DETERMINATION AND ANALYSIS OF BIOMECHANICAL PROPERTIES OF POD PEPPERS UNDER DIFFERENT MOISTURE CONTENTS FOR MECHANIZED HARVESTING
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不同含水量下机械化收获朝天椒的生物力学特性的测定与分析

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ABSTRACT
Pod pepper is widely cultivated worldwide and serves diverse agricultural and industrial value. To reduce the loss and damage rate of mechanized harvesting of pod peppers, this study conducted multiple measurement experiments on the planting modes and biomechanical characteristics of pod peppers under different moisture contents. The experimental results are as follows: the average size of pod pepper fruit is 63.2 mm in length and 10.5 mm in diameter, the average density is 0.82×10³ kg·m⁻³, and the elastic modulus is 9.6 MPa. The maximum tensile force required for detaching pod pepper stalks from stems is 13.85 N, and the average value is 11.62 N; whereas the maximum tensile force required for separating pepper fruit from stalk ranges from 16.0N to 35.0 N, indicating that the fruit-stalk connection is stronger than the stalk-stem connection. In addition, the moisture content has a significant effect on the biomechanical properties of pod peppers. Within a certain range, the compressive resistance of pod peppers increases first and then decreases with the decrease of moisture content.

摘要
朝天椒在世界范围内广泛种植，具有多种农业和工业价值。为了降低机械化收获辣椒的损失和损坏率，本研究对朝天椒的种植模式和不同含水量下的生物力学特性进行了多次测量实验。实验结果如下：朝天椒果实的平均尺寸为长 63.2 毫米，直径 10.5 毫米，平均密度为 0.82×10³ 千克/立方米，弹性模量为 9.6 兆帕。从茎杆上分离果柄所需的最大拉力为 13.85 N，平均值为 11.62N；而分离朝天椒果实与果柄所需的最大拉力范围为 16.0 N 至 35.0 N，可见果实与果柄之间的连接力大于果柄与茎杆之间的连接力。此外，水分含量对朝天椒的生物力学性能有显著影响，在一定范围内，朝天椒的抗压强度随着含水量的降低先增加后减小。

INTRODUCTION
Pod pepper is not only a kind of vegetable with a spicy taste and multiple nutrients, but also a raw material for extracting industrial pigments *(Do Nascimento et al., 2014; Zhang et al., 2021)*. Therefore, pod pepper is widely cultivated in the globally with the global area reached 2.83 million hectares (ha) in 2020 *(FAOSTAT, 2025)*. Especially, China is a major producer and consumer of chili peppers, and China's demand for chili peppers is also growing with the development of industrial level and a large population. Pepper harvesters are replacing manual harvesting of chili peppers due to their high efficiency *(Zou et al., 2022; Han et al., 2024).*

To improve the mechanized harvesting performance of pod pepper, reducing loss and damage rates, the biomechanical properties of pod pepper should be determined before a harvester is developed. This helps to explore the optimal structural and motion parameters of a pepper harvester. The geometric characteristics of pod pepper are of great significance for the harvesting performance of pepper harvesters. Currently, there are two mainstream structural forms of pod pepper harvesters, one structure is to use a toothed roller device to comb pod peppers, and the other structure is to use a double spiral rod to pull pod peppers *(Tai et al., 2025)*. During the mechanized harvesting of pod peppers, the forces exerted by mechanical components on the pepper fruits should exceed the connecting force between the fruit and stalk to detach from the main stems. If the force is exerted heavily, the pepper fruits may be damaged *(Kang et al., 2016; Song et al., 2024)*.

In recent years, many scholars have conducted research on the biological and mechanical properties of chili peppers. For example, *Du et al. (2023)* obtained some contact parameters of pod pepper through direct discrete element models (DEM). *Chen et al. (2024)* determined the static friction coefficient and coefficient of restitution between the seeds and steel plates through incline and free-fall tests. *Wang et al. (2024)* studied the damage mechanism of collision between pod pepper and comb teeth based on Hertz theory*. Han D. et al. (2024)* developed an inclined double-spiral pod pepper harvester to improve the harvest rate and reduce loss rate*.* To meet the power requirements of operations in hilly and mountainous areas, *Wu D. et al. (2023)* analyzed the load sensitivity of the hydraulic system of the pod pepper picking machine, and *Wang et al. (2023)* analyzed the vibration characteristics of a pepper harvester under different operating conditions.

To summarize the existing research, they focused on the biological and mechanical properties of pigmented chili peppers and string chili peppers in the mature stage. While, there is a lack of research on the biological and mechanical properties of pod peppers under different moisture contents. To address this gap, this study will conduct experimental measurements and analysis of the biological and mechanical properties of pod peppers under different moisture contents, including pepper density, compressive resistance of chili fruits, and the connection force between fruits and stems. It will provide basic data for the structural development of pod pepper harvesting equipment (e.g., picking devices, cleaning and separation devices) and the optimization of harvesting quality.

MATERIALS AND METHODS

Selection of pod pepper samples

The pod pepper samples were selected for experiments from a field in Shouxian Town, Xuzhou City, Jiangsu Province, as shown in Fig. 1. The row spacing was 70 cm, the plant spacing was 25 cm, the planting density was approximate 71700 plants per hectare, and the height of pod pepper plants measured using a tape measure was within 550 mm to 810 mm, the average plant height was 653 mm. The average plant width was 228 mm.

a) b)

Fig. 1 – Pod pepper samples

a) Pod pepper plants; b) Measurement of pod pepper plant height

Geometric measurements of pod pepper

A total of 300 pod pepper samples were randomly collected from the experimental field. The length (*L*) and diameter (*D*) of the pod pepper fruits were measured using a vernier caliper with an accuracy of 0.02 mm, as shown in Fig. 2.

a) b)

Fig. 2 – Determination of pod pepper's geometric characteristics

a) Pod pepper samples; b) Determination of the length (L) and diameter (D) of pod pepper fruits.

Determination of pod peppers' density

To determine the density of the pod peppers, the total masses and volume of several pod peppers should be measured first. Then, the density can be obtained based on the density calculation formula (1).

$$\rho_b = \frac{m}{V_t} \tag{1}$$

Eight pod peppers were randomly selected, and the total masses of them were measured by an electronic balance and denoted as m.

To measure the total volume of these pod peppers, drainage method was used in this study due to the irregular shape and size of the pod peppers. First, an appropriate amount of water was added to a graduated cylinder (with the volume sufficient to submerge the pod peppers), and the initial water volume in the cylinder was recorded as v_1. Then, these pod peppers were put into the cylinder, as shown in Fig. 3.

Since the density of pod pepper is lower than that of water, pod pepper would float on the water surface. To prevent pod peppers from floating, slight pressing force was applied to the eight pod peppers in the cylinder. After this operation, these pod peppers did not float in the cylinder, which was prevented by the compressive forces between the peppers and between the peppers and the cylinder wall. The water volume in the cylinder after submersion was recorded as v_2.

The total volume of the eight pod peppers was thus calculated as $V_t = v_2 - v_1$. To minimize experimental measurement errors, five identical tests were conducted. Then the density of the pod pepper samples was derived using Equation (1).

a) *b)*

Fig. 3 – Determination of pod pepper's density

a) Measuring the total masses of pod peppers; b) Pod peppers put into the cylinder.

Determination of the moisture content of pod pepper fruits

The moisture content of pod pepper fruits has a significant impact on their mechanical properties, and moisture content can be used to characterize the maturity of pod peppers. Therefore, moisture content is an important material characteristic. To determine the moisture content of pod peppers and prepare for different moisture contents of pod pepper samples, the relevant determination method was conducted in accordance with the method of determining grain moisture content specified in GB/T 5262-2008 *(China Machinery Industry Federation, 2008)*.

A total of 100 pod pepper samples were randomly selected and evenly divided into five groups (20 samples per group). Before drying, the weight of each group of pod peppers fruits was weighed. Then, these pod pepper samples were placed into evaporating dishes, and the total mass of pod peppers in each dish was measured separately using a balance. The five groups of pod pepper samples were then simultaneously placed into a DHG-9053A electric constant temperature blast drying oven (Fig. 4 (a)) for constant-temperature drying. The temperature was set at 105°C.

After drying for 30 minutes, pod peppers samples of Group 1 were taken out and placed into a sealed desiccator to cool to room temperature, and their masses were weighed. After drying for 60 minutes, pod pepper samples of Group 2 were taken out again. After it cooled to room temperature, and the mass was weighed. The same processing method as described above was referred to record as Group 3, Group 4, and Group 5, respectively. Especially, the mass of group 5 was measured every 30 minutes until the mass difference between two consecutive measurements was no more than 0.05 g. The pod pepper that has not undergone drying treatment was recorded as sample Group 0.

In this way, six groups of pod pepper samples with different moisture content gradients were obtained for subsequent mechanical measurement experiments, as shown in Fig. 4 (b). The average moisture content of the pod peppers was calculated for five sets of experiments using Equation (2):

$$m_d = \frac{w_{si} - w_{gi}}{w_{si}} \times 100\% \tag{2}$$

where:

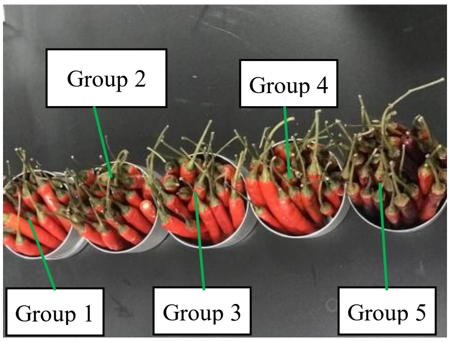
m_d - moisture content of pod pepper, %;

w_{si} - the mass of the i-th group of pod peppers before drying, in grams;

w_{gi} - the mass of dried chili peppers in group i, measured in grams;

i - group i experiment, i = 1, 2, 3, 4, 5.

a)



b)

Fig. 4 – Drying five groups of pod pepper samples with varying degrees of moisture content

a) A DHG-9053A electric constant temperature blast drying oven; b) Five groups of pod pepper samples with different moisture content.

Measurement of static friction contact coefficient

An angle tilt platform was used to measure the static friction coefficient of a pod pepper, the structure of which consists of a working surface, a frame, and an angle adjustment mechanism, as shown in Fig. 5. The tilt angle formed by the slope and the horizontal plane can be adjusted by the angle adjustment mechanism.

The measurement principle is that the gravity G of an object stationary on the working surface can be decomposed into two forces: a force F parallel to the slope downwards and a force T perpendicular to the slope downward, as shown in Fig. 6. If the tilt angle α of the working surface is less than the sliding critical angle, F is less than the static friction force between the pod pepper and the working surface, and the pod pepper is still in a relatively static state. As the tilt angle α increases, F becomes larger, if α exceeds the sliding critical angle of the pod pepper, it will begin to slide down along the tilt direction.

During the measuring process, a pod pepper was placed on the working surface of the angle tilt platform, then the tilt angle was adjusted, until the pod pepper was about to slide down but hasn't slid yet, the tilt angle formed by the slope and the horizontal plane was considered as the friction angle, and its tangent value was the measured friction coefficient of the pod pepper.

The relationship between the static friction coefficient μ_s and the tilt angle α is shown in Equation (3) *(Zhang et al., 2023)*.

$$\mu_s = \frac{f}{F} = \frac{mg\sin\alpha}{mg\cos\alpha} = \tan\alpha \tag{3}$$

Fig. 5 – Angle tilt platform (SXGX65) and digital display instrument

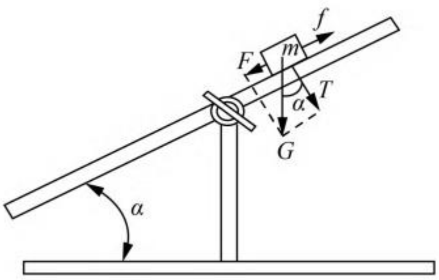


Fig. 6 – Schematic diagram of measuring the friction coefficient of an object

Measurement of rolling friction contact coefficient

To measure the rolling friction coefficient of the pod pepper, a pod pepper at a specific height on the angle tilt platform was released from rest to roll downward and subsequently transitions onto a horizontal steel plate. Then, the pod pepper rolled a certain distance on the horizontal surface before it stopped to rest. The test required that the pod pepper underwent pure rolling motion, with the static friction effect neglected during the rolling process, such that the resistance was treated as rolling friction resistance. The rolling distance along the incline was measured as S, and the rolling distance on the horizontal steel plate was measured as *B*. Based on the law of conservation of energy, the rolling friction coefficient was calculated using Equation (4):

$$\mu_r = \frac{mgS\sin\alpha}{mg\left(S\cos\alpha + B\right)} = \frac{S\sin\alpha}{S\cos\alpha + B} \tag{4}$$

Determination of restitution coefficient

The method of the free-fall collision rebound test was used determine the restitution coefficient of the pod pepper. During the free-fall collision rebound test, a pod pepper was initially released from a relative height H_1, allowing it to fell freely under gravity until it collided with a collision plate (steel or rubber) *(Kong et al., 2019; Huang et al., 2014)*. After the collision, the pod pepper rebounded, and the maximum relative rebound height H_2 was recorded. And the collision process was captured using a high-speed image acquisition system (i-SPEED TR, Olympus Corporation, Tokyo, Japan) at a frame rate of 100 fps. The restitution coefficient e of the pod pepper with a collision plate was calculated using Equation (5). To ensure reliability, the test is repeated five times using five different pod peppers per trial.

$$e = \frac{v_2}{v_1} = \frac{\sqrt{2gH_2}}{\sqrt{2gH_1}} = \frac{\sqrt{H_2}}{\sqrt{H_1}} \tag{5}$$

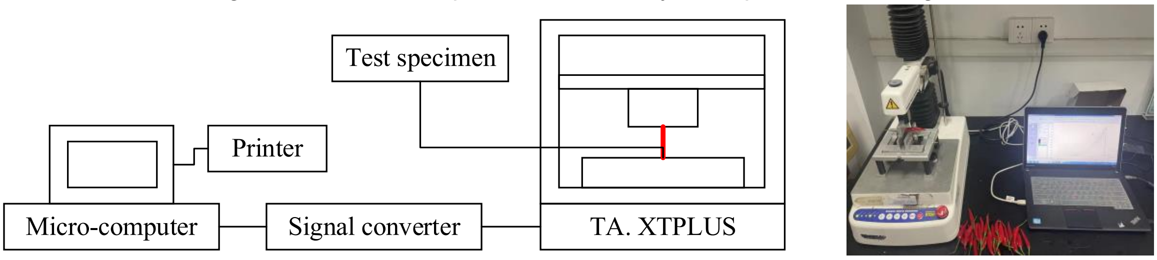
where, e denotes the restitution coefficient of the pod pepper collision with contact material; v_1 represents the instantaneous velocity of the pod pepper prior to the collision; v_2 represents the instantaneous velocity of the pod pepper after the collision.

Application methods of texture analyzer

A Texture Analyzer (TA. XT plus, UK) was used to measure the tensile, compressive, and shear stresses of pod peppers. Prior to conducting experiments, height correction and force correction should be performed. Height correction aims to calibrate the probe's zero reference point relative to the platform base, facilitating precise calculation of the sample's height when the probe makes contact. Force correction ensures the accuracy and traceability of test data by validating the precision of the sensor's measurements.

To configure the test, the "Return to Start" mode was selected. Within this mode, the "Go-to-Distance" method was employed, with "Force" designated as the primary measurement parameter. This configuration ensured that upon activation, the probe would move to the preset distance (Distance) and automatically return to its initial position after measurement. Additionally, the x-axis was configured to record distance (or time), whereas the y-axis was set to record force, aligning with experimental requirements to capture stress-strain relationships during mechanical testing of pod pepper samples. During these tests, the Texture Analyzer applied progressively increasing force, and the force sensed by the sensor was transmitted to a computer workstation and generated real-time force-displacement curves. These curves allow for the extraction of key parameters, including maximum tensile strength, elastic modulus, and elongation at fracture.

The schematic diagram of the TA.XT plus Texture Analyzer is presented in Fig. 7.



a) *b)*

Fig. 7 – Structure schematic diagram of the Texture Analyzer.
a) Structure schematic diagram; b) TA. XT plus Texture Analyzer.

Determination of test speed

Testing speed (i.e., strain rate, defined as strain per unit time) significantly influences the mechanical response of materials and is critical for evaluating their mechanical behavior under different loading rates. Therefore, the selection of testing speed for tensile/compressive tests using a TA. XT plus texture analyzer must be based on material properties and experimental objectives. For instance, slow loading scenarios (e.g., material creep testing) typically require a testing speed of 0.1–1.0 mm/s, whereas high-speed scenarios (e.g., simulating impact or rapid deformation, such as material tear resistance) generally use relatively high speeds of 5.0–20.0 mm/s.

The purpose of this study is to analyze the impact and shear forces applied to pod peppers by a toothed drum. Therefore, high-speed testing was chosen for conducting tensile/compression tests. Nine pod pepper samples were randomly selected to undergo tensile testing at three testing speeds: 5 mm/s, 10 mm/s, and 15 mm/s. Each speed condition was conducted in triplicate, and the resultant curves with tensile-displacement are presented in Fig. 8.

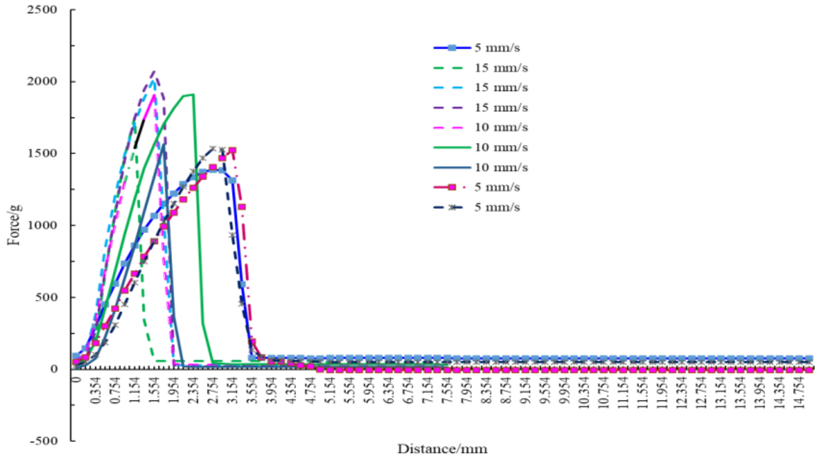
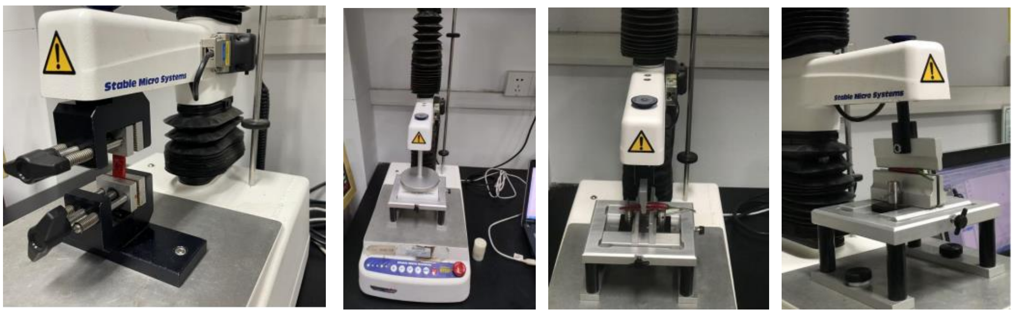


Fig. 8 – Tensile force-displacement curves at different speeds

As illustrated in Fig. 8, when the stretching speed was increased to 15 mm/s, the force-displacement curve become steeper, indicating a higher fracture strength. Under this high-speed condition, the pod chili pepper samples lack sufficient time for plastic deformation and energy absorption. Conversely, at a stretching speed of 5 mm/s, the force-displacement curve exhibited a relatively flatter profile with lower fracture strength, which better reflected the intrinsic mechanical response characteristics of pod chili peppers.

Determination of the mechanical properties of pod peppers

Tensile testing, compression testing, and shear testing are the three most commonly used testing methods in the study of material mechanical properties. Before the experiment, it is necessary to replace the texture analyzer probe corresponding to the specific testing method and configure the testing mode and speed parameters. Tensile tests were used to apply tensile loads to the stems and peels of pod pepper samples to characterize their tensile properties. Before testing, the A/TG clamping probe was used to clamp both ends of the pod pepper samples, as shown in Fig. 9 (a). The tensile distance was set to 15 mm, and the tensile speed was adjusted to 5 mm/s. To minimize experimental variability, five replicate tests were conducted.



a) *b)* *c)* *d)*

Fig. 9 – Mechanical property test of pod chili pepper

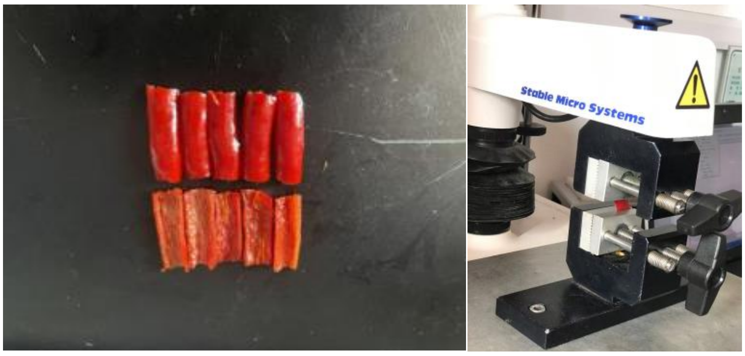
a) Tensile test; b) Compression test; c) Shear test; d) Longitudinal shear test

During compression tests, a pod pepper sample was positioned centrally on the testing platform of the texture analyzer, and the P/100 disc compression probe was used to compress pod pepper samples at a speed of 2 mm/s to acquire compressive force-displacement data curves. After testing, the pod pepper sample was replaced, and five replicate experiments were conducted to ensure reproducibility.

During shear testing, a pod pepper sample was placed on the support platform in a way that it spanned both ends of the platform, with care taken to position the pepper sample as symmetrically as possible relative to the shear probe's centerline to prevent relative sliding. To minimize experimental errors, five shear tests were conducted using the same method.

Tensile test of pod pepper peel

To carry out tensile test of pod pepper peel, pod pepper samples were selected from Group 0, and the seeds and placenta inside the fruit cavity were removed. Then the pod pepper peel was cut into rectangular strip samples with a length of 50 mm and a width of 10 mm, as shown in Fig. 10. Each strip sample was numbered, and its thickness was measured and recorded. To reduce experimental errors, four replicate experiments were conducted. In addition, pod pepper samples were selected from Group 1, Group 3, Group 5 to conduct tensile tests of pod pepper peel with different moisture contents.



a) *b)*

Fig. 10 – Tensile test of pod pepper peel

a) Strip-like thin slices; b) Tensile test

Poisson's ratio and Elastic modulus

In addition, the Poisson's ratio and Elastic modulus of pod peppers were derived based on these test results, providing a scientific reference for optimizing the structural and motion parameters of harvesting devices. Poisson's ratio describes the absolute value ratio of the transverse normal strain to the axial normal strain of a material under uniaxial tension or compression, denoted by the Greek letter *v*. For most isotropic materials, the Poisson's ratio ranges between 0 and 0.5. The definition formula of Poisson's ratio is:

$$v = -\frac{\varepsilon_l}{\varepsilon} = -\frac{\Delta D / D_0}{\Delta L / L_0} = -\frac{\left(D - D_0\right)/D_0}{\left(L_1 - L_0\right)/L_0} \tag{6}$$

where, v is the Poisson's ratio of pod pepper; denotes the transverse normal strain; represents the axial normal strain; D_0 is the radial diameter of the pod pepper before loading; D is the radial diameter of the pod pepper after breakage; L_0 is the axial length of the pod pepper before loading; and L_1 is the axial length of the pod pepper after breakage.

Young's modulus (E) specifically describes the elastic stiffness of a material under uniaxial tension or compression, characterizing the relationship between normal stress and normal strain. The calculation formula for Young's modulus is,

$$E = \frac{\sigma}{\varepsilon} \tag{7}$$

RESULTS

Determining the biological properties of pod peppers

The external shape feature of pod peppers is that their diameters are the largest near the fruit base, gradually decreases from the base to the tip, and sharply decreases from the area near the tip to the tip. The fruit length was classified at intervals of 5.0 mm, and the diameter was classified at intervals of 1.0 mm. The measurement results of geometric dimensions of pod pepper are shown in Table 1.

Table 1

Classification of shape and determination of length and diameter of pod pepper fruits

Length (mm)	Diameter (mm)	Frequency	Proportion (%)
(35, 40]	(6.0, 7.0]	5	1.67
(40, 45]	(7.0, 8.0]	35	11.67
(45, 50]	(8.0, 9.0]	36	12.00
(50, 55]	(9.0, 10.0]	38	12.66
(55, 65]	(10.0, 11.0]	130	43.33
(65, 70]	(11.0, 12.0]	56	18.67

The density of pod pepper calculated by the drainage method is presented in Table 2. Due to the irregular shape and presence of cavities in pod peppers, the density is not an absolute density, but a bulk density.

Table 2

The density data of pod pepper measured

No. / Item	1	2	3	4	5	Average density g/cm^3
Weight /g	22.576	25.230	20.869	22.423	26.597	
Volume /ml	27.0	31.0	25.0	28.0	32.0	0.823
Density g/cm^3	0.836	0.814	0.835	0.801	0.831	

The data of moisture content of pod pepper fruits obtained from five groups of measuring experiment and the average values are shown in Table 3.

Table 3

Moisture content of pod pepper

Test No. / Item	1	2	3	4	5	Average moisture content /%
Quality before drying（w_s）/g	64.42	59.99	57.81	60.28	58.82	/
Quality after drying（w_g）/g	24.80	22.10	16.01	23.98	18.25	/
Moisture content /%	61.50	63.17	72.31	60.21	68.97	65.23

Determination of contact coefficients of pod pepper

Table 4 presents the experimental results of the static friction coefficient, rolling friction coefficient, and coefficient of restitution between pod pepper and steel plate in the above experiment.

Table 4

The contact coefficient between pod pepper and steel plate

Material	Static friction coefficient	Rolling friction coefficient	Coefficient of restitution
Pod pepper-steel plate	0.42	0.24	0.42

Determination of mechanical properties of pod peppers

Fig.11 shows the force displacement curve of the fruit-stalk fracture for pod pepper samples from Group 0. In order to further determine the tensile strength of pod peppers with different moisture contents, three pod pepper samples were randomly selected from Group 1 to Group 5 (with decreasing moisture content from Group 1 to Group 5), and subjected to fruit-stalk tensile tests on these pod pepper samples. The obtained tensile displacement curves are shown in Fig. 12.

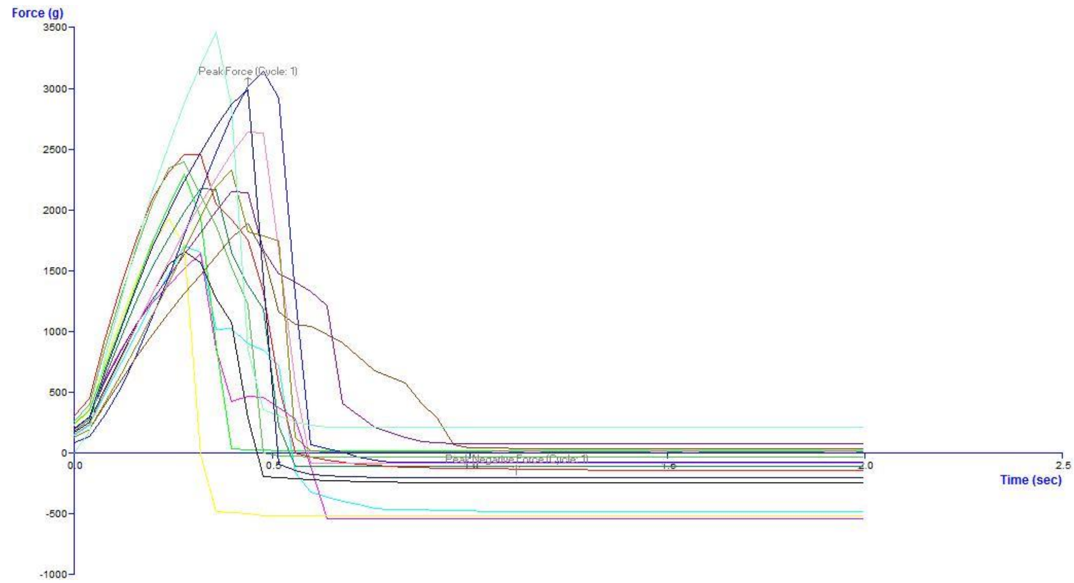


Fig. 11 – Tensile force-displacement curves

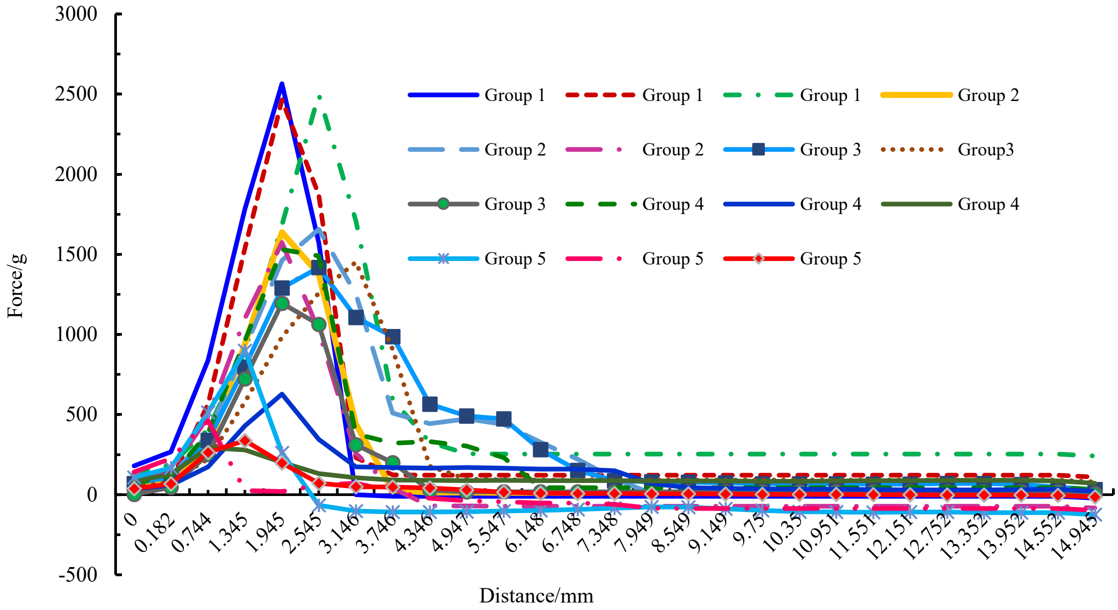


Fig. 12 – Tensile displacement curves at different moisture contents

The results of the tensile test of strip-shaped pod pepper peels

Table 5 presents the relevant tensile test data of strip-shaped pod pepper peel with different thicknesses. Fig. 13 shows the tensile force-displacement curve with varying moisture contents. It can be seen from Fig. 13 that the lower the moisture content, the lower the maximum tensile force required during stretching.

Table 5

Tensile test data of strip-shaped pod pepper peel with different thicknesses

Item / Number	1	2	3	4	Average	Tensile stress/ MPa	E/ MPa
Thickness /mm	1.22	1.58	1.58	1.40	1.45	0.76	9.60
Tensile force /N	8.6	12.3	12.0	11.2	11.0		
ΔL /mm	3.5	4.3	4.2	4.0	4.0	/	
Strain ε	0.07	0.09	0.08	0.08	0.08	/	

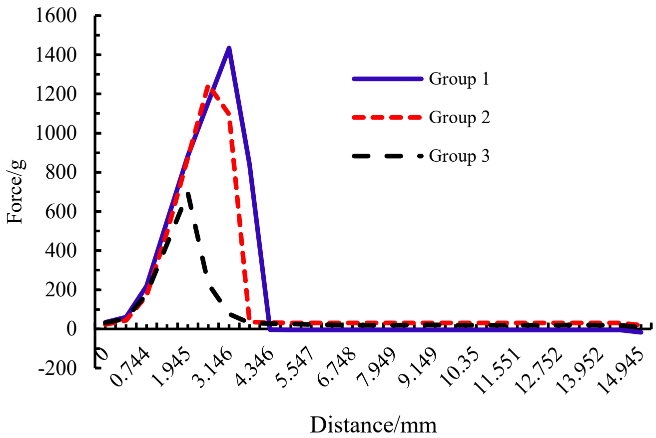


Fig. 13 – Tensile force-displacement curve with varying moisture contents

The results of the pod pepper compression tests

Fig. 14 presents the compressive force-displacement curve of pod pepper samples from Group 0. As shown in Fig. 14, the maximum compressive force that pod peppers can withstand ranges from 13 kg to 40 kg, indicating a yield-point behavior. Prior to reaching the yield point, the compressive force increases approximately linearly with deformation. Once the maximum compressive force is reached, the force decreases sharply with further deformation *(Seok et al., 2018)*.

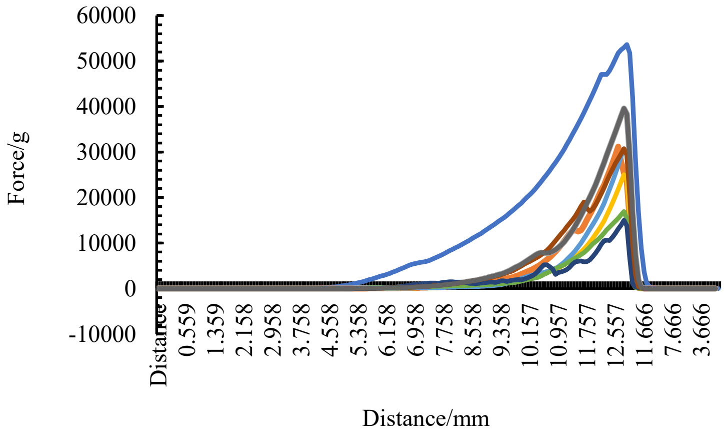
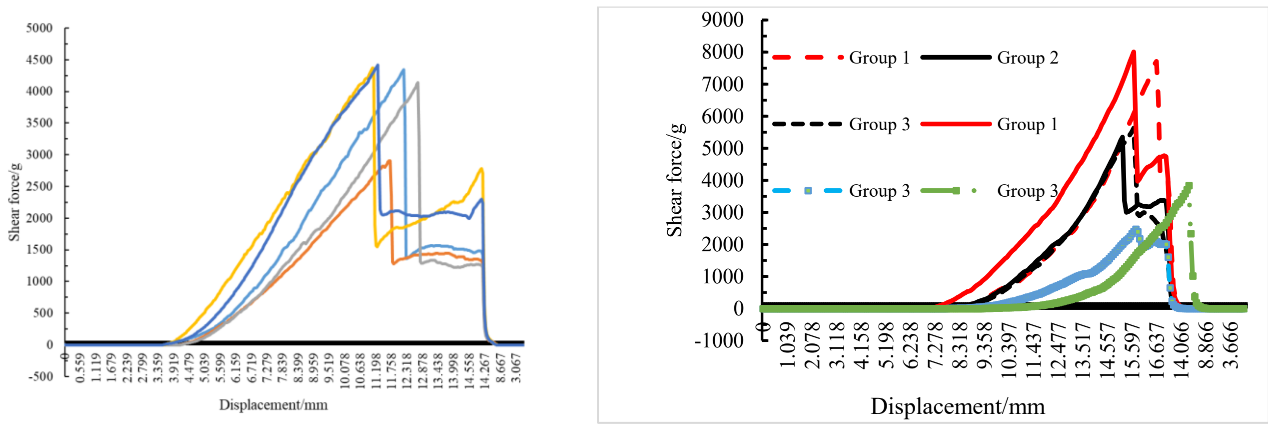


Fig. 14 – The compressive force-displacement curve of pod pepper samples from Group 0

The results of the pod pepper shear tests

Fig. 15(a) presents the shear force-displacement data curves of six test sets, and Fig. 15(b) presents the shear force-displacement curves of pod pepper samples under different moisture contents.



a) ***b)***

Fig. 15 – Shear force-displacement curve

As shown in Fig. 15(a), the maximum shear force ranges from 30.0 N to 45.0 N, corresponding to the plastic deformation of pod pepper, specifically, the yield point. Before reaching the yield point, the shear force increases gradually with deformation, showing a direct proportionality between the two, which is characteristic of elastic deformation. From Fig. 15(b), it can be observed that within a specific moisture content range (50%–70%), pod pepper samples with lower moisture content exhibit greater shear force at rupture. This is primarily because pod pepper becomes more brittle at higher moisture contents but demonstrates increased toughness as moisture content decreases.

DISCUSSION

The contact coefficients between pod pepper and steel plate are determined in this study as following: a static friction coefficient of 0.42, a rolling friction coefficient of 0.24, and a coefficient of restitution of 0.42. For comparison, *Du et al. (2023)* reported the following values from their experiments: the restitution coefficient was 0.42 ± 0.082, the static friction coefficient was 0.39, and the rolling friction coefficient was 0.19. Similarly, *Zhang et al. (2023)* reported the following values from their experiments: a restitution coefficient of 0.43, a static friction coefficient of 0.56, and a rolling friction coefficient of 0.31. Comparing these results reveals that the average static and rolling friction coefficients are not entirely consistent across different studies. The primary source of this discrepancy is likely attributed to variations in the surface roughness of the steel plates used in the respective experimental setups.

The maximum tensile force required for separating pepper fruit from stalk ranges from 16 N to 35 N in Fig. 11. In addition, pod pepper samples with lower moisture content (e.g., Group 5) require a smaller maximum tensile force to separate, whereas pod pepper samples with higher moisture content (e.g., Group 1) exhibit a larger maximum tensile force at the breaking point, as shown in Fig. 12. This study result aligns with the result reported by other scholars, and their results showed that the average tensile force for separation fruit from stalk decreases as the moisture content decreases with maturity level *(Liu et al., 2022; Wu et al., 2021; Xu et al., 2018)*. The higher the maturity level, the lower the required tensile force for separation, making it easier to separate. Conversely, the higher the required tensile force, the more difficult it is to separate *(Zhang et al., 2025)*. These test results confirm that the moisture content of pod pepper fruits has a notable influence on their tensile/compressive stress characteristics.

The maximum tensile force required to detach pod pepper stalks from stems was 13.85 N, with an average value of 11.62 N obtained in this study. Compared with the results reported by *Zhang et al. (2023)*, the average connection force between fruit and stalk was 11.54 N, while that between stalk and stem was 10.11 N, indicating that the fruit-stalk connection is stronger than the stalk-stem connection.

Elastic modulus is defined as the ratio of stress to strain under elastic loading, and it reflects the material's stiffness. A higher E value indicates greater resistance to stretching or compression (e.g., diamond exhibits an E of approximately 1000 GPa). Using relevant mechanical formulas, the Young's modulus of the pod pepper peel is calculated as 9.6 MPa.

This study focuses on exploring the planting mode and biomechanical characteristics of pod peppers in northern Jiangsu province. The results of this study are not entirely consistent with those of other scholars, and of course, the differences are not significant. It can be inferred that different regional terrains and climates in China have led to tailored planting patterns, which in turn affect the biomechanical properties of pod pepper plants.

CONCLUSIONS

This study investigated the biological and mechanical properties of pod pepper through experimental measurements combined with a review of relevant literature. The research aimed to enhance harvesting performance and reduce damage rates by integrating principles of agricultural machinery and agronomy. The findings provide foundational data to support the design and development of specialized harvesting machinery and equipment for pod pepper.

The main conclusions drawn are as follows: (1) Plant height, pepper length, pepper diameter are the main factors affecting the structural parameters of harvesting mechanisms. (2) The moisture content of pod peppers has a significant impact on their biological and mechanical properties. When the moisture content is around 50%, the pod peppers have the highest resistance to damage, making it the best period for mechanized harvesting. (3) The connection force between pepper fruit and stalk, between stalk and stem are the main factors affecting the motion parameters of a harvesting mechanism.

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