energy per unit area of tea stems with different aging degrees, and the results showed that the shear strength of tea stems increased with an increase in stem aging degree [8].

China is the country with the largest cucumber cultivation area in the world, with a cultivation area of 1.27 million hectares in 2022 [9]. The demand for seedlings in China is great; cucumber plug seedling is one of the cucumber seedling methods [10], which has the advantages of saving seeds and labor, improving cucumber seed germination rate and large-scale production. However, the aperture of the plug is small, the planting density of cucumber seedlings is large, the leaf area is large and they cover each other after they fully expand. If the adversity conditions of high temperature, high humidity and low light are encountered, the air circulation between the plants is poor and the seedlings appear overgrown [11]. At present, there are few studies on the effects of airflow disturbance on the biochemical components and mechanical properties of cucumber seedling stems at home and abroad. In this paper, the experimental analysis of cucumber seedlings after airflow disturbance was carried out to analyze the response strategy of cucumber seedlings to airflow disturbance. By analyzing the effects of different airflow velocities and airflow temperatures on the biochemical components and mechanical properties of cucumber seedlings, the physiological changes of cucumber seedlings after airflow disturbance were discussed, which provided a practical basis for airflow to inhibit the excessive growth of cucumber seedlings.

2. Materials and Methods

2.1. Experimental Materials

The experiment was conducted in the artificial climate chamber of Jiangsu University from June to July 2022. The cucumber seedlings of 'Jinyou No. 1' (Cucumber Research Institute of Tianjin Academy of Agricultural Sciences) were used as the experimental materials. The substrate was a combination of peat, perlite, vermiculite, humus and coconut bran at a ratio of 3:1:1:1:0.5 (v/v), respectively. After high temperature sterilization, it was loaded into 72-well seedling trays. The seedling trays were placed in a shadeless place in the center of the greenhouse. Cucumber seeds were germinated before sowing, soaked in 55 °C~60 °C water and continuously stirred until the water temperature dropped to about 30 °C. After 6 h of soaking, they were fished out and washed with distilled water 2~3 times before sowing. The environmental conditions in the seedling chamber were 35 °C/20 °C (day/night) and 12 h/12 h (light/dark). The average photosynthetic photon flux density (PPFD) was 1470 μmol m^{-2} s^{-1}. No obvious pest damage and straight stem were selected for experiment.

2.2. Experimental Design

After the two cotyledons of cucumber seedlings were flattened, the airflow disturbance device was used for treatment. The split-plot design was performed in this study. Two levels of airflow temperature (25 ± 5 °C and 35 ± 5 °C) and four levels of airflow velocity (1, 3, 6 and 9 m/s) were designed as the main and secondary factors, respectively. The cucumber seedlings without airflow disturbance were used as the controls (as depicted in Table 1). There were 8 airflow disturbances per day, each lasting for 5 min, with an interval of 10 min. The airflow disturbance time was at 10:00–11:00 in the morning and 15:00–16:00 in the afternoon, for a total of 28 days. Different airflow temperatures and airflow velocities were achieved by adjusting the disturbance device. A high-precision airflow velocity measuring instrument was placed in the parallel crop position in the seedling tray to monitor the airflow temperature and airflow velocity in real time (see Figure 1).

Table 1. Airflow disturbance test design.

Treatment	Number	Airflow Temperature (°C)	Airflow Velocity (m/s)
Airflow disturbance (cool)	TA1	25 ± 5	1
	TA2		3
	TA3		6
	TA4		9
Airflow disturbance (hot)	TB1	35 ± 5	1
	TB2		3
	TB3		6
	TB4		9
Control (no airflow disturbance)	CK	Room temperature	0

Figure 1. Cucumber seedling airflow disturbance diagram.

2.3. Experimental Method

2.3.1. Determination of Biochemical Components in Cucumber Seedling Stem

The stems of cucumber seedlings that completed the mechanical properties test were placed in an oven at 105 °C for 20 min and then baked at 80 °C until constant weight. The dried cucumber seedling stems were fully ground and crushed, then passed through a 60-mesh sieve. About 0.1000 g of each sample was weighed to determine the content of biochemical components in seedling stems. The determination of cellulose, hemicellulose and lignin was carried out according to the method of Zhao (2021) [12]. The experiment was repeated three times, and the results were averaged.

1. Cellulose determination: The stem sample was placed in a test tube, mixed with a mixture of acetic acid and glacial acetic acid, heated in a boiling water bath and centrifuged after cooling, and only the precipitate was retained. After the precipitate was dried, a mixture of sulfuric acid and potassium dichromate was added. After mixing, the mixture was heated in a boiling water bath. After cooling, KI solution and starch solution were added, and the solution was titrated with sodium thiosulfate to give a blue color. The titration of sulfuric acid and potassium dichromate mixture was designated as the blank experiment. The cellulose content calculation formula is as follows:

$$X = \frac{m(a - b)}{24n} \quad (1)$$

In the formula, m is the concentration of sodium thiosulfate, mol·L^{-1}; a is the volume of sodium thiosulfate consumed in the blank experiment, mL; b is the volume of sodium thiosulfate consumed in the titration of each treatment solution, mL; n is the mass of cucumber seedling stem powder, g; 24 is 1 moL $C_6H_{10}O_5$ equivalent to the titration of sodium thiosulfate.

2. Hemicellulose determination: The stem sample was placed in a beaker, mixed with calcium nitrate solution, heated in a boiling water bath and centrifuged after cooling, and only the precipitate was retained. After the precipitate was dried, hydrochloric acid was added to the boiling water bath for heating. After cooling, phenolphthalein was added dropwise, and the solution was titrated with saturated NaOH solution until the rose red did not fade. The filtrate was taken in the test tube, and the DNS reagent was added to the test tube to mix well, heated in a boiling water bath and diluted with distilled water after cooling. The absorbance of the solution at a wavelength of 540 nm was measured by an ultraviolet spectrophotometer, and the content was calculated according to the range of the glucose standard curve. If the measured content was within the range of the glucose standard curve, the coefficient was multiplied by 0.9.
3. Determination of lignin: The stem samples were placed in a centrifuge tube, soaked in the acetic acid solution, mixed well and centrifuged. Only the precipitate was retained and rinsed with the acetic acid solution and transferred to a glass test tube. After the precipitate was dried, the mixture of ethanol and ether was added to soak and the supernatant was discarded. The mixture was heated in a boiling water bath until the water was completely evaporated. Then the mixture was mixed with sulfuric acid and placed for 16 h. After mixing with distilled water, the mixture was heated in a boiling water bath. After cooling, barium chloride solution was added. After mixing, the mixture was centrifuged and filtered to remove the supernatant and the precipitate was dried. A mixture of sulfuric acid and potassium dichromate was added to the precipitate, heated in a boiling water bath, cooled and transferred to a conical flask, and then KI solution and starch solution were added. The solution was titrated with sodium thiosulfate to just show blue that did not fade after shaking. The titration of sulfuric acid and potassium dichromate mixture was designated as the blank experiment. The lignin content calculation formula is as follows:

$$X = \frac{m(a - b)}{48n} \quad (2)$$

In the formula, m is the concentration of sodium thiosulfate, mol·L^{-1}; a is the volume of sodium thiosulfate consumed in the blank experiment, mL; b is the volume of sodium thiosulfate consumed in the titration of each treatment solution, mL; n is the mass of cucumber seedling stem powder, g; 48 is the titration degree of 1 moL $C_6H_{10}O_5$ equivalent to sodium thiosulfate.

2.3.2. Determination of Mechanical Properties of Cucumber Seedling Stem

Ten cucumber seedlings under each treatment were selected for the mechanical properties test and repeated three times. The stem interception was processed rapidly, and the fresh-keeping film was wrapped after sampling to avoid water loss. The bending and shearing tests of cucumber seedling stems were carried out by the TA.XTplus physical property tester using the test method of wood physical and mechanical properties [13].

1. Seedling stem bending test.

Cucumber seedling stem bending elastic modulus E calculation formula is:

$$I = \frac{\pi r^4}{4} \tag{3}$$

$$E = \frac{P_{\max} l^3}{48 f I} \tag{4}$$

In the formula, r is the diameter of the cucumber seedling stem, mm; $P_{\max}$ is the maximum bending load of the cucumber seedling stem, N; l is the gauge distance between the three-point bending supports of the texture analyzer, mm; f is bending deflection, mm; I is the moment of inertia of the cucumber seedling stem section, mm^4.

Cucumber seedling stem bending strength σ calculation formula is:

$$M_{\max} = \frac{1}{4\gamma} P_{\max} \tag{5}$$

$$W_z = \frac{\pi r^3}{32} \tag{6}$$

$$\sigma = \frac{M_{\max}}{W_z} \tag{7}$$

In the formula, $M_{\max}$ is the maximum bending moment of the cucumber seedling stem, N; W_z is the modulus of the bending section; γ is the section plastic development coefficient, take 1.15.

2. Seedling stem shear test.

The calculation formula of shear strength τ_s of cucumber seedling stem is:

$$\tau_s = \frac{F_{\max}}{2A} \tag{8}$$

$$A = \frac{\pi r^2}{4} \tag{9}$$

In the formula, $F_{\max}$ is the maximum shear force of the cucumber seedling stem, N; r is the diameter of the cucumber seedling stem, mm; A is the cross-sectional area of the cucumber seedling stem sample section, mm^2.

2.3.3. Grey Relational Analysis Method

1. Select reference sequence (system characteristic sequence) and comparison sequence (correlation factor sequence) [14]: The mechanical properties of cucumber seedling stems were set as the system characteristic sequence and the biochemical components were set as the related factor sequence. Reference sequence $X_0 = (x_{01}, x_{02}, x_{03}, x_{04}, x_{05}, \ldots, x_{0n})$; comparison sequence $X_i = (x_{i1}, x_{i2}, x_{i3}, x_{i4}, x_{i5}, \ldots, x_{in})$, $i = 1, 2, 3, \ldots, n$.
2. Original data selection: The mechanical parameters (elastic modulus, flexural strength, shear strength) of cucumber seedling stems were selected as the system characteristic index values to reflect the growth of plant stems and the content of stem biochemical components (cellulose, hemicellulose, lignin) was selected as the related factor sequence index value.
3. Data dimensionless processing: This study used the initial value method, that is using the first number of the sequence to remove all the numbers of the same sequence.

$$X_i' = \frac{X_i}{X_{i1}} \tag{10}$$

$i = 1, 2, 3, \ldots, n$

4. Difference sequence, maximum difference, minimum difference.

Difference sequence:

$$\Delta_{0i}(t) = |X'_0(t) X'_i(t)| \tag{11}$$

$t = 1, 2, 3, \ldots, m$

maximum difference:

$$\Delta\max = \frac{\max}{i} \frac{\max}{k} \Delta i(t) \tag{12}$$

$i = 1, 2, 3, \ldots \ldots, n; t = 1, 2, 3, \ldots, m$

minimum difference:

$$\Delta\min = \frac{\min}{i} \frac{\min}{k} \Delta i(t) \tag{13}$$

$i = 1, 2, 3, \ldots, n; t = 1, 2, 3, \ldots, m$

5. Calculate the correlation coefficient:

$$\varepsilon_{0i} = \frac{\Delta\min + \rho\Delta\max}{\Delta_{0i}(t) + \rho\Delta\max} \tag{14}$$

In the formula, ρ is the resolution coefficient, the value range is [0.1, 0.5], this test takes $\rho = 0.5$.

6. Calculate the correlation degree:

$$\xi_{0i} = \frac{1}{n} \sum_{t=1}^{n} \xi_{0i}(t) \tag{15}$$

$i = 1, 2, 3, \ldots, n$

7. Permutation order.

According to the size of ξ_{0i}, the larger the value, the higher the correlation degree, indicating that the tightness between the sub-factors and the parent factors is large.

2.4. Data Processing and Analysis

The bending and shear displacement load curve data of cucumber seedlings were collected by TA.XTplus physical property tester. Microsoft Excel 365 software was used to sort out the data of seedling biochemical component content and stem bending and shearing test. According to the relevant formula, the biochemical component content of the seedling stem and the elastic modulus, bending strength and shear strength of stem were calculated using the Microsoft Excel software, and the correlation degree between the biochemical component of the seedling stem and the mechanical property parameters was calculated. It was usually considered that the biochemical component of the stem has an influence on the mechanical property parameters of the stem when the correlation degree was greater than 0.60. The experimental data of elastic modulus, bending strength and shear strength of cucumber seedling stems under airflow disturbance were analyzed by one-way ANOVA using IBM SPSS Statistics data software of 23.0 version. The data were marked with different letters, the average value and standard error of mean indicate that there was significant difference at the $p \leq 0.05$ level. Duncan was used to compare the differences of different airflow disturbance parameters at the 5% significant level ($p \leq 0.05$). Microsoft Word 365 software was used to draw a three-line table of the correlation degree between biochemical components and mechanical properties of seedling stems under airflow disturbance. The 2019b version of Origin software was used for plotting the figures.

3. Results

3.1. Effect of Airflow Disturbance on the Content of Biochemical Components in Cucumber Seedling Stems

Under the treatment of TA (25 ± 5 °C) and TB (35 ± 5 °C) airflow temperature, the content of biochemical components in cucumber seedling stems was positively correlated with airflow velocity and increased with an increase in airflow velocity (see Figure 2). Under the same airflow velocity, the cellulose and lignin content of seedling stems under TA (25 ± 5 °C) airflow temperature treatment was higher than that under TB (35 ± 5 °C) airflow temperature treatment, and the hemicellulose content of seedling stems under TA (25 ± 5 °C) airflow temperature treatment was lower than that under TB (35 ± 5 °C) airflow temperature treatment. Under different airflow temperature conditions, the content of biochemical components in the stems of cucumber seedlings at 1 m/s airflow velocity was not much different from that under CK treatment, and the content of biochemical components in the stems at 3 m/s, 6 m/s and 9 m/s airflow velocity were higher than that under CK treatment.

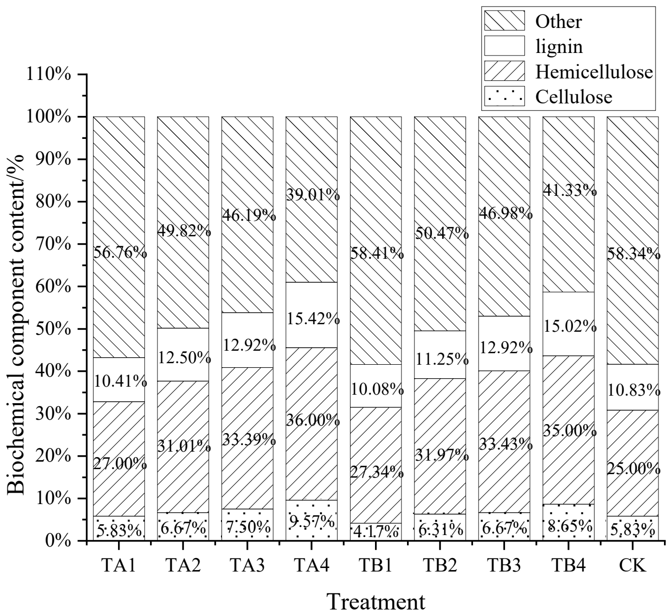

Figure 2. Effect of airflow disturbance on the content of biochemical components in cucumber seedling stems.

3.2. Cucumber Seedling Stem Bending Displacement–Load Curve Changes

The changes in the bending displacement–load curve of cucumber seedling stems under different airflow temperature treatments are shown in Figure 3. The results showed that the bending displacement–load curves of cucumber seedlings under different airflow temperature treatments were basically the same, showing a trend of increasing first and then decreasing, and the bending displacement of the stem was roughly the same. When the displacement was about 4 mm, the seedling stem produced the maximum bending load, but the maximum load value accepted by the stem was different. The maximum bending load accepted by the seedlings under TA (25 ± 5 °C) treatment was 2.5-times that of TB (35 ± 5 °C) treatment and 5-times that of CK treatment. With the increase in airflow temperature, the bending displacement of the seedling stem did not increase when the maximum bending load was generated, and the maximum bending load accepted decreased, indicating that the toughness of the seedling stem decreased.

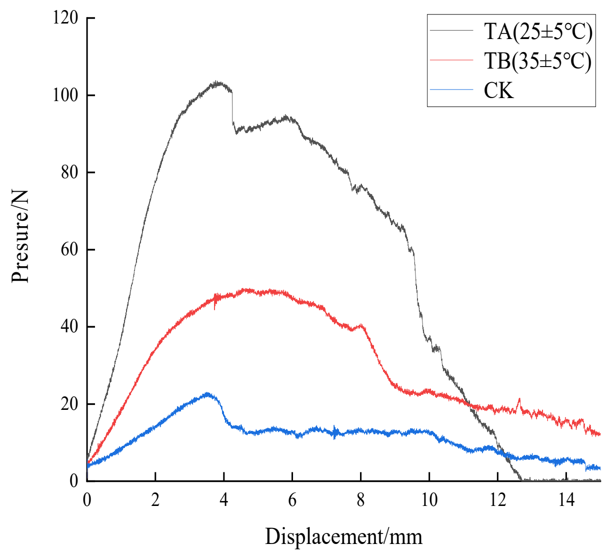

Figure 3. Cucumber seedling stem bending displacement–load curve under different airflow temperature treatment.

The changes in the bending displacement–load curve of cucumber seedling stems under different airflow velocity treatments are shown in Figure 4. The results showed that the variation in bending displacement–load curve of cucumber seedlings under different airflow velocity treatments was basically the same, which increased first and then decreased. The stem toughness of cucumber seedlings treated with airflow velocity was higher. With the increase in displacement, the maximum load of stem increased linearly. With the increase in airflow velocity, the displacement and bending load of the maximum bending load of stem increased significantly. The bending load of seedling stem treated with 9 m/s airflow velocity was the largest, which was 5.5-times that of CK treatment. With the increase in seedling stem deformation, the load began to decrease, but the stem did not completely break, so there would be obvious fluctuation of the bending load curve. With the increase in airflow velocity, the bending displacement of the seedling stem increased when the maximum bending load was generated, and the maximum bending load accepted increased, indicating that the toughness of seedling stem increases with the increase in airflow velocity.

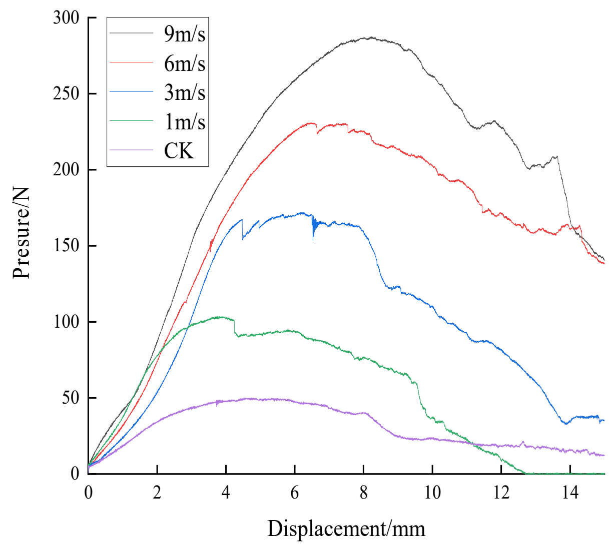

Figure 4. Cucumber seedling stem bending displacement–load curve under different airflow velocity treatment.

3.3. Effects of Airflow Disturbance on Elastic Modulus and Bending Strength of Cucumber Seedling Stem

The effects of airflow temperature and airflow velocity on the elastic modulus of cucumber seedlings are shown in Figure 5. The elastic modulus represents the ability of the material to resist deformation. The larger the elastic modulus, the harder the material. Under TA (25 ± 5 °C) and TB (35 ± 5 °C) airflow temperature treatments, the elastic modulus of the cucumber seedling stem was positively correlated with airflow velocity and increased with the increase in airflow velocity, indicating that the hardness of the seedling stem was enhanced. Under the same airflow velocity, the elastic modulus of seedling stems under TA (25 ± 5 °C) airflow temperature treatment was lower than that under TB (35 ± 5 °C) airflow temperature treatment. Under different airflow temperature conditions, the elastic modulus of stems at 9 m/s airflow velocity was higher than that under CK treatment.

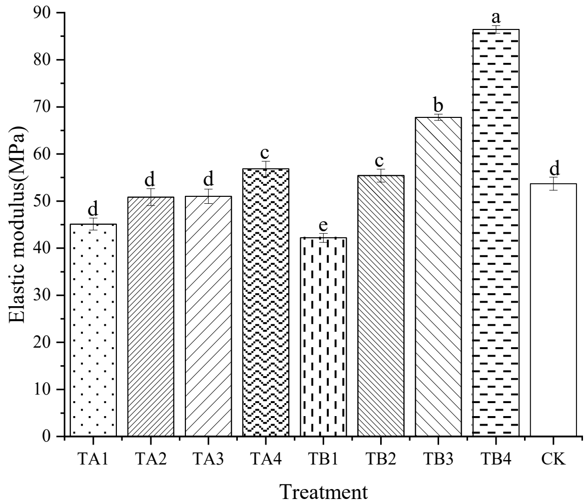

Figure 5. Effect of airflow disturbance on stem elastic modulus of cucumber seedlings. Note: different lowercase letters above the error bars of the elastic modulus indicate that subsequent values significantly differed at $p \leq 0.05$, according to one-way ANOVA.

It can be seen from Figure 6 that the bending strength refers to the maximum stress received when the material undergoes bending deformation, reflecting the ability of the material to resist bending deformation. Under the treatment of TA (25 ± 5 °C) and TB (35 ± 5 °C) airflow temperatures, the bending strength of cucumber seedling stems was positively correlated with the airflow velocity and increased with the increase in airflow velocity, indicating that the hardness of seedling stems was enhanced. Under different airflow temperature treatment conditions, there was no significant difference in the bending strength of seedling stems at 1 m/s airflow velocity and CK treatment. The bending strength of seedling stems at 3, 6 and 9 m/s airflow velocities were higher than that under CK treatment. Under the conditions of 6 m/s and 9 m/s airflow velocity, the bending strength of seedling stems under TA (25 ± 5 °C) airflow temperature treatment was lower than that under TB (35 ± 5 °C) airflow temperature treatment.

3.4. Cucumber Seedling Stem Shear Displacement–Load Curve Changes

The shear displacement–load curves of cucumber seedling stems under different airflow temperature treatments are shown in Figure 7. The results showed that the maximum shear load of cucumber seedling stems under different airflow temperature treatments was roughly the same. At about 180 N, the shear displacement of seedling stems under TA (25 ± 5 °C) and TB (35 ± 5 °C) treatments was the same. When the displacement was about 3.5 mm, it was completely cut, and the shear load dropped sharply to 0. Under CK treatment, the seedling stems were completely cut at about 3.2 mm. With the increase in airflow temperature, the amount of shear displacement and the maximum shear load received by the seedling stem when the maximum shear load was generated remained unchanged, indicating that airflow temperature does not increase the ability of seedling stem to resist shear force.

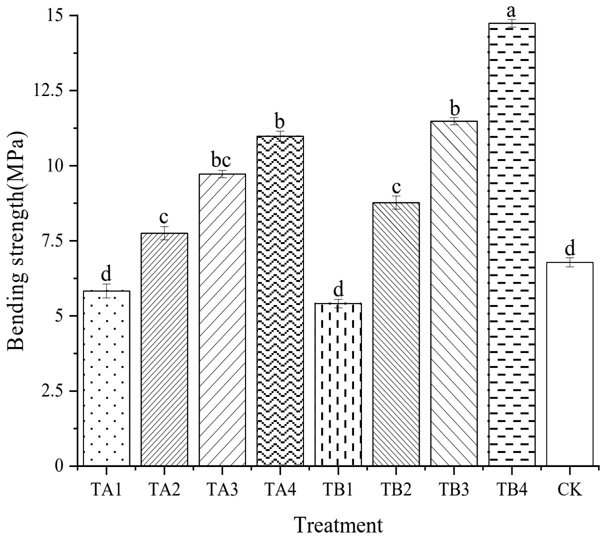

Figure 6. Effect of airflow disturbance on stem bending strength of cucumber seedlings. Note: different lowercase letters above the error bars of the bending strength indicate that subsequent values significantly differed at $p \leq 0.05$, according to one-way ANOVA.

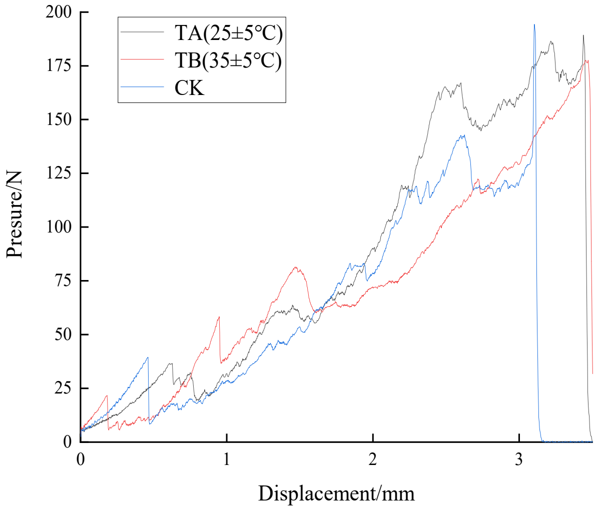

Figure 7. Shear displacement–load curves of cucumber seedling stems under different airflow temperature treatments.

The changes in shear displacement–load curves of cucumber seedling stems under different airflow velocity treatments are shown in Figure 8. The results showed that the maximum shear load and shear displacement of cucumber seedlings were different under different airflow velocity treatments, and the variation of shear displacement–load curve was also different, but the shear displacement–load curve showed double peaks. Cucumber seedlings were stimulated by airflow velocity to produce resistance, the internodes of seedlings were dwarfed and thickened and the fibrous tissue in the structure showed strong viscosity, so the shear load was greater than that of the control. When the shear just contacted the stem, the shear load increased with the increase in shear displacement, showing the first peak in the curve. The medullary cavity of the seedling stem increased with the increase in airflow velocity, and the empty and large medullary cavity was easy to be sheared. The shear load in the corresponding shear displacement–load curve gradually decreased after the first peak. As the shear displacement continued to increase, the shear knife cut again after passing through the medullary cavity, and the shear load rebounded until the stem was completely cut off. Due to the uneven distribution of biochemical components in the stem, the curve fluctuated. With the increase in airflow velocity, the shear displacement of the seedling stem decreased when the maximum shear load was generated, but the maximum shear load accepted increased, indicating that the hardness of the seedling stem increased and the viscosity of the fiber tissue in the structure did not increase.

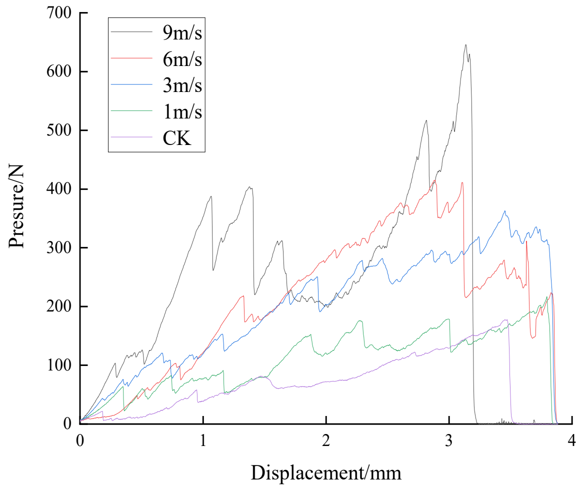

Figure 8. Shear displacement–load curves of cucumber seedling stems under different airflow velocity treatments.

3.5. Effect of Airflow Disturbance on Shear Strength of Cucumber Seedling Stem

The effects of airflow temperature and airflow velocity on the shear strength of cucumber seedlings are shown in Figure 9. Under TA (25 ± 5 °C) and TB (35 ± 5 °C) airflow temperature treatments, the shear strength of the cucumber seedling stem increased with the increase in airflow velocity, and the shear strength of the stem was the largest at 9 m/s airflow velocity. Under different airflow temperature treatment conditions, there was no significant difference in the shear strength of seedling stems between 1 m/s airflow velocity and CK treatment. The shear strength of seedling stems at 3, 6 and 9 m/s airflow velocities were higher than that under CK treatment. Under the conditions of 1, 3 and 6 m/s airflow velocities, the shear strength of seedling stems had little difference under different airflow temperatures.

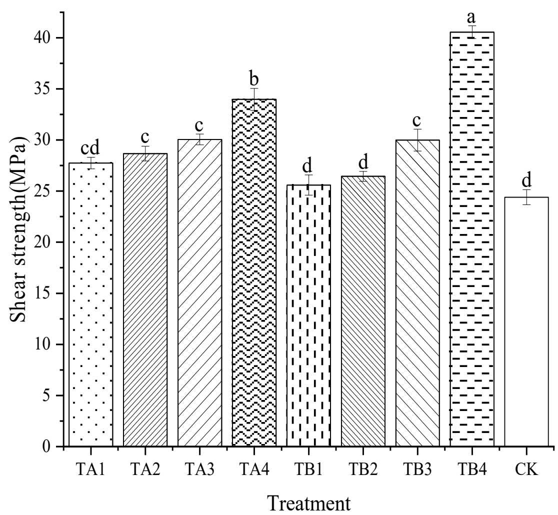

Figure 9. Effect of airflow disturbance on shear strength of cucumber seedling stems. Note: different lowercase letters above the error bars of the shear strength indicate that subsequent values significantly differed at $p \leq 0.05$, according to one-way ANOVA.

3.6. Grey Relational Analysis of Biochemical Components and Mechanical Properties of Cucumber Seedling Stems

3.6.1. Correlation Degree between Biochemical Components and Mechanical Properties of Seedling Stems under Different Airflow Temperature Treatments

The correlation between biochemical components and mechanical properties of cucumber seedlings under airflow temperature treatment is shown in Table 2. It can be seen from Table 2 that the elastic modulus, bending strength and shear strength of cucumber seedlings were affected by the content of cellulose, hemicellulose and lignin in stems. The correlation degree of elastic modulus and shear strength with stalk biochemical components at TA (25 ± 5 °C) airflow temperature was hemicellulose lignin hemicellulose, and the correlation degree was greater than 0.60, indicating that stalk biochemical components had a greater influence on stalk elastic modulus. The correlation degree of bending strength with stalk biochemical components was cellulose lignin hemicellulose, and the correlation degree between hemicellulose and stalk biochemical components was less than 0.60, indicating that hemicellulose had less influence on stalk bending strength.

Table 2. Correlation degree between biochemical components and mechanical properties of seedling stems under different airflow temperature treatments.

Airflow Temperature	Biochemical Component	Mechanical Properties Parameters		
		Modulus of Elasticity	**Bending Strength**	**Shear Strength**
TA (25 ± 5 °C)	Cellulose	0.7006	0.6372	0.6285
	Hemicellulose	0.8162	0.5816	0.7262
	lignin	0.7046	0.6200	0.6496
TB (35 ± 5 °C)	Cellulose	0.8941	0.7441	0.5088
	Hemicellulose	0.6402	0.5985	0.7292
	lignin	0.6525	0.6050	0.7898

Note: when the correlation degree was greater than 0.60, the biochemical components of seedling stems had an influence on the mechanical properties of the stem, otherwise it had no effect.

The correlation degree between elastic modulus and stem biochemical components at TB (35 ± 5 °C) airflow temperature was ranked as cellulose lignin hemicellulose, and the correlation degree was greater than 0.60, indicating that the stem biochemical components had a greater influence on the elastic modulus of the stem. The correlation degree between bending strength and stem biochemical components was ranked as cellulose lignin hemicellulose, and the correlation degree between hemicellulose and stem biochemical components was less than 0.60, indicating that hemicellulose had less influence on stem bending strength. The correlation degree between shear strength and stem biochemical components was ranked as hemicellulose lignin cellulose, and the correlation degree between cellulose and stem biochemical components was less than 0.60. It shows that cellulose had little effect on stem shear strength.

3.6.2. Correlation Degree between Biochemical Components and Mechanical Properties of Cucumber Seedlings under Different Airflow Velocity Treatments

Different airflow velocity treatments caused the arrangement of the cell structure in the stem of cucumber seedlings, formed different spatial structures, affected the distribution of biochemical components and thus affected the mechanical properties of the stem. The correlation between biochemical components and mechanical properties of cucumber seedlings under different airflow velocities is shown in Table 3. The correlation between biochemical components and mechanical properties of seedling stems at different airflow velocities was greater than 0.60, indicating that the airflow velocity had a greater influence on the mechanical properties of stems. The correlation degree of stem mechanical properties and stem biochemical components at 1 m/s airflow velocity was lignin hemicellulose, indicating that lignin had the greatest influence on stem mechanical properties and cellulose had the least influence on stem mechanical properties. The order of correlation between elastic modulus and bending strength and stem biochemical components at 3 m/s airflow velocity was hemicellulose lignin, indicating that hemicellulose had the greatest influence on stem elastic modulus and bending strength and lignin had the least influence on stem mechanical properties. The order of correlation between shear strength and stem biochemical components was lignin cellulose hemicellulose, indicating that lignin had the greatest influence on stem shear strength and hemicellulose had the least influence on stem mechanical properties, which was opposite to the correlation between stem biochemical components and elastic modulus and bending strength. Under the airflow velocity of 6 m/s, the correlation degree of elastic modulus and flexural strength with stalk biochemical components was hemicellulose lignin cellulose, indicating that hemicellulose had the greatest influence on the elastic modulus and flexural strength of the stalk and cellulose had the least influence on the mechanical properties of the stalk. The correlation degree of shear strength with stalk biochemical components was lignin hemicellulose, indicating that lignin had the greatest influence on the shear strength of the stalk and cellulose had the least influence on the mechanical properties of the stalk. The correlation degree of stem mechanical properties and stem biochemical components at 9 m/s airflow velocity was lignin hemicellulose, indicating that lignin had the greatest influence on stem mechanical properties and cellulose had the least influence on stem mechanical properties.

Table 3. Correlation degree between biochemical components and mechanical properties of cucumber seedlings under different airflow velocity treatments.

Airflow Velocity	Biochemical Component	Mechanical Properties Index		
		Modulus of Elasticity	Bending Strength	Shear Strength
1 m/s	Cellulose	0.6667	0.6667	0.6667
	Hemicellulose	0.7941	0.7784	0.7674
	lignin	0.8852	0.8625	0.8467
3 m/s	Cellulose	0.6987	0.6921	0.8477
	Hemicellulose	0.8082	0.7675	0.6667
	lignin	0.6667	0.6667	0.8549
6 m/s	Cellulose	0.6667	0.6667	0.6667
	Hemicellulose	0.7007	0.7239	0.8619
	lignin	0.7003	0.7231	0.8687
9 m/s	Cellulose	0.6667	0.6667	0.6667
	Hemicellulose	0.6800	0.6860	0.6978
	lignin	0.6803	0.6866	0.6988

Note: when the correlation degree was greater than 0.60, the biochemical components of seedling stem had an influence on the mechanical properties of stem, otherwise it had no effect.

4. Discussion

The high temperature and high humidity environment in the seedling greenhouse aided in the cucumber seedlings to grow excessively, and the support ability was poor when the stem was slender, which was not conducive to the life activities of the aboveground stems and leaves. The artificial application of airflow disturbance significantly changed the morphology of seedling stems, and the content of biochemical components and mechanical properties of stems also changed, which realized the regulation of airflow disturbance on the growth of cucumber seedlings.

The stem plays a role in supporting the aboveground part of plants, transporting water and nutrients. The changes in stem morphology are the most obvious and observable features of environmental response. Cellulose, hemicellulose and lignin are the main chemical components of plant stems. The determination of biochemical components of cucumber seedling stems is helpful to understand the response of stems to airflow disturbance. The results showed that the content of biochemical components in seedling stems increased with the increase in airflow velocity and the content of cellulose and lignin decreased with the increase in airflow temperature. The airflow velocity will pull the plant, and a large degree of pulling will cause damage to the plant. The plant first chooses to change its own morphological structure to maintain stability. The principle was that the seedling resists the larger airflow disturbance by thickening the cell wall. The shorter the internode of the seedling and the thicker the stem, it was more conducive to maintaining stability. The research results were consistent with Liu's research results. In the study by Liu (2022), the thicker the stem of barley and wheat and the higher the lignin content, the stronger the lodging resistance of the stem [15]. Ma's (2019) study pointed out that higher airflow temperature can promote the growth of seedlings [2]. Hemicellulose mostly exists in young parts, so hemicellulose content was positively correlated with airflow temperature and increased with the increase in airflow temperature.

Numerous studies have shown that the mechanical properties of stems were closely related to stem diameter, cellulose content, hemicellulose content, lignin content and other indicators [16]. Cellulose and lignin are important components of the plant cell wall, which are linked by special chemical bonds and significantly affect the hardness of seedling stems. In this study, the bending and shear loads and elastic modulus, bending strength and shear strength of cucumber seedling stems increased with the increase in airflow velocity. The bending and shear loads of seedling stems under lower airflow temperature treatment were larger than those under higher airflow temperature treatment and the displacement of stem deformation was more. Under different airflow temperature conditions, the mechanical properties of seedling stems were the highest at 9 m/s airflow velocity. Consistent with the results of Hu (2015) and Lu (2014), the increase in cellulose and lignin content significantly enhanced the toughness and bending ability of stems [17,18]. The contents of cellulose and lignin in seedling stem were lower at higher airflow temperature, which affected the hardness of the seedling stem.

The grey relational analysis technique was used to analyze the relationship between the biochemical components of the seedling stem and the mechanical properties of the stem. The results showed that under the different airflow temperature conditions, the biochemical components of stem had a great influence on the elastic modulus, and the influence of different biochemical components on the mechanical properties was different. Under different airflow velocity conditions, the biochemical components of the stem had a great influence on the mechanical properties of the stem. This method confirmed the above experimental results. The airflow disturbance treatment significantly affected the biochemical component content of the seedling stem, and the mechanical properties of the stem also changed. Comprehensive analysis showed that airflow disturbance promoted the development of seedling stems in the direction of increasing biochemical components and enhancing stem hardness.

5. Conclusions

The mechanical properties of cucumber seedling stems under different airflow disturbance treatments were measured and analyzed. The results showed that the airflow temperature and airflow velocity treatments increased the bending load and shear load of the seedling stems. Under the airflow disturbance treatment, the bending displacement–load curve of the seedling stems showed a linear increase and then a slow decline. The shear displacement–load curve of the seedling stems showed two shear load peaks. With the increase in airflow velocity, the elastic modulus, bending strength and shear strength increased, and the numerical variation range of mechanical properties of seedling stems under 35 ± 5 °C airflow temperature treatment was larger than that under 25 ± 5 °C airflow temperature treatment. By measuring the content of biochemical components in the stems of cucumber seedlings under the treatment of airflow temperature and airflow velocity, it was concluded that the content of biochemical components in the stems of cucumber seedlings increased with the increase in airflow velocity, and the content of biochemical components in the stems of cucumber seedlings under the treatment of 25 ± 5 °C airflow temperature was higher than that under the treatment of 35 ± 5 °C airflow temperature. The correlation between cellulose, hemicellulose, lignin and stem mechanical properties of cucumber seedlings was analyzed by the grey relational analysis method. The correlation degree between the biochemical components in the stems of seedlings and the mechanical properties of stems was different under different airflow temperature treatments. The correlation degree between hemicellulose and elastic modulus and shear strength in the stems of seedlings under 25 ± 5 °C airflow temperature treatment was about 0.72, indicating that hemicellulose had a great influence on the elastic modulus and shear strength of stems. Under 35 ± 5 °C airflow temperature treatment, the correlation between cellulose and lignin in seedling stems and various mechanical properties was high. The correlation degree between biochemical components and mechanical properties of stems under different airflow velocities was higher than 0.60, indicating that biochemical components in stems affected the mechanical properties of stems.

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