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DIFFERENCES IN THE PHYSICAL AND MECHANICAL PROPERTIES OF DIFFERENT VARIETIES OF LOTUS ROOT

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KEYWORDS

physical properties, mechanical properties, lotus root.

ABSTRACT

The traditional way of harvesting lotus root consumes a lot of labor and has low harvesting efficiency. Therefore, it is necessary to explore the automated harvesting device of lotus root. And the physical and mechanical properties of lotus root are crucial for the design of harvesting device. In this study, the mechanical properties of "Baoying Beauty Red" and "E-Lian No.7" lotus roots in different positions were tested by compression, bending and tensile methods. The results showed that the mechanical properties of "Baoying Beauty Red" were better than those of "E-Lian No.7", which were not easy to be damaged during harvesting, and the minimum compressive strength of "Baoying Beauty Red" was 4.04 MPa, the minimum bending force of lotus root breakage was 97 N, and the minimum tensile force was 182.73 N.

INTRODUCTION

Lotus root has a large medicinal and economic value, and its roots, stems, leaves, flowers and fruit can be used as medicine, and also can be made lotus root powder, lotus root juice and many other lotus root products. The planting area of lotus root in China is up to more than 4 million hectares, which is one of the largest aquatic vegetables in the planting area, and the cropping pattern was studied by Wang et al. (2013). At present, the lotus root industry is developing rapidly and the lotus root planting area shows a steady growth trend, as seen in the work of Yusufujiang et al. (2023). Although the planting and management of lotus root is relatively easy, the whole process of growth, development and maturation of lotus root is completed in the silt. Lotus roots grow randomly in the silt with no apparent pattern. Deep-water roots were deeper into the mud, usually more than 1 m. Shallow-water roots were shallower, usually 30 to 50 cm. How to judge the location and distribution of lotus root during harvesting requires rich practical experience. Thus it is difficult to complete the lotus root harvesting operation in the silt manually, and the harvesting efficiency is low. To improve the efficiency of lotus root harvesting, it is urgent to promote the mechanization of lotus root harvesting. Mechanical harvesting of lotus root is divided into three types: mechanical, jet, and combined mechanical and jet. Of the three ways jet is less damaging according to the work of Dellaripa & Bailard (1986) and Bailard & Camperman (1983). However, the jet harvesting process may also cause damage to the lotus root. Hence, it is necessary to experimentally investigate the physical and mechanical properties (Aristizabal et al., 2003) of lotus root to provide reference for mechanized harvesting (Zeng et al., 2021; Hu et al., 2018).

At present, most researches on lotus root still remain on the appearance and nutritional value, and the study of mechanical properties of lotus root can only been seen in the work of Xiao et al. (2016). However, there are no comparative studies on the mechanical properties of lotus root varieties, just like the work done on bamboo by Gomes et al. (2021). The purpose of this study was to obtain different physical and mechanical parameters of lotus root under different mechanical treatments, such as those by Feng et al. (2022) and Xue et al. (2022), and select suitable varieties to provide theoretical basis for the design of lotus root harvesting equipment.

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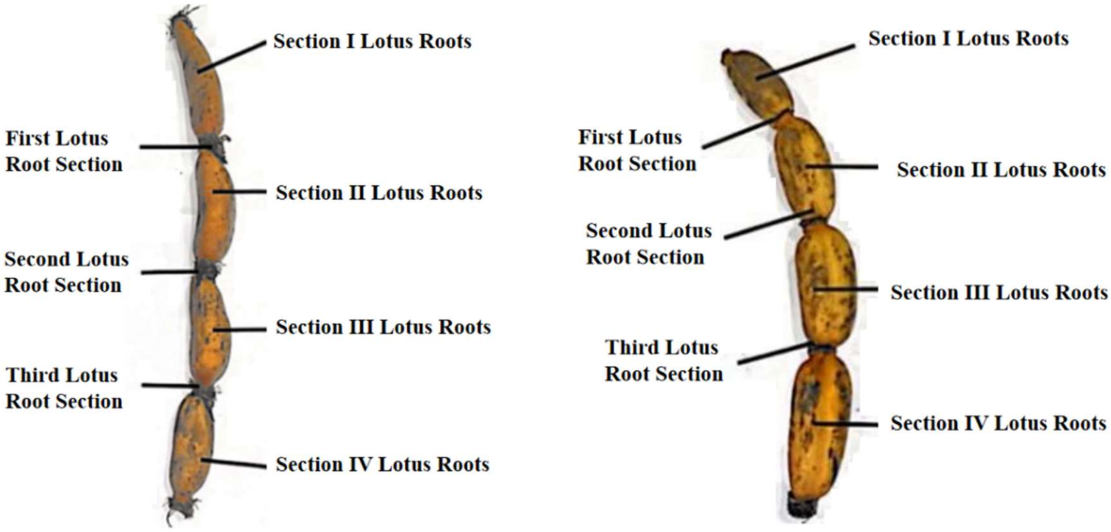
MATERIAL AND METHODS

Materials

The experimental materials were selected from two varieties of lotus root, "Baoying Beauty Red" and "E-Lian No.7", which are commonly grown in China (Yang et al., 2020). The lotus root should be selected in such a way that the length and thickness of each lotus root is not too different, and it is thick and strong, without damage or cracks (Mohit & Selvan, 2019). Before the start of the experiment, it is necessary to wash the silt from each lotus root and remove the branches as well as the roots. The structure of a typical lotus root of the two species and the names defined for each part are shown in Figure 1.



(a) Baoying Beauty Red (b) E-Lian No.7

FIGURE 1. Typical lotus root structure of the two species and the names of the parts.

Sample preparation

Compression test samples

The compression test of lotus root is mainly divided into compression of lotus root body and compression of lotus root flesh.

According to the existing literature (Guo, 2015), the average compressive strength of Section I Lotus Roots is the smallest. Therefore, we took 5 pieces of "Baoying Beauty Red" and 5 pieces of "E-Lian No.7", and took Section I Lotus Roots of each variety as a sample for the lotus root body compression tests.

According to the existing literature (Showkat et al., 2021), the axial compressive strength of the outer flesh of the lotus root is slightly less than the radial compressive strength, and the radial compressive strength of the flesh of the heart is less than the axial compressive strength. So the compressive strength experiments were carried out on the outer flesh of the lotus root in the axial direction and the heart flesh in the radial direction. And 10 pieces of each variety of lotus root, namely, "Baoying Beauty Red" and "E-Lian No. 7", were taken with a knife as shown in Figure 2. The samples are rectangular, the range of length was 7.24 cm to 12.36 cm, the range of widths was 6.58 cm to 11.42 cm, the range of height was 5.72 cm to 13.52 cm.

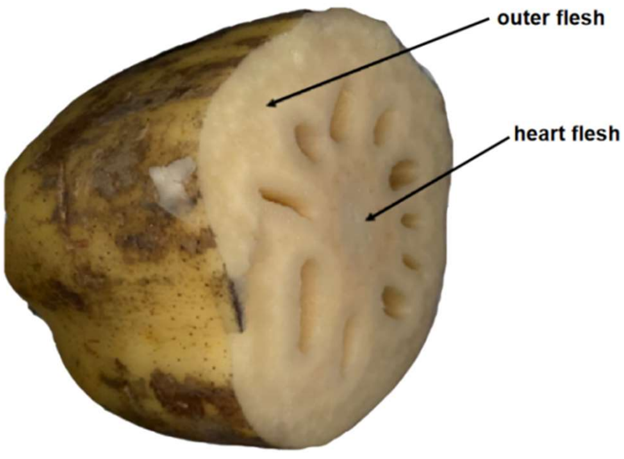


FIGURE 2. Schematic diagram of sampling location of lotus root.

Bending test samples

Five lotus roots of each variety were taken, and each branch of lotus root were broken in the middle of the section of Lotus Roots, containing First Lotus Root Section, Second Lotus Root Section and Third Lotus Root Section.

Tensile test samples

Nine lotus roots of each variety were taken, and a 50 mm length of the root body was retained on both sides centered on each root node. For each variety, three specimens each containing the first, second and third root nodes were obtained.

Lotus root size and moisture content

Lotus root contains a large amount of moisture, but the moisture content of each part is not uniform and constant. It mainly related to the species of lotus root, the characteristics of the organs and tissues themselves (Kohyama et al., 2009) and the environmental conditions (Ercisli et al., 2011). The moisture content of the lotus root was measured by using a blower drying oven and an electronic scale.

Measure the dimensions of the first, second, third and fourth sections of two kinds of lotus roots with vernier calipers and tape measure respectively. Weigh the mass of Petri dish with electronic scale(m_0); cut one lotus root slice from the front, middle and back of each section of lotus root and put the three slices of lotus root cut out from each section into the same Petri dish, and then weigh the Petri dish along with the total mass of lotus root slices with electronic scale(m_1); put the Petri dish containing lotus root slices into the drying oven, adjust the temperature of the drying oven to 80°, and dry it until the results of the two mass weighings no longer change. the dried lotus root is shown in Figure 3, and weighed the petri dish together with the lotus root slices(m_2). The average moisture content of different varieties of lotus root was calculated by using the formula (Zhou, 1994).

$$\mathbf{W} = \frac{\mathbf{m_1 - m_2}}{\mathbf{m_1 - m_0}} \times \mathbf{100\%}$$

Where:

W = moisture content of Lotus root (%);

$\mathbf{m_1}$ = mass of root slices and petri dishes before drying (g),

$\mathbf{m_2}$ = mass of root slices and petri dishes after drying (g),

$\mathbf{m_0}$ = mass of petri dishes (g).

FIGURE 3. Measurement of moisture content of lotus root.

Handpi tensile pressure tester

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

Compression mechanical properties

As shown in Figure 4, for the lotus root body compression test, the first section of the lotus root body of each species was placed on the compression fixture and the fixture bolts were tightened. The compression experiment was carried out on the lotus root body by using a 5mm cylindrical indenter, the loading rate was 10 mm/min.

FIGURE 4. Lotus root body compression test.

FIGURE 5. Lotus root flesh compression test.

Lotus root body flesh compression tests were carried out on the tester, as shown in Figure 5. The indenter used was a flat-topped cylindrical indenter with a diameter of 15 mm, the loading rate was 10 mm/min, the loading displacement was 4 mm.

Bending mechanical properties

The tests were carried out on the tester, as shown in Figure 6, using three-point bending to find out the bending strength and flexural modulus of elasticity of the lotus root section. The span was set to 80 mm for the bending experiments. The indenter used was 50 mm wide and 12 mm thick, and the loading speed was 10 mm/min.

FIGURE 6. Lotus root bending test.

FIGURE 7. Lotus root tensile test.

Tensile mechanical properties

The tests were carried out on the tester, as shown in Figure 7, where both ends of the lotus root were clamped with clamps, and the wire was clamped using the tester tensile fixture to start the tensile test (Zhou, 2011). The loading rate of the experiment was 10 mm/min.

RESULTS AND DISCUSSION

Lotus root size and moisture content

The size and average moisture content of each variety of lotus root are shown in Table 1 and Table 2. The results showed that the average size of "E-lian No.7" was larger than that of "Baoying Beauty Red". The moisture content of the first, second, third and fourth sections of the two varieties of lotus root were reduced in order, with the average moisture content of "Baoying Beauty Red" being 63.99% and that of "E-lian No.7" being 76%. The average moisture content of "Baoying Beauty Red" was 63.99%, and the average moisture content of "E-lian No.7" was 76.95%.

TABLE 1. Mean size and moisture content of "Baoying Beauty Red".

Lotus root position	Length (mm)	Width (mm)	Height (mm)	Mean moisture content (%)
Section I	87	50	44	65.24
Section II	106	56	47	64.14
Section III	111	58	48	63.56
Section IV	118	51	46	62.04

TABLE 2. Mean size and moisture content of "E-Lian No. 7".

Lotus root position	Length (mm)	Width (mm)	Height (mm)	Mean moisture content (%)
Section I	132	64	55	78.93
Section II	136	78	64	77.65
Section III	165	88	75	76.42
Section IV	192	80	64	74.81

Compressive mechanical properties

Compression of lotus root body

The results of the compressive force on the body (Li et al., 2022) of two varieties of lotus root are shown in Table 3 and Table 4, which show that the average value of the maximum destructive force of the first section of the body of the lotus root of "Baoying Beauty Red" was 84.21 N. The average value of the compressive strength was 4.29 MPa, and the range of the compressive strength was 4.04 to 4.54 MPa. The average value of the maximum destructive force of the first section of lotus root body of "E-Lian No.7" was 62.01 N. The average value of compressive strength was 3.16 MPa, and the range of compressive strength was 2.98 to 3.31 MPa. By comparison, "Baoying Beauty Red" has a higher compressive strength than "E-Lian No.7" lotus root.

TABLE 3. Results of lotus root body compression test of "Baoying Beauty Red".

Serial number	Force (N)	Area (mm^2)	Compressive strength (MPa)
1	83.45	19.63	4.25
2	79.32	19.63	4.04
3	89.25	19.63	4.54
4	83.64	19.63	4.26
5	85.39	19.63	4.35

TABLE 4. Results of lotus root body compression test of "E-Lian No.7".

Serial number	Force (N)	Area (mm^2)	Compressive strength (MPa)
1	65.13	19.63	3.31
2	58.59	19.63	2.98
3	62.89	19.63	3.20
4	60.24	19.63	3.07
5	63.18	19.63	3.22

The destructive force of "Baoying Beauty Red" is significantly larger, thus resulting in the larger compressive strength. While the destructive force is determined by many factors, and one possible factor is the moisture content mentioned above. As shown in Table 1 and Table 2, the average moisture content of "Baoying Beauty Red" is comparatively small, and less moisture internally may lead to stronger structure. However, this study did not go deeper into this aspect, because of the purpose of the study is choosing mechanized varieties.

Compression of lotus root flesh

The results of the compressive strength and modulus of elasticity of the flesh of the two lotus root roots are shown in the table below. The average value of the maximum axial destructive force of the flesh of the outer part of "Baoying Beauty Red" was 91.26N. The average value of the compressive strength was 0.90 MPa, and the range of the compressive strength was 0.69 to 1.20 MPa. The average value of modulus of elasticity was 1.83 MPa. The average value of the maximum radial destructive force of the flesh in the heart was 69.04 N. The average value of the compressive strength was 0.82 MPa, and the range of compressive strength was 0.63 to 1.20 MPa. The average value of the modulus of elasticity was 2.34 MPa. The average value of the maximum axial destructive force of the external flesh of "E-Lian No.7" was 66.28N. the average value of the compressive strength was 0.74 MPa, and the range of the compressive strength was 0.64 to 0.83 MPa. The average value of the modulus of elasticity was 1.66 MPa. The average value of the maximum radial destructive force of the flesh in the heart was 73.62 N. The average value of the compressive strength was 0.72 MPa, and the range of the compressive strength was 0.63 to 0.81 MPa. The average value of the modulus of elasticity was 1.51 MPa.

TABLE 5 Results of axial compression test of external flesh of "Baoying Beauty Red".

Serial number	Length (mm)	Width (mm)	Height (mm)	Force (N)	Compressive strength (MPa)	Modulus of elasticity (MPa)
1	9.74	7.42	5.72	62.99	0.87	1.24
2	7.50	7.46	7.48	54.16	0.97	1.81
3	12.36	9.50	10.38	81.82	0.69	1.79
4	12.28	11.42	8.64	102.22	0.73	1.58
5	9.38	8.98	6.92	81.78	0.97	1.68
6	10.42	7.96	10.52	71.54	0.86	2.26
7	14.14	10.88	6.48	184.64	1.20	1.94
8	10.32	8.64	7.76	93.65	1.05	2.04
9	11.68	11.08	11.48	99.19	0.77	2.21
10	11.38	7.58	7.32	80.63	0.93	1.70

TABLE 6 Results of the radial compression test of heart flesh of "Baoying Beauty Red".

Serial number	Length (mm)	Width (mm)	Height (mm)	Force (N)	Compressive strength (MPa)	Modulus of elasticity (MPa)
1	7.24	6.58	11.28	46.62	0.98	2.76
2	8.90	8.48	11.28	63.44	0.84	2.37
3	9.74	8.14	11.76	51.83	0.65	1.91
4	14.18	8.08	13.52	80.52	0.70	2.37
5	8.62	7.68	12.12	67.67	1.02	3.09
6	10.08	9.32	11.28	59.15	0.63	1.78
7	8.72	8.04	12.22	59.45	0.85	2.60
8	13.42	10.96	13.12	97.54	0.66	2.16
9	10.22	9.32	8.52	114.51	1.20	2.56
10	11.38	6.58	10.58	49.64	0.66	1.75

TABLE 7. Results of axial compression test of external flesh of "E-Lian No.7".

Serial number	Length (mm)	Width (mm)	Height (mm)	Force (N)	Compressive strength (MPa)	Modulus of elasticity (MPa)
1	10.96	7.44	9.45	61.15	0.75	1.77
2	7.72	11.21	6.42	70.12	0.81	1.30
3	10.13	8.31	7.99	69.84	0.83	1.66
4	10.22	8.99	10.45	66.14	0.72	1.88
5	11.05	7.85	6.89	59.87	0.69	1.19
6	10.18	9.57	8.56	78.94	0.81	1.73
7	10.33	9.12	9.42	60.32	0.64	1.50
8	7.86	11.56	6.01	67.24	0.74	1.11
9	7.18	11.94	8.65	66.87	0.78	1.68
10	9.50	9.79	10.40	62.34	0.67	2.74

TABLE 8. Results of the radial compression test of heart flesh of "E-Lian No.7".

Serial number	Length (mm)	Width (mm)	Height (mm)	Force (N)	Compressive strength (MPa)	Modulus of elasticity (MPa)
1	10.77	9.28	8.03	70.97	0.71	1.43
2	9.74	11.24	8.13	74.45	0.68	1.38
3	13.79	7.12	6.85	76.56	0.78	1.34
4	11.14	8.74	7.56	78.84	0.81	1.53
5	14.10	7.79	10.07	69.21	0.63	1.59
6	12.97	7.66	9.55	71.53	0.72	1.72
7	15.73	6.60	5.97	71.65	0.69	1.03
8	9.58	10.70	9.36	74.85	0.73	1.71
9	8.72	10.72	10.69	71.98	0.77	2.06
10	10.37	10.34	7.50	76.11	0.71	1.33

In the two varieties of lotus root flesh compression tests (Desmet et al., 2022), with the increasing pressure, compression displacement increases, and moisture was continuously pressed out. When a certain value is reached, the flesh along the diagonal cross-section of the cube appeared cracks, which is in line with the characteristics of the compression damage section of brittle materials. Therefore it is concluded that "Baoying Beauty Red" and "E-Lian No.7" lotus root body flesh are brittle materials.

Bending mechanical properties

As shown in Table 9 and Table 10, the average value of the maximum bending force of "Baoying Beauty Red" lotus root was 133.28 N. The average value of the bending strength was 2.11 MPa, and the range of bending strength was 1.36 to 2.65 MPa. The average bending modulus of elasticity was 9.70 MPa, and the range of modulus of elasticity was 5.63 to 14.49 MPa. The average bending strength of "E-Lian No.7" lotus root was 327.68 N. The average value of the bending strength was 2.13 MPa, and the range of the bending strength was 1.29 to 2.73 MPa. The average bending modulus of elasticity was 7.30 MPa, and the range of modulus of elasticity was 4.25 to 11.68 MPa.

Comparison shows that the bending strength of "E-Lian No.7" is similar to that of "Baoying Beauty Red", while the bending modulus of "E-Lian No.7" is smaller than that of "Baoying Beauty Red", and "Baoying Beauty Red" has better lotus root section bending resistance.

TABLE 9. Results of lotus root bending test of "Baoying Beauty Red".

Serial number	Section	Diameter (mm)	Force (N)	Bending strength (MPa)	Modulus of elasticity (MPa)
1	1	23.92	125.87	1.87	8.35
	2	22.08	113.16	2.14	10.35
	3	21.02	101.51	2.23	11.22
2	1	21.76	104.33	2.06	10.11
	2	22.76	138.53	2.39	11.22
	3	19.54	97.22	2.65	14.49
3	1	25.58	111.45	1.36	5.63
	2	27.06	174.04	1.79	7.05
	3	24.92	105.71	1.39	5.91
4	1	21.64	109.42	2.20	10.80
	2	24.16	173.48	2.51	11.03
	3	22.98	141.14	2.37	10.99
5	1	23.12	136.82	2.26	10.34
	2	26.74	212.23	2.26	9.01
	3	24.62	154.31	2.11	9.11

TABLE 10. Results of lotus root bending test of "E-Lian No.7".

Serial number	Section	Diameter (mm)	Force (N)	Bending strength (MPa)	Modulus of elasticity (MPa)
1	1	29.47	210.15	1.67	6.05
	2	34.25	486.16	2.47	7.68
	3	32.81	375.33	2.16	7.04
2	1	32.07	208.41	1.29	4.25
	2	33.17	439.41	2.45	7.88
	3	31.37	319.45	2.11	7.17
3	1	29.91	315.08	2.40	8.55
	2	32.62	420.63	2.47	8.07
	3	24.92	207.32	2.73	11.68
4	1	29.70	236.73	1.84	6.61
	2	35.05	423.07	2.00	6.09
	3	30.73	335.31	2.35	8.17
5	1	32.05	322.16	1.99	6.63
	2	33.40	339.12	1.85	5.92
	3	29.66	276.89	2.16	7.77

Tensile Mechanical Properties

As shown in the table below, the average tensile force of "Baoying Beauty Red" lotus root section was 213.90 N, and the range of tensile force was 182.73 to 241.70 N. The average tensile strength was 0.53 MPa, and the range of tensile strength was 0.49 to 0.62 MPa. The average tensile force of lotus root section of "E-Lian No.7" was 334.47 N, and the range of tensile force was 264.20 to 398.25 N. The average tensile strength was 0.49 MPa, and the range of tensile strength was 0.47 to 0.52 MPa.

TABLE 11. Results of lotus root section tensile test of "Baoying Beauty Red".

Lotus root section	Serial number	Diameter (mm)	Area (mm^2)	Force (N)	Tensile strength (MPa)
First lotus root section	1	24.80	483.05	249.10	0.52
	2	21.18	352.32	187.98	0.53
	3	21.38	359.01	182.73	0.51
Second lotus root section	4	23.45	431.89	210.87	0.49
	5	22.19	386.73	198.25	0.51
	6	20.56	331.00	188.67	0.57
Third lotus root section	7	23.78	444.13	195.42	0.44
	8	21.53	364.06	203.87	0.56
	9	25.16	497.18	308.25	0.62

TABLE 12. Results of lotus root section tensile test of "E-Lian No.7".

Lotus root section	Serial number	Diameter (mm)	Area (mm^2)	Force (N)	Tensile strength (MPa)
First lotus root section	1	26.75	562.13	264.20	0.47
	2	26.55	553.81	287.98	0.52
	3	27.10	577.00	282.73	0.49
Second lotus root section	4	28.72	647.65	310.87	0.48
	5	32.85	847.34	398.25	0.47
	6	31.78	793.20	388.67	0.49
Third lotus root section	7	32.73	841.32	395.42	0.47
	8	28.87	654.65	333.87	0.51
	9	29.20	669.71	348.25	0.52

Comparison shows that the tensile strength of "Baoying Beauty Red" is larger than that of "E-Lian No. 7". "The average tensile strength of the first root section of "Baoying Beauty Red" was 0.52 MPa, and the second was 0.52 MPa, and the third was 0.54 MPa. The average tensile strength of the first root section of "E-Lian No.7" was 0.49 MPa, and the second was 0.48 MPa, and third was 0.50 MPa. The experiments showed that there was little correlation between the location of the root section and the tensile strength of the two varieties of lotus roots.

CONCLUSIONS

The moisture content of "Baoying Beauty Red" and "E-Lian No.7" decreased in each section, and the average moisture content of "Baoying Beauty Red" was less than that of "E-Lian No.7".

The compressive strength of lotus root body of "Baoying Beauty Red" ranged from 4.04 to 4.54 MPa, and that of "E-Lian No.7" ranged from 2.98 to 3.31 MPa, according to the compression test of lotus root body.

According to the compression test of lotus root flesh, the range of axial compressive strength of outer flesh of "Baoying Beauty Red" was 0.69 to 1.20 MPa, and the average value of modulus of elasticity was 1.83 MPa. The range of radial compressive strength of heart flesh was 0.63 to 1.20 MPa, and the average value of modulus of elasticity was 2.34 MPa. The range of the axial compressive strength of the outer flesh of "E-Lian No.7" was 0.64 to 0.83 MPa, and the average value of the modulus of elasticity was 1.66 MPa. The range of the radial compressive strength of the flesh of the heart was 0.63 to 0.81 MPa, and the average value of the modulus of elasticity was 1.51 MPa.

The bending strength of "Baoying Beauty Red" root section ranged from 1.35 to 2.65 MPa, and the bending modulus of elasticity ranged from 5.63 to 14.49 MPa. The bending strength of lotus root section of "E-Lian No.7" ranged from 1.29 to 2.73 MPa, and the bending modulus of elasticity ranged from 4.25 to 11.68 MPa.

The tensile strength of lotus root joints of "Baoying Beauty Red" ranged from 0.49 to 0.62 MPa, and that of "E-Lian No.7" ranged from 0.47 to 0.52 MPa.

The mechanical properties of "Baoying Beauty Red" are better than those of "E-Lian No.7", and it is not easy to be damaged during harvesting. The minimum bending force to fracture the lotus root nodule of "Baoying Beauty Red" was 97 N, and the minimum tensile force was 182.73 N. The above study selected lotus root varieties suitable for mechanized harvesting.

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