# STUDY ON THE BIOMECHANICAL PROPERTIES OF STALKS OF DIFFERENT GINGER VARIETIES
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# 不同生姜品种的茎秆生物力学特性研究

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## ABSTRACT
*To address the problems of ginger stalks being easily broken and incompletely cut during the clamp-pull ginger harvesting process, two ginger varieties, small yellow ginger and red ginger, were selected as experimental subjects. The basic biophysical parameters of the two varieties were measured, and the mechanical properties of their stalks were tested through shear, compression, tensile, and pull-out tests. The results showed that the mechanical properties of red ginger stalks were superior to those of small yellow ginger, and the stalks were less prone to breakage during harvesting. Moreover, the mechanical properties of the middle part of red ginger stalks were better than those of the upper and lower parts, making it more suitable as the clamping position in clamp-pull harvesting. The maximum shear strength of red ginger stalks was 1.42 MPa, the maximum compressive strength was 0.21 MPa, the maximum tensile strength was 4.31 MPa, and the average pull-out force was 68.45 N. This study provides a basis for low-damage ginger harvesting and for the selection of varieties suitable for mechanized harvesting.*

## 摘要
*为了解决夹拔式生姜收获过程中生姜茎秆易断裂、茎秆切割不完全等问题，本研究选择了小黄姜和红芽姜两个生姜品种作为试验对象。测量了生姜的基本生物学参数，并通过剪切、压缩、拉伸和拉拔试验方法测试了两生姜品种茎秆的力学性能。结果表明，红芽姜茎秆的力学性能优于小黄姜，收获时茎秆不易断裂，且红芽姜茎秆中部的力学性能优于上部和下部，更适合选作夹拔式收获的夹持部位。红芽姜茎秆的最大剪切强度为1.42MPa，最大抗压强度为0.21MPa，最大抗拉强度为4.31MPa，平均拉拔力为68.45N。本研究为生姜的低损伤收获和宜机化收获品种的选择提供依据。*

## INTRODUCTION
Ginger is a perennial herb that can be used not only as a seasoning in daily life, but also for treating colds, relieving coughs and other symptoms *(Akhlaghi & Najafpour-Darzi, 2023; Ayustaningwarno et al., 2024; Li et al., 2016)*. It has great edible and medicinal value. With the improvement of living standards and the diversification of processing technologies, people's demand for ginger is constantly increasing. The cultivation of ginger mainly relies on underground rhizomes for asexual reproduction, which is suitable for growing in warm and humid environments with low light intensity *(Seran, 2013)*. At present, there are two main mechanized harvesting methods for ginger: digging harvesting and clamping-pulling harvesting *(Narender & Shrivastava, 2022; Wang et al., 2023)*. The digging harvesting extracts ginger rhizomes from the soil with a digging shovel, but it causes a high damage rate to ginger. The clamping-pulling harvesting lifts the entire ginger plant out of the soil by gripping the ginger stalk, and it results in a low damage rate to ginger. However, this method has problems such as easy breakage of ginger stalks and incomplete cutting of stalks. During the clamping-pulling harvesting process, ginger stalks mainly bear shear force, pressure, and tensile force. When the shear force, pressure, or tensile force is too high, the ginger stalks break, which affects the working performance of the clamp-pull ginger harvester.

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Therefore, studying the physical and biomechanical properties of ginger stalks is of great significance for reducing the damage rate of ginger harvesting and improving the level of mechanized harvesting.

Currently, research on ginger mainly focuses on the appearance and quality of ginger stalks and leaves. Existing biomechanical studies have primarily focused on the mechanical properties of ginger rhizomes, with little research into the physical and biomechanical properties of ginger stalks *(Jia et al., 2023; Zhang et al., 2024)*. *Xu et al. (2024)* used Box-Behnken response surface methodology to study the mechanical properties of ginger rhizomes. The results showed that the compressive strength of the middle part of ginger rhizome was the smallest, and the shear strength at the bottom and top was smaller. *Gao et al. (2024)* conducted mechanical property experiments on tomato stalks, with leaf angle, moisture content, and sampling range as the experimental factors. The results showed that leaf angle had no significant effect on the mechanical shear properties of tomato stalks, while leaf moisture content and sampling location had a significant impact on the mechanical shear properties of tomato stalks. *Chalachai & Soni (2019)* measured and analyzed the physical and mechanical properties of cassava stalks. The results showed that cassava stalks are anisotropic materials, and loading speed and different knife bevel angles have an impact on the shearing effect of cassava stalks. In this study, the research methods for the mechanical properties of ginger rhizomes, tomato stalks, and cassava stalks were drawn on. Two ginger varieties, small yellow ginger and red ginger, were selected for physical measurement and mechanical testing. To obtain the physical parameters and mechanical properties of stalks from different ginger varieties, providing a basis for the low-damage harvesting of ginger and the selection of varieties suitable for clamp-pull mechanical harvesting.

## MATERIALS AND METHODS

### *Materials*

There are many varieties of ginger, which can be divided into sparse-seedling type and dense-seedling type according to their botanical characteristics and growth habits *(Li et al., 2023)*. The sparse-seedling type ginger plants are tall in size, with few stalk branches and sparse rhizome nodes. The ginger tubers are large in size and mostly arranged in a single layer. The dense-seedling type ginger has many stalk branches and dense rhizome nodes, and its ginger tubers are mostly arranged in multiple layers. To screen out ginger varieties suitable for clamp-pull harvesting, typical sparse-seedling small yellow ginger and typical dense-seedling red ginger, which are commonly planted in China, were selected as test samples in this study, as shown in Fig. 1. After purchasing fresh plants of two ginger varieties (at the harvest stage) from the market, mechanical property experiments were immediately conducted, with all experiments ensured to be completed within 24 hours. All experiments were conducted in the laboratory of the School of Mechanical Engineering, Yangzhou University, Jiangsu Province, at 25 ± 1 °C and 50 ± 5% relative humidity.

*(a) Small yellow ginger* *(b) Red ginger*

**Fig. 1 - Schematic diagram of two ginger plant structures**

The lateral buds of ginger rhizomes and the upper leaves of stalks were removed, and ginger parts were divided according to their different shapes, as shown in Fig. 2. The part below the lateral bud branching point is the lower part of the rhizome, the lateral bud branching point is the middle part of the rhizome, the part above the lateral bud branching point is the upper part of the rhizome, the part with a light yellow epidermis is the lower part of the stalk, the part with a dark green epidermis is the middle part of the stalk, and the part with a pale green epidermis is the upper part of the stalk.

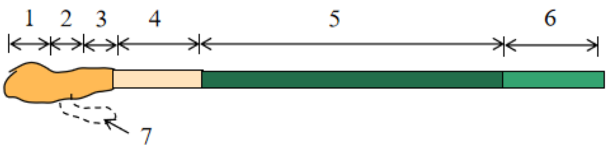


**Fig. 2 - Schematic diagram of ginger parts division**

*1 - Lower part of rhizome; 2 - Middle part of rhizome; 3 - Upper part of rhizome; 4 - Lower part of stalk; 5 - Middle part of stalk; 6 - Upper part of stalk; 7 - Lateral bud*

***Sample preparation***

***Biophysical parameters and moisture content of ginger rhizomes and stalks***

Twenty ginger plant samples were randomly selected from each variety. A tape measure (accuracy: 1 mm) and a vernier caliper (accuracy: 0.02 mm) were used to measure the length and diameter of rhizomes and stalks, respectively. Through comparison, it was found that the rhizomes of small yellow ginger are relatively long and straight with fewer lateral buds, while the rhizomes of red ginger have irregular shapes. Therefore, the diameter of the rhizomes of red ginger was not measured in this study. For each variety, 20 sets of data were collected, and the average of these measurements was used for subsequent analysis. This ensures a reliable evaluation of the physical properties of each ginger variety.

Ginger contains a large amount of water in all parts, but there are certain differences in the moisture content of different varieties and parts, which are mainly related to factors such as the type of ginger and the structural composition of each part *(Boydas et al., 2019; Li et al., 2024; Teng et al., 2023)*. Three 20 mm long samples were cut from the upper, middle, and lower parts of the rhizomes and stalks of two ginger varieties and weighed using an electronic balance (accuracy: 0.0001 g). Due to the irregular shape of the rhizomes of red ginger, the upper, middle, and lower parts of its rhizomes were not distinguished when measuring the rhizome moisture content in this study. Instead, a section of the rhizomes was randomly selected for moisture content testing. The initial weight was recorded as $m_0$. The samples were placed in a petri dish and dried in a forced-air drying oven at 65°C for 10 hours, followed by a weighing process. After the initial drying, the samples were returned to the drying oven for an additional two hours before being weighed again. This cycle was repeated until the difference between two consecutive weight measurements was less than 0.005 g, indicating that drying was complete. The weight of the samples in the final measurement was recorded as $m_1$. The moisture content of various parts of ginger can be calculated by the Equation (1) *(Moya-Ignacio et al., 2024)*.

$$W = \frac{m_0 - m_1}{m_0} \times 100\% \tag{1}$$

where: $W$ is the moisture content, %; $m_0$ is the initial weight of the sample, g; $m_1$ is the weight of the sample after drying, g.

***Samples for mechanical property testing of ginger stalks***

Ten straight and undamaged ginger stalks were randomly selected from each variety, and surface dirt, leaves, and raised nodules were removed. A utility knife was used to cut 20 mm segments from the upper, middle, and lower parts of the stalks respectively, which were used as samples for shear test. In addition, 10 straight and undamaged ginger stalks were randomly selected from each variety, and 20 mm segments were cut from the upper, middle, and lower parts of the stalks as samples for radial compression test. To conduct the tensile mechanical property test of ginger stalks, 10 straight and undamaged ginger stalks were randomly selected from each variety, and 40 mm segments were cut from the upper, middle, and lower parts of the stalks as test samples *(Butiter et al., 2013; Jahanbakhshi et al., 2020; Song et al., 2022)*.

***Samples for pull-out force testing of ginger stalk***

Clamp-pull ginger harvesting involves clamping the ginger stalks with a mechanical structure, and then pulling them out of the soil. This requires that the ginger harvester should be able to provide the pulling force to extract ginger from the soil. Therefore, it is necessary to study the pull-out force of ginger, so as to provide a theoretical reference for the design of clamp-pull ginger harvesters.

Five fresh ginger plants were randomly selected from each variety and planted in soil troughs. They were then watered and cultivated for one week to restore their normal growth state, after which the pull-out force test was conducted on the ginger plants.

***Experimental methods***

The experiments were conducted using a DK-10KN universal testing machine produced by Deka Precision Meter Co., Ltd, with the stress-displacement curves read through the corresponding control software. This testing machine can apply forces of varying magnitudes and directions, as well as different testing speeds; calibration must be performed before each experiment.

***Shear mechanical properties***

During the experiment, the ginger stalk samples were horizontally placed in the shear fixture of the DK-10KN universal testing machine and fixed in place with medical tape *(Desmet et al., 2002)*, as shown in Fig.3.

The moving speed of the shear blade was set to 10 mm·min$^{-1}$. At the beginning of the experiment, the pressure increased with the displacement of the blade, and the maximum pressure was reached when the surface of the ginger stalk samples was cut through by the blade, marking the end of the experiment. The maximum shear force was recorded, and a vernier caliper was used to measure the cross-sectional diameter at the cutting point. Then, the shear strength $\tau$ of the ginger stalk was calculated using the shear strength formula.

$$\tau = \frac{F_{Amax}}{A} \tag{2}$$

where: $\tau$ is the shear strength, MPa; $F_{Amax}$ is the maximum shear force, N; $A$ is the shear cross-sectional area, mm$^2$.

**Fig. 3 - Process of ginger stalk shear test**

***Radial compression mechanical properties***

During the experiment, the ginger stalk samples were horizontally placed on the compression plate aligned with the axis, as shown in Fig. 4. The moving speed of the compression plate was set to 10 mm·min$^{-1}$. At the beginning of the experiment, the pressure increased with displacement. When the ginger stalk sample fractured, the pressure reached its maximum value, marking the end of the experiment, and the maximum compressive force was recorded *(Gao et al., 2025)*. The contact area of radial compression of ginger stalks can be regarded as a rectangle with a length of 2a and a width of 20 mm, and its calculation formula is as follows:

$$2a = 2\sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{D-\Delta D}{2}\right)^2} = \sqrt{2D \cdot \Delta D - \Delta D^2} \tag{3}$$

where: $D$ is the diameter of the stalk sample, mm; $\Delta D$ is the deformation amount of the stalk sample, mm.

The area $S$ of the radial compression contact surface of ginger stalks can be calculated by the Eq. (4):

$$S = \sqrt{2D \cdot \Delta D - \Delta D^2} \cdot 20 \tag{4}$$

The radial compressive strength $\sigma$ of ginger stalks can be calculated by the Equation (5):

$$\sigma = \frac{F_{max}}{S} \tag{5}$$

where: $\sigma$ is the compressive strength, MPa; $F_{max}$ is the maximum compressive force, N; $S$ is the compressed cross-sectional area, mm$^2$.

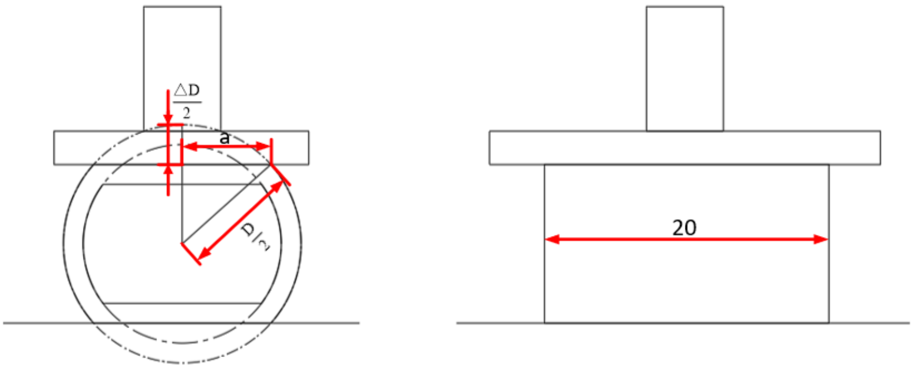


**Fig. 4 - Schematic diagram of radial compression test on ginger stalk**

### *Tensile mechanical properties*

The upper and lower ends of the ginger stalk samples were clamped using the tensile fixture of the DK-10KN universal testing machine, as shown in Fig. 5. The stretching speed was set to 10 mm·min$^{-1}$. To prevent the ginger stalk samples from slipping out of the fixture during measurement, medical tape was used to wrap the upper and lower ends of the samples *(Cao et al., 2023; Shen et al., 2024)*.

At the start of the experiment, the tensile force increases with the displacement, reaching its maximum when the ginger stalk samples fractured, marking the end of the experiment. The maximum tensile force was recorded, and a vernier caliper was used to measure the cross-sectional diameter at the fractured position. The tensile strength $\sigma_b$ of the ginger stalk was calculated by applying the tensile strength calculation Equation:

$$\sigma_b = \frac{F_{bmax}}{A} \tag{6}$$

where: $\sigma_b$ is the tensile strength, MPa; $F_{bmax}$ is the maximum tensile force, N; $A$ is the tensile cross-sectional area, mm$^2$.

**Fig. 5 - Process of ginger stalk tensile test**

### *Ginger stalk pull-out force test*

The pull-out force of ginger stalks was measured using a Handpi tension and compression testing machine. During the experiment, the middle part of the ginger stalk was tied with a plastic cable tie. Then, the Handpi testing machine was used to pull the cable tie to extract the ginger from the soil, and the pull-out force of the ginger at the moment it just emerged from the soil was recorded *(Nath et al., 2019; Yang et al., 2022)*, as shown in Fig. 6.

**Fig. 6 - Process of ginger stalk pull-out force test**

## RESULTS

### *Results of biophysical parameters and moisture content of ginger*

The biophysical parameters and average moisture content of the rhizomes and stalks of various ginger varieties are shown in Table 1 and Table 2.

**Table 1**

**Biophysical parameters and moisture content of small yellow ginger**

| Part | Length (mm) | Sampling location | Diameter (mm) | Moisture Content (%) | Average number of stalks (root) |
|---|---|---|---|---|---|
| Stalk | 643.72 | Upper | 5.04 | 88.95 | 1 |
| | | Middle | 7.59 | 89.83 | |
| | | Lower | 11.10 | 95.66 | |
| Rhizome | 135.25 | Upper | 16.91 | 95.21 | |
| | | Middle | 17.31 | 94.64 | |
| | | Lower | 17.40 | 90.21 | |

**Table 2**

**Biophysical parameters and moisture content of red ginger**

| Part | Length (mm) | Sampling location | Diameter (mm) | Moisture Content (%) | Average number of stalks (root) |
|---|---|---|---|---|---|
| Stalk | 770.53 | Upper | 2.01 | 86.74 | 4.1 |
| | | Middle | 3.77 | 90.18 | |
| | | Lower | 5.66 | 92.00 | |
| Rhizome | 123.75 | / | / | 80.22 | |

### *Results of shear mechanical performance test*

The shear mechanical performance test results of stalks of various ginger varieties are shown in Table 3 and Table 4. The average shear forces on the upper, middle, and lower parts of the small yellow ginger stalk are 21.70 N, 22.33 N, and 24.25 N respectively, and the average shear strengths are 1.36 MPa, 0.47 MPa, and 0.28 MPa respectively. The average shear forces on the upper, middle, and lower parts of the red ginger stalk are 2.46 N, 6.63 N, and 5.36 N respectively, and the average shear strengths are 1.42 MPa, 0.56 MPa, and 0.31 MPa respectively.

**Table 3**

**Results of shear test of small yellow ginger stalk**

| Test No. | Shear force (N) | | | Shear strength (MPa) | | |
|---|---|---|---|---|---|---|
| | Upper | Middle | Lower | Upper | Middle | Lower |
| 1 | 24.53 | 22.82 | 22.24 | 1.40 | 0.39 | 0.27 |
| 2 | 23.96 | 14.78 | 23.62 | 1.42 | 0.30 | 0.30 |
| 3 | 26.52 | 24.62 | 22.38 | 1.47 | 0.45 | 0.29 |
| 4 | 20.42 | 19.82 | 21.98 | 1.34 | 0.39 | 0.26 |
| 5 | 19.65 | 24.57 | 21.84 | 1.38 | 0.60 | 0.23 |
| 6 | 20.78 | 24.84 | 22.46 | 1.39 | 0.85 | 0.28 |
| 7 | 17.36 | 21.33 | 42.12 | 1.16 | 0.44 | 0.36 |
| 8 | 19.22 | 23.76 | 21.81 | 1.23 | 0.40 | 0.25 |
| 9 | 21.93 | 22.96 | 22.12 | 1.39 | 0.48 | 0.28 |
| 10 | 22.55 | 23.81 | 21.91 | 1.41 | 0.42 | 0.25 |

**Table 4**

**Results of shear test of red ginger stalk**

| Test No. | Shear force (N) | | | Shear strength (MPa) | | |
|---|---|---|---|---|---|---|
| | Upper | Middle | Lower | Upper | Middle | Lower |
| 1 | 2.87 | 4.21 | 9.11 | 1.33 | 0.51 | 0.41 |
| 2 | 3.45 | 7.14 | 4.37 | 1.52 | 0.52 | 0.27 |
| 3 | 2.37 | 2.03 | 6.32 | 1.50 | 0.47 | 0.33 |
| 4 | 1.54 | 5.28 | 4.55 | 1.51 | 0.63 | 0.28 |
| 5 | 2.84 | 6.23 | 3.41 | 1.45 | 0.59 | 0.25 |
| 6 | 1.69 | 3.52 | 3.18 | 1.36 | 0.51 | 0.24 |
| 7 | 2.93 | 9.61 | 5.62 | 1.42 | 0.55 | 0.36 |
| 8 | 2.61 | 18.62 | 5.01 | 1.37 | 0.72 | 0.37 |
| 9 | 1.13 | 3.27 | 7.24 | 1.28 | 0.49 | 0.34 |
| 10 | 3.14 | 6.35 | 4.81 | 1.45 | 0.58 | 0.29 |

### *Results of radial compression mechanical performance test*

The radial compression mechanical performance test results of stalks of various ginger varieties are shown in Table 5 and Table 6. The average compressive forces on the upper, middle, and lower parts of the small yellow ginger stalk are 2.11 N, 20.66 N, and 28.62 N respectively, and the average compressive strengths are 0.03 MPa, 0.13 MPa, and 0.14 MPa respectively. The average compressive forces on the upper, middle, and lower parts of the red ginger stalk are 4.64 N, 18.12 N, and 22.74 N respectively, and the average compressive strengths are 0.10 MPa, 0.21 MPa, and 0.16 MPa respectively.

**Table 5**

**Results of radial compression test of small yellow ginger stalk**

| Test No. | radial compression force (N) | | | radial compression strength (MPa) | | |
|---|---|---|---|---|---|---|
| | Upper | Middle | Lower | Upper | Middle | Lower |
| 1 | 2.31 | 25.41 | 32.22 | 0.03 | 0.16 | 0.15 |
| 2 | 3.00 | 16.39 | 26.81 | 0.04 | 0.11 | 0.13 |
| 3 | 1.32 | 28.12 | 29.31 | 0.02 | 0.17 | 0.14 |
| 4 | 1.85 | 15.23 | 30.52 | 0.02 | 0.11 | 0.15 |
| 5 | 2.23 | 24.25 | 28.18 | 0.03 | 0.15 | 0.14 |
| 6 | 1.13 | 19.64 | 27.91 | 0.02 | 0.14 | 0.13 |
| 7 | 2.42 | 21.72 | 25.24 | 0.03 | 0.15 | 0.13 |
| 8 | 1.71 | 17.66 | 31.27 | 0.02 | 0.12 | 0.14 |
| 9 | 2.49 | 14.62 | 25.93 | 0.03 | 0.10 | 0.13 |
| 10 | 2.62 | 23.52 | 28.83 | 0.03 | 0.14 | 0.14 |

**Table 6**

**Results of radial compression test of red ginger stalk**

| Test No. | radial compression force (N) | | | radial compression strength (MPa) | | |
|---|---|---|---|---|---|---|
| | Upper | Middle | Lower | Upper | Middle | Lower |
| 1 | 5.63 | 15.81 | 22.21 | 0.12 | 0.20 | 0.17 |
| 2 | 3.98 | 16.52 | 20.82 | 0.08 | 0.21 | 0.16 |
| 3 | 5.22 | 20.64 | 23.67 | 0.11 | 0.24 | 0.17 |
| 4 | 5.95 | 19.91 | 21.52 | 0.13 | 0.23 | 0.16 |
| 5 | 4.71 | 17.62 | 19.86 | 0.11 | 0.20 | 0.15 |
| 6 | 4.92 | 19.54 | 19.08 | 0.10 | 0.23 | 0.15 |
| 7 | 3.53 | 13.69 | 22.72 | 0.07 | 0.19 | 0.16 |
| 8 | 5.31 | 19.82 | 24.16 | 0.11 | 0.22 | 0.16 |
| 9 | 2.9 | 18.92 | 27.97 | 0.06 | 0.21 | 0.18 |
| 10 | 4.24 | 18.76 | 25.39 | 0.09 | 0.22 | 0.17 |

### *Results of tensile mechanical performance test*

The tensile mechanical performance test results of stalks of various ginger varieties are shown in Table 7 and Table 8. The average tensile forces on the upper, middle, and lower parts of the small yellow ginger stalk are 26.64 N, 69.69 N, and 37.51 N respectively, and the average tensile strengths are 1.94 MPa, 2.25 MPa, and 1.09 MPa respectively. The average tensile forces on the upper, middle, and lower parts of the red ginger stalk are 13.53 N, 40.41 N, and 35.44 N respectively, and the average tensile strengths are 3.71 MPa, 4.31 MPa, and 1.86 MPa respectively.

**Table 7**

**Results of tensile test of small yellow ginger stalk**

| Test No. | tensile force (N) | | | tensile strength (MPa) | | |
|---|---|---|---|---|---|---|
| | Upper | Middle | Lower | Upper | Middle | Lower |
| 1 | 29.54 | 78.36 | 36.82 | 2.33 | 2.55 | 1.07 |
| 2 | 25.62 | 68.21 | 42.71 | 1.75 | 2.18 | 1.28 |
| 3 | 23.78 | 74.39 | 39.76 | 1.59 | 2.45 | 1.18 |
| 4 | 32.83 | 70.11 | 33.63 | 2.42 | 2.40 | 0.94 |
| 5 | 27.42 | 65.76 | 40.66 | 2.16 | 1.96 | 1.20 |
| 6 | 24.53 | 67.35 | 35.43 | 1.75 | 2.18 | 1.02 |
| 7 | 28.52 | 63.82 | 37.54 | 2.18 | 1.73 | 1.11 |
| 8 | 23.21 | 69.82 | 35.92 | 1.58 | 2.33 | 1.03 |
| 9 | 24.76 | 70.28 | 38.74 | 1.69 | 2.41 | 1.14 |
| 10 | 26.17 | 68.83 | 33.86 | 1.95 | 2.30 | 0.96 |

Table 8

**Results of tensile test of red ginger stalk**

| Test No. | tensile force (N) | | | tensile strength (MPa) | | |
|---|---|---|---|---|---|---|
| | Upper | Middle | Lower | Upper | Middle | Lower |
| 1 | 14.37 | 45.38 | 32.81 | 3.85 | 4.94 | 1.77 |
| 2 | 11.65 | 38.63 | 41.65 | 3.50 | 4.06 | 2.14 |
| 3 | 14.94 | 43.82 | 33.68 | 3.93 | 4.66 | 1.79 |
| 4 | 10.96 | 37.81 | 38.92 | 3.42 | 3.98 | 2.03 |
| 5 | 13.68 | 40.03 | 30.55 | 3.60 | 4.31 | 1.61 |
| 6 | 15.85 | 42.64 | 40.71 | 3.95 | 4.54 | 2.11 |
| 7 | 11.23 | 36.15 | 32.95 | 3.51 | 3.85 | 1.76 |
| 8 | 13.27 | 37.52 | 35.43 | 3.56 | 4.09 | 1.86 |
| 9 | 16.63 | 39.97 | 31.52 | 4.30 | 4.35 | 1.62 |
| 10 | 12.69 | 42.18 | 36.16 | 3.46 | 4.34 | 1.87 |

***Results of ginger stalk pull-out force test***

The pull-out force test results of stalks of various ginger varieties are shown in Table 9. The average pull-out force of small yellow ginger is 61.27 N, and the average pull-out force of red ginger is 68.45 N. According to the results of the tensile test on ginger stalk, the average tensile force on the middle part of the ginger stalk is 69.69 N, which is greater than its average pull-out force of 61.27 N. The average tensile force on the middle part of a single red ginger stalk is 40.41 N, and its average number of stalks is about 4. Since the tensile forces of multiple stalks can be superimposed, the actual overall tensile force of its stalks is much greater than its average pull-out force of 68.45 N. From this, it can be seen that the tensile force on the middle part of both types of ginger stalks is greater than their average pull-out force, and there will be no situation where the stalks are pulled broken, resulting in missed harvesting.

Table 9

**Results of ginger stalk pull-out force test.**

| Test No. | pull-out force of small yellow ginger (N) | pull-out force of red ginger (N) |
|---|---|---|
| 1 | 58.18 | 65.47 |
| 2 | 64.32 | 66.28 |
| 3 | 60.94 | 70.56 |
| 4 | 61.52 | 72.08 |
| 5 | 61.38 | 67.86 |

## CONCLUSIONS

(1) According to the biophysical parameter testing experiment of ginger, the average length of the small yellow ginger stalk is 643.72 mm, and the average length of the rhizome is 135.25 mm; the average length of the red ginger stalk is 770.53 mm, and the average length of the rhizome is 123.75 mm. The moisture content of the stalks of small yellow ginger and red ginger increases sequentially from top to bottom, and the moisture content of the rhizomes of red ginger is significantly lower than that of small yellow ginger. Compared to the small yellow ginger with only one main stalk, the average number of stalks in red ginger is about 4, and the stalk density is higher, which can improve clamping stability and reduce the risk of falling off.

(2) According to the stalk shear test, the shear strength of the upper, middle, and lower parts of the red ginger stalk is greater than that of the small yellow ginger stalk. The maximum shear force of red ginger stalk occurs in the middle part, with an average of 6.63 N, and the average shear strength of the middle part of the stalk is 0.56 MPa. From the actual needs of clamping operations, the middle part has both relatively high shear force and moderate shear strength, and has good clamping adaptability.

(3) According to the stalk radial compression test, the compressive strength of the upper, middle, and lower parts of the red ginger stalk is greater than that of the small yellow ginger stalk. The maximum radial compressive strength of red ginger stalk occurs in the middle part, with an average of 0.21 MPa.

(4) According to the stalk tensile test, the tensile strength of the upper, middle, and lower parts of the red ginger stalk is greater than that of the small yellow ginger stalk. From this, it can be seen that red ginger stalks have overall higher tensile strength and stronger fracture resistance, making them more suitable for clamp-pull mechanical harvesting. Moreover, the tensile force and tensile strength of the middle of ginger stalks are both highest, with the best resistance to clamping damage, making it more suitable as the clamping position.

(5) According to the stalk pull-out force test, the average pull-out force of small yellow ginger is 61.27 N, and the average pull-out force of red ginger is 68.45 N. the tensile force on the middle part of both types of ginger stalks is greater than their average pull-out force, and there will be no situation where the stalks are pulled broken, resulting in missed harvesting.

In summary, the physical and mechanical properties of red ginger are superior to those of small yellow ginger, and it is less likely to be damaged during harvesting, making it more suitable for clamp-pull harvesting. The mechanical properties of the middle part of red ginger stalks are overall superior to those of the upper and lower parts, so the middle part of the stalks can be prioritized as the clamping position during the clamp-pull harvesting process. The physical parameters and mechanical properties of two types of ginger stalks will provide a basis for the design of ginger clamping mechanisms.

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