

DESIGN AND EXPERIMENTAL OPTIMIZATION OF A CONTINUOUS VIBRATION-BASED *LYCIUM BARBARUM* L. HARVESTING DEVICE

枸杞连续采收振动装置设计与试验优化

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ABSTRACT

Compared with manual harvesting of *Lycium barbarum*, existing large-scale harvesters have achieved a certain degree of efficiency improvement. Nevertheless, their intermittent operation mode remains a bottleneck restricting overall harvesting performance. To address this issue, a continuous vibration-based *L. barbarum* harvesting device was developed in this study. Plackett–Burman experiments indicated that vibration angle, vibration frequency, and the spacing between the upper and lower vibrating rods were the primary factors affecting the harvesting performance. Further parameter optimization experiments were carried out by considering the harvesting rate of ripe fruits, the mis-harvesting rate of unripe fruits, and the damage rate of ripe fruits. The optimal parameter combination was determined as a vibration angle of 46°, a vibration frequency of 9 Hz, and a spacing of 62 mm between the upper and lower vibrating rods. Based on these parameters, performance verification tests were conducted. The results showed that the harvesting rate of ripe fruits reached 85.40%, the mis-harvesting rate of unripe fruits was 4.61%, and the damage rate of ripe fruits was 3.19%. These findings provide technical and equipment support for the development of continuous mechanized harvesting of *L. barbarum*.

摘要

相较于人工采摘枸杞，现有大型枸杞采收机能够在一定程度上提高采收效率，但受限于其间歇式的作业方式，作业效率仍有待进一步提高，因此，本研究设计了一种枸杞连续采收振动装置。通过 Plackett-Burman 试验分析表明，影响连续作业采收效果的主要因素为振动角度、振动频率和上下层杆间距。进一步通过参数优化试验，从成熟果实采净率、未熟果误采率和熟果损伤率三个方面对上述关键参数进行优化，确定最优参数组合为：振动角度 46°、振动频率 9Hz、上下层振动杆间距 62mm。基于此对枸杞连续采收振动装置的性能进行试验验证，结果表明，熟果采摘率为 85.40%，未熟果误采率为 4.61%，熟果损伤率为 3.19%，为枸杞连续机械化采收的发展提供了技术与装备支撑。

INTRODUCTION

Lycium barbarum L. (*L. barbarum*) has indeterminate inflorescences and continuous flowering and fruiting (Kulczyński B., Gramza-Michałowska A., 2016; Yu et al., 2023; Liang et al., 2024). Ripe *L. barbarum* fruits are small, densely clustered, and ovoid to elliptical (Ma et al., 2022; Cao et al., 2024). Harvesting is seasonal and largely manual, and the increasing gap between labor supply and demand limits production efficiency and economic returns (Mei et al., 2024; Liu et al., 2025).

Since *L. barbarum* is mainly cultivated in Ningxia, Gansu, Qinghai, and Xinjiang in China, related mechanization research has been primarily conducted in China (Zhao et al., 2016; Skenderidis et al., 2018; Principal et al., 2022; Ma et al., 2023). The vibration harvesting method, owing to its high picking efficiency and superior performance in detaching ripe fruits, has become the mainstream approach for the mechanized harvesting of *L. barbarum* (Liu et al., 2025; Wang et al., 2024). According to differences in operation scale and application scenarios, vibration harvesting equipment can be categorized into two types: portable and large self-propelled.

The portable *L. barbarum* harvester is suitable for small- and medium-scale densely planted orchards, with relatively low agronomic requirements but a higher dependence on manual operation. In contrast, the large self-propelled inter-row harvester is designed for large-scale standardized plantations and offers high operational efficiency; however, it requires a higher degree of agronomic standardization and still has room for improvement in reducing fruit damage rate and impurity content (Li et al., 2024; Liu et al., 2025; Yang et al., 2025; Su et al., 2025). Zhang et al. (2018) developed a portable *L. barbarum* vibration-based harvester that achieved a 93.52% ripe fruit harvesting rate and 5.5 times the efficiency of manual picking. Zhang et al. (2015) developed the 4GZ-1500A self-propelled *L. barbarum* harvester using four rows of vibrating rods, reaching 5.43 times the efficiency of manual picking. Mei et al. (2024) designed a *L. barbarum* harvester with arrayed vibration units and optimized parameters for different harvests, achieving an 88.95% harvesting rate and about 26.9 times the efficiency of manual picking.

Both handheld and large self-propelled harvesters can improve harvesting efficiency, but their performance is limited by operator fatigue and intermittent operation. To overcome these issues, this study developed a continuous vibration-based *L. barbarum* harvesting device. Plackett-Burman experiments identified the main factors affecting ripe fruit harvesting, and further parameter optimization determined the optimal settings based on ripe fruit harvesting rate, unripe fruit harvesting rate, and ripe fruit damage rate, providing technical and equipment support for continuous mechanized harvesting.

MATERIALS AND METHODS

Experimental condition

The experiment was carried out at an ecological *L. barbarum* science and technology demonstration base located in Guyuan City (106°15'25"E, 36°00'36"N), Ningxia Hui Autonomous Region, China. The base employs hedge planting cultivation (Fig. 1), with level land and standardized planting practices, making it suitable for mechanized operations.



Fig. 1 - Hedge planting mode of *L. barbarum*

To develop a continuous vibration-based *L. barbarum* harvesting device and improve its adaptability to different varieties, key agronomic parameters of multiple fruit-bearing *L. barbarum* varieties were investigated, as shown in Table 1. It was found that the planting height of *L. barbarum* at the base was mostly below 2 m, and for all varieties, the first layer of fruiting branches was wider than the second layer, indicating a denser distribution of fruits in the lower layer. Compared with other varieties, Keqi No. 1 and No. 2 exhibited more vigorous branch growth and denser branching, resulting in greater plant height. Since plant height is defined as the distance from the highest point of the plant to the ground, the design primarily considers layer height and layer width. As these parameters vary among different *L. barbarum* varieties, the continuous vibration-based harvesting device should be equipped with adjustable operational parameters to accommodate varying agronomic conditions.

Table 1

Agronomic parameters of hedgerow cultivation mode

Variety	Plant height [m]	First layer		Second layer	
		Height [m]	Width [m]	Height [m]	Width [m]
Ningqi No.1	1.70	0.73	0.98	1.27	0.76
Ningqi No.5	1.52	0.77	1.11	1.33	0.82
Ningqi No.6	1.70	0.67	1.31	1.18	1.03
Ningqi No.7	1.78	0.67	1.61	1.24	1.22
Ningqi No.8	1.74	0.73	1.24	1.15	1.16
Ningqi No.10	1.69	0.89	1.11	1.22	1.28
Keqi No.1	2.06	0.78	1.47	1.42	1.20
Keqi No.2	2.07	0.98	1.39	1.39	1.36

Continuous canopy vibration device

The continuous canopy vibration device is shown in Fig. 2, and its mechanism motion diagram is presented in Fig. 3. The aluminum profile is used as the mounting frame for the vibration mechanism, allowing it to rotate with the motor to achieve continuous harvesting. The vibration mechanism is arranged in two layers. Both layers of rods are evenly distributed on the mounting disc, with the upper layer fixed directly to the aluminum frame and rotating synchronously. The lower layer has a different structure: its rod mounting frame is fixed to the aluminum frame, while a rotating bearing disc is installed below, enabling the lower vibration rods and their mounting disc to rotate freely. The motor is fixed to the aluminum frame via a motor mounting bracket, and when it rotates, it drives the lower vibration rods to oscillate through a crank mechanism, generating vibration.

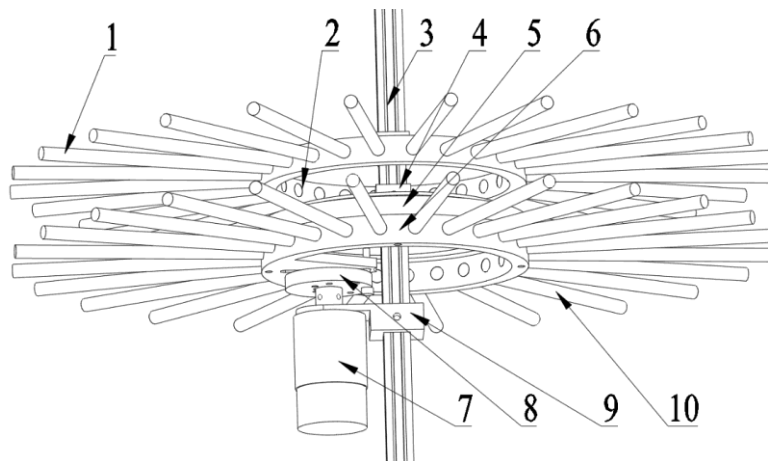


Fig. 2 - Continuous canopy vibration device

1. upper clamping rod; 2. upper clamping rod mounting disc; 3. aluminum profile frame; 4. lower vibration rod support frame; 5. rotating bearing disc; 6. lower vibration rod mounting disc; 7. DC motor; 8. Crank

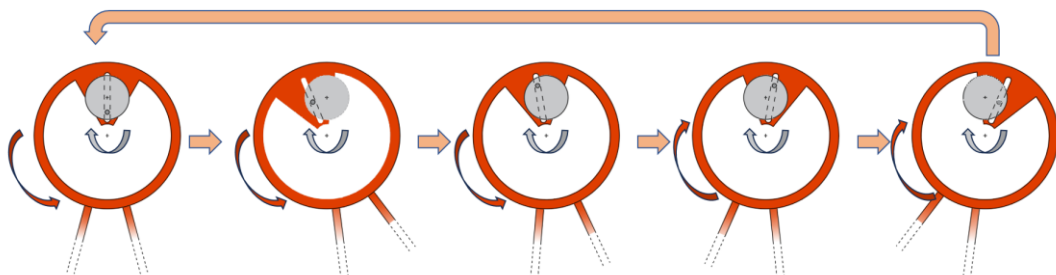


Fig. 3 - Schematic diagram of the vibration transmission mechanism

During harvesting, the mobile chassis forwards at a constant speed. The vibration device, driven by a DC motor, performs reciprocating vibrations to harvest fruit-bearing branches within the canopy.

Simultaneously, the assembly rotates with the main shaft, providing torque to counteract inertia-induced forces generated by the vibration and to assist in dislodging *L. barbarum* branches, thereby reducing branch breakage and entanglement caused by chassis movement. The motion schematic is shown in Fig. 4. According to the geometric relationships, the following can be obtained:

$$x_o = v_m t \quad (1)$$

$$\theta_m = \omega_m t \quad (2)$$

$$x_B = v_m t - R_B \sin(\omega_m t) \quad (3)$$

$$y_B = R_B \cos(\omega_m t) \quad (4)$$

where:

x_o - the position of the center of the vibration device, m; v_m - the velocity of the chassis, m/s; θ_m - the rotation angle of the device, rad; ω_m - the angular velocity of the device, rad/s; x_B - the x-direction position of point B on the vibration rod, m; y_B - the y-direction position of point B on the vibration rod, m; R_B is the distance from point B on the vibration rod to the center of the vibration device, m.

The analysis indicates that, in order to effectively excite the *L. barbarum* branches with the vibration rod while minimizing dragging forces and preventing branch breakage caused by excessive chassis speed or high main shaft rotation speed, the chassis velocity and the angular velocity of the motor should be maintained at a certain proportional relationship, as expressed below:

$$v_m \approx \omega_m R_{B0} \quad (5)$$

where: R_{B0} - the distance from the center of the contact point between the vibration rod and the *L. barbarum* branch to the center of the vibration device, m.

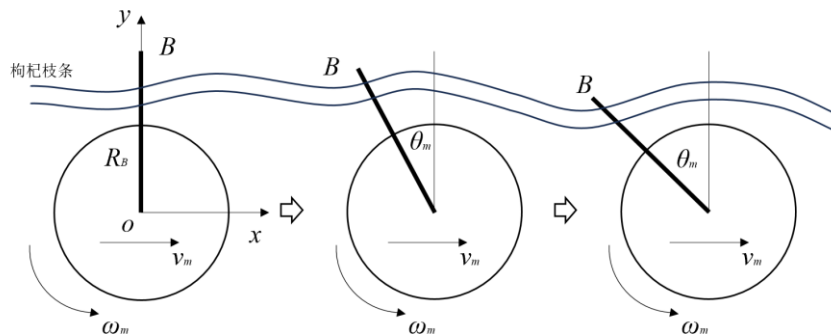


Fig. 4 - Schematic diagram of the mechanism transmission

Design of Plackett-Burman and parameter experiments

The primary objective of mechanized *L. barbarum* harvesting is to collect as many ripe fruits as possible from the fruit-bearing branches while minimizing the harvesting of unripe fruits and reducing damage to ripe fruits, thereby avoiding negative impacts on subsequent yields. Considering the main factors affecting the economic benefits of *L. barbarum*, the subsequent performance tests of the harvesting device focus on evaluating its comprehensive harvesting effectiveness. Three key indicators were selected for this purpose: the ripe fruit harvesting rate I_1 , the unripe fruit mis-harvesting rate I_2 , and the ripe fruit damage rate I_3 . Their calculation methods are as follows:

$$I_1 = \frac{n_1}{n_1 + n_2} \times 100\% \quad (6)$$

$$I_2 = \frac{n_3}{n_3 + n_4} \times 100\% \quad (7)$$

$$I_3 = \frac{n_5}{n_1} \times 100\% \quad (8)$$

where:

I_1 - the rate of harvested ripe fruit, %; I_2 - the rate of mis-harvested unripe fruit, %; I_3 - the rate of damaged ripe fruit, %; n_1 - the number of harvested ripe fruits; n_2 - the number of unharvested ripe fruits; n_3 - the number of harvested unripe fruits; n_4 - the number of unharvested unripe fruits; n_5 is the number of damaged harvested ripe fruits.

Different combinations of harvesting parameters affect the vibration intensity, which in turn influences the harvesting performance. Since the ripe fruit harvesting rate is the primary concern of the *L. barbarum* harvesting device, seven factors were selected to design a Plackett-Burman experiment to identify the parameters that significantly affect the ripe fruit harvesting rate I_1 of the continuous vibration-based *L. barbarum* harvesting device, as shown in Table 2.

Specifically, the vibration angle X_1 can be adjusted by changing the crank length, the vibration frequency X_2 can be modified by varying the rotational speed of the DC motor, and the vertical distance between the upper and lower rods X_3 can be altered by adjusting the position of the support frame. The angles between rods (X_4 and X_5) can be adjusted by replacing the rod mounting plates, the length of the vibration rod X_6 can be directly changed by swapping rods, and the operation speed X_7 can be adjusted by changing the traveling speed of the mobile chassis.

In addition, the height of the vibration device is adjusted according to the height of the ripe fruit region for each crop, aiming to excite the branches from above the ripe fruit region without direct contact with the fruits. The symmetrically arranged vibration devices on both sides should be positioned as close as possible without interfering with the primary and secondary branches to ensure effective excitation of the *L. barbarum* canopy. The rotational speed is determined according to the previously mentioned Eq. 5, so as to maintain a proportional relationship between the linear velocity of the mobile chassis and the angular velocity of the motor, thereby minimizing dragging forces on the branches.

Table 2

Plackett-Burman factor coding

Symbol	Parameters	Low-level (-1)	High-level (+1)
X_1	Vibration angle [°]	30	60
X_2	Vibration frequency [Hz]	4	10
X_3	Distance between the upper and lower poles [mm]	50	100
X_4	Angle between upper rods [°]	15	30
X_5	Angle between lower rods [°]	15	30
X_6	The length of the rods [mm]	30	40
X_7	Chassis movement speed [m/s]	0.5	1
X_8, X_9, X_{10}, X_{11}	Virtual parameters	-	-

To reduce the number of experiments and improve efficiency due to the large number of parameters, a Plackett-Burman experiment was designed, including seven real parameters and four virtual parameters, with each parameter set at two levels. A total of 12 experimental runs were conducted, each with five replicates. The experimental site and conditions were as described above.

RESULTS AND DISCUSSION

Plackett-Burman experiment

The results of the Plackett-Burman experiment are shown in Table 3, and the analysis results are presented in Table 4. The analysis indicates that the vibration angle X_1 , vibration frequency X_2 , and the vertical distance between the upper and lower rods X_3 have significant effects on the ripe fruit harvesting rate ($p < 0.05$), whereas the upper rod angle X_4 , lower rod angle X_5 , rod length X_6 , and operation speed X_7 do not have significant effects.

Table 3

Experiment scheme and results

No.	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	I_1 [%]
1	1	1	-1	1	1	1	-1	-1	-1	1	-1	75.61

No.	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	I_1 [%]
2	-1	1	1	-1	1	1	1	-1	-1	-1	1	12.69
3	1	-1	1	1	-1	1	1	1	-1	-1	-1	22.75
4	-1	1	-1	1	1	-1	1	1	1	-1	-1	36.37
5	-1	-1	1	-1	1	1	-1	1	1	1	-1	2.23
6	-1	-1	-1	1	-1	1	1	-1	1	1	1	10.23
7	1	-1	-1	-1	1	-1	1	1	-1	1	1	32.60
8	1	1	-1	-1	-1	1	-1	1	1	-1	1	70.31
9	1	1	1	-1	-1	-1	1	-1	1	1	-1	52.56
10	-1	1	1	1	-1	-1	-1	1	-1	1	1	18.45
11	1	-1	1	1	1	-1	-1	-1	1	-1	1	12.94
12	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	7.27

Table 4

Analysis of experiment results

Items	Sum of squares	Freedom of degree	Mean square	p
Model	6463.83	7	923.40	18.07
X_1	2993.36	1	2993.36	58.58
X_2	2351.16	1	2351.16	46.02
X_3	846.27	1	846.27	16.56
X_4	10.69	1	10.69	0.21
X_5	30.52	1	30.52	0.60
X_6	158.75	1	158.75	3.11
X_7	73.10	1	73.10	1.43
X_8	204.38	4	51.10	
Residual	6668.21	11		
Cor Total	6463.83	7	923.40	18.07

The results of the experiments indicated that the vibration angle and vibration frequency are the primary factors affecting the vibration intensity, and thus have a significant impact on the ripe fruit harvesting rate. The vertical distance between the upper and lower rods also significantly affects the harvesting rate. This is because, under the excitation mode with the upper rods stationary and the lower rods vibrating, a smaller rod spacing allows the branches to experience greater torque, effectively increasing branch vibration intensity. In contrast, the angles between the upper and lower rods have no significant effect on the ripe fruit harvesting rate, likely due to structural limitations that restrict the adjustable range of rod angles. However, excessively small rod angles may interfere with the interaction between the rods and branches, causing branch dragging and curling, whereas overly sparse rod angles may fail to cooperate effectively with the vibration angle, reducing excitation efficiency. Therefore, the rod angles were set to 15°. The rod length was designed according to the canopy thickness to ensure effective excitation to the branches, while excessively long rods may increase the risk of contact with primary and secondary branches. In addition, the operation speed noticeably affects harvesting efficiency, but within the adjustable range of the chassis speed, it does not significantly influence the ripe fruit harvesting rate.

Parameter experiment**Parameter determination**

The experimental site and conditions were as described above. According to the results of the Plackett-Burman experiment, vibration angle X_1 , vibration frequency X_2 , and the vertical spacing between the upper and lower rods X_3 were selected as the factors for the parameter optimization experiment. Preliminary trials were conducted to determine the ranges of these factors: vibration angle of 20 – 60°, vibration frequency of 4 – 10 Hz, and horizontal spacing between vibration rods of 50 – 100 mm. The codes of factor are presented in Table 5, and the experimental design and results are shown in Table 6. The experiment consisted of 17 groups, each with five replicates.

Table 5

The codes of experimental factors

Codes	X_1 [mm]	X_2 [Hz]	X_3 [mm]
-1	30	4	50
0	45	7	75
1	60	10	100

Table 6

The experimental design and results

No.	X_1	X_2	X_3	I_1 [%]	I_2 [%]	I_3 [%]
1	-1	-1	0	22.54	2.39	5.45
2	1	-1	0	31.73	9.69	8.80
3	-1	1	0	35.70	8.33	0.74
4	1	1	0	66.67	11.07	4.08
5	-1	0	-1	35.07	3.64	0.99
6	1	0	-1	58.77	7.89	4.84
7	-1	0	1	22.31	7.01	9.26
8	1	0	1	43.29	11.62	13.95
9	0	-1	-1	34.15	7.63	9.18
10	0	1	-1	59.21	5.70	1.02
11	0	-1	1	34.00	4.33	15.29
12	0	1	1	55.86	12.64	4.84
13	0	0	0	57.97	3.70	1.25
14	0	0	0	55.35	2.20	1.68
15	0	0	0	55.21	5.65	3.77
16	0	0	0	54.87	1.57	2.96
17	0	0	0	63.87	2.95	4.92

Regression modeling and ANOVA

Based on the above experimental results, a quadratic regression fitting equation was constructed by Design-Expert 12 software, and the polynomial regression equation with the ripe fruit picking rate as the response variable and the coded values of the factors as independent variables was obtained as follows:

$$I_1 = 57.45 + 10.61X_1 + 11.88X_2 - 3.97X_2 + 5.44X_1X_2 - 0.68X_1X_3 - 0.80X_2X_3 - 12.12X_1^2 - 6.17X_2^2 - 5.47X_3^2 \quad (9)$$

Table 7

ANOVA results for the rate of harvested ripe fruit I_1

Sources	Sum of squares	Degree of freedom	Mean square	F	p
Model	3270.09	9	363.34	18.59	0.0004
X_1	899.73	1	899.73	46.04	0.0003
X_5	1128.60	1	1128.6	57.75	0.0001
X_2	125.93	1	125.93	6.44	0.0388
X_1X_5	118.59	1	118.59	6.07	0.0433
X_1X_2	1.85	1	1.85	0.10	0.7673
X_2X_5	2.56	1	2.56	0.13	0.7281
X_1^2	618.45	1	618.45	31.64	0.0008
X_5^2	160.52	1	160.52	8.21	0.0241

Sources	Sum of squares	Degree of freedom	Mean square	F	p
X_2^2	126.19	1	126.19	6.46	0.0386
Lack of fit	79.24	3	26.41	1.84	0.2810
Pure error	57.57	4	14.39		
Total	3406.90	16			

The regression model was subjected to analysis of variance (ANOVA), as presented in Table 7. The results indicated that the regression model for the ripe fruit harvesting rate was statistically significant ($p < 0.05$). Factors X_1 , X_2 , X_3 , X_1X_2 , X_1X_3 , X_2^2 and X_3^2 had significant effects on the rate of harvested ripe fruit ($p < 0.05$), whereas the other factors were not significant. The lack-of-fit term was not significant ($p > 0.05$), indicating that the regression equation adequately represented the experimental data.

Similarly, a polynomial regression model was fitted with the rate of harvested ripe fruit as the response variable and the coded values of the factors as independent variables. The model was expressed as follows:

$$I_2 = 3.21 + 2.36X_1 + 1.71X_2 + 1.34X_3 - 1.14X_1X_2 + 0.09X_1X_3 + 2.56X_2X_3 + 2.31X_1^2 + 2.35X_2^2 + 2.02X_3^2 \quad (10)$$

Table 8

ANOVA results for the rate of harvested unripe fruit I_2

Sources	Sum of squares	Degree of freedom	Mean square	F	p
Model	184.06	9	20.45	12.18	0.0017
X_1	44.65	1	44.65	26.60	0.0013
X_5	23.46	1	23.46	13.97	0.0073
X_2	14.42	1	14.42	8.59	0.0220
X_1X_5	5.20	1	5.20	3.10	0.1219
X_1X_2	0.03	1	0.03	0.02	0.8934
X_2X_5	26.21	1	26.21	15.61	0.0055
X_1^2	22.48	1	22.48	13.39	0.0081
X_5^2	23.16	1	23.16	13.80	0.0075
X_2^2	17.10	1	17.10	10.19	0.0152
Lack of fit	1.78	3	0.59	0.24	0.8659
Pure error	9.97	4	2.49		
Total	195.81	16			

The regression model for the rate of harvested unripe fruit was subjected to ANOVA, as presented in Table 8. The results indicated that the regression model was statistically significant ($p < 0.05$). Factors X_1 , X_2 , X_3 , X_1X_2 , X_2X_3 , X_1^2 , X_2^2 and X_3^2 had significant effects on the rate of harvested unripe fruit ($p < 0.05$), whereas the other factors were not significant. The lack-of-fit term was not significant ($p > 0.05$), indicating that no lack-of-fit existed in the regression equation.

Similarly, a polynomial regression model was fitted with the rate of harvested unripe fruit as the response variable and the coded values of the factors as independent variables. The model was expressed as follows:

$$I_3 = 2.92 + 1.90X_1 - 3.51X_2 + 3.41X_3 - 0.0025X_1X_2 + 0.21X_1X_3 - 0.5725X_2X_3 + 0.7645X_1^2 + 1.09X_2^2 + 3.58X_3^2 \quad (11)$$

Table 9

ANOVA results for the rate of damaged ripe fruit I_3

Sources	Sum of squares	Degree of freedom	Mean square	F	p
Model	287.25	9	31.92	8.29	0.0054
X_1	28.99	1	28.99	7.53	0.0287

Sources	Sum of squares	Degree of freedom	Mean square	F	p
X_5	98.28	1	98.28	25.53	0.0015
X_2	93.23	1	93.23	24.22	0.0017
X_1X_5	0.00	1	0.00	0.00	0.9980
X_1X_2	0.18	1	0.18	0.05	0.8366
X_2X_5	1.31	1	1.31	0.34	0.5778
X_1^2	2.46	1	2.46	0.64	0.4503
X_5^2	4.98	1	4.98	1.29	0.2931
X_2^2	53.95	1	53.95	14.01	0.0072
Lack of fit	17.90	3	5.97	2.64	0.1861
Pure error	9.05	4	2.26		
Total	314.20	16			

The regression model for the ripe fruit damage rate was subjected to ANOVA, as presented in Table 9. The results indicated that the regression model was statistically significant ($p < 0.05$). Factors X_1 , X_2 , X_3 and X_3^2 had significant effects on the rate of damaged ripe fruit, whereas the other factors were not significant. The lack-of-fit term was not significant ($p > 0.05$), indicating that no lack-of-fit existed in the regression equation.

Response surface analysis of experimental results

The effects of the experimental factors on the rate of harvested ripe fruit were analyzed, and the response surface of the regression model for the rate is shown in Fig. 5. According to Eq. 9 and Table 7, the vibration frequency of the rod has the greatest effect on the rate of harvested ripe fruit, followed by the vibration angle, and the horizontal spacing between the upper and lower rods has the least effect. The interaction between vibration angle and vibration frequency is also significant. As shown in Fig. 5, the rate of harvested ripe fruit initially increases and then decreases with increasing vibration angle, because an excessively large angle causes the branches to move beyond the effective range of the vibrating rod. With increasing vibration frequency, the rate of harvested ripe fruit gradually increases, as the frequency directly affects the vibration intensity and, consequently, the harvesting efficiency. As the spacing between the upper and lower rods increases, the rate of harvested ripe fruit decreases slightly. This is because a larger spacing reduces the torque applied by the vibrating device to the branches, rendering the upper rod less effective and relying primarily on the lower rod, which weakens the overall excitation and leads to a decrease in the rate of harvested ripe fruit.

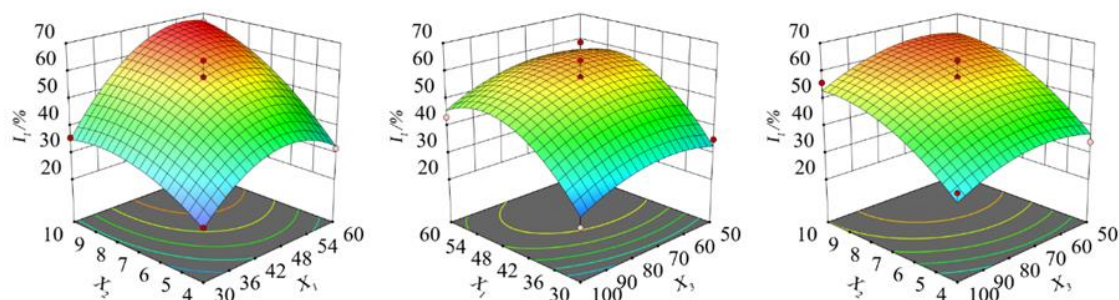


Fig. 5 - Response surface for the rate of harvested ripe fruit

The effects of the experimental factors on the rate of harvested unripe fruit were analyzed, and the response surface of the regression model is shown in Fig. 6. According to Eq. 10 and Table 8, the factors affecting the rate ranked from most to least influential are the vibration angle, vibration frequency, and the horizontal spacing between the upper and lower rods, with a significant interaction observed between vibration frequency and rod spacing. As shown in Fig. 6, the rate of harvested unripe fruit gradually increases with increasing vibration angle, as a larger angle leads to higher vibration intensity and makes the vibrating rods more likely to contact the regions where unripe fruits grow, causing them to fall. With increasing vibration frequency, the rate of harvested unripe fruit also gradually increases due to the higher vibration intensity.

As the spacing between the upper and lower rods increases, the rate of harvested unripe fruit initially decreases and then increases. When the rod spacing is small, the branches experience greater shear forces, which may cause breakage and sharply increase the rate of harvested unripe fruit. Conversely, when the spacing is large, the vibrating rods are more likely to contact unripe fruits, resulting in an increased rate of harvested unripe fruit.

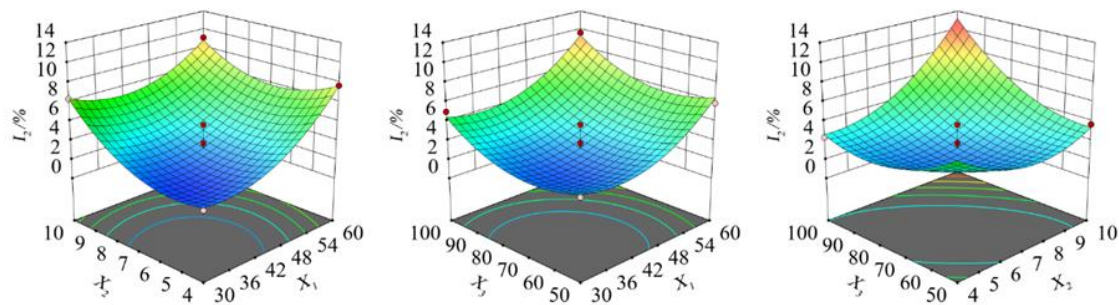


Fig. 6 - Response surface for the rate of harvested unripe fruit

The effects of the experimental factors on the rate of damaged ripe fruit were analyzed, and the response surface of the regression model is shown in Fig. 7. According to Eq. 11 and Table 9, the factors affecting the damage rate ranked from most to least influential are vibration frequency, the horizontal spacing between the upper and lower rods, and vibration angle, with no significant interaction effects observed among the factors. As shown in Fig. 7, the damage rate of ripe fruit gradually increases with increasing vibration angle, as a larger angle causes the vibrating rods to contact the ripe fruits, resulting in impact damage. With increasing vibration frequency, the damage rate gradually decreases because a higher excitation intensity allows the fruits to detach more quickly, thereby reducing the damage rate. As the spacing between the upper and lower rods increases, the damage rate gradually increases. This is similar to the effect of vibration angle: a larger spacing increases the likelihood of contact between the rods and the fruits, causing mechanical damage to the ripe fruits.

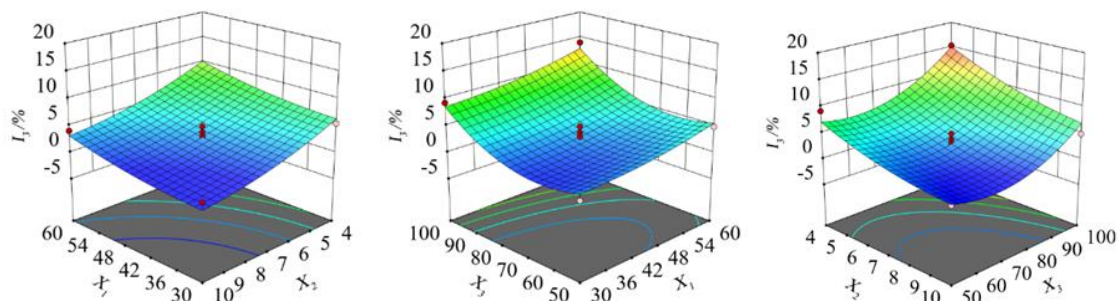


Fig. 7 - Response surface for the rate of damaged ripe fruit

Parameter optimization and experimental validation

Design-Expert 12 software was used to optimize the three evaluation indicators: rate of harvested ripe fruit (I_1), rate of harvested unripe fruit (I_2), and rate of damaged ripe fruit (I_3), with the optimization objective given by Eq. 12. Since the primary goal of the harvesting machine is to maximize the rate of harvested ripe fruit, the weights of the three evaluation indicators were assigned based on experience in a ratio of 4:3:3.

Solving the objective function yielded the optimal parameter combination for the factors: a vibration angle of 46° , a vibration frequency of 9 Hz, and an upper-lower rod spacing of 62 mm. As shown in Fig. 8, the results of field test indicated that the rate of harvested ripe fruit was 85.40%, the rate of harvested unripe fruit was 4.61%, and the rate of damaged ripe fruit was 3.19%. The continuous vibration-based *L. barbarum* harvesting device developed in this study adopts the vibration harvesting method that does not require direct contact with the fruits, resulting in a significant improvement in the damage rate of ripe fruits, with the rate of harvested ripe fruit exceeding 85%, the rate of harvested unripe fruit below 5%, and the damage rate of ripe fruit below 5%, thereby effectively meeting the harvesting requirements while enabling continuous harvesting operations.

$$\begin{cases} \max I_1(X_1, X_2, X_3) \\ \min I_2(X_1, X_2, X_3) \\ \min I_3(X_1, X_2, X_3) \\ 30^\circ \leq X_1 \leq 60^\circ \\ 4\text{Hz} \leq X_2 \leq 10\text{Hz} \\ 50\text{mm} \leq X_3 \leq 100\text{mm} \end{cases} \quad (12)$$



Fig. 8 - Field test

CONCLUSIONS

This study measured key agronomic parameters of *L. barbarum* under the double-layer hedge cultivation mode, including fruit-bearing height and width, which provided data support for the structural design and optimization of the *L. barbarum* harvesting device. A continuous vibration-based harvesting device was developed based on a non-contact vibration method and an optimized excitation mode featuring a static upper rod and a vibrating lower rod. Significance analysis indicated that vibration angle, vibration frequency, and upper-lower rod spacing had significant effects on harvesting performance. Subsequently, these key factors were used as inputs for parameter experiments to determine the optimal combination, which was then validated through field tests. The parameter optimization results showed that the optimal parameter combination of the continuous vibration-based *L. barbarum* harvesting device was: vibration angle of 46° , vibration frequency of 9 Hz, and upper-lower rod spacing of 62 mm. Field test results indicated that the rate of harvested ripe fruit was 85.40%, the rate of harvested unripe fruit was 4.61%, and the damage rate of ripe fruit was 3.19%, effectively meeting the harvesting requirements. Overall, the continuous vibration-based harvesting device proposed in this study effectively improves the harvesting efficiency of *Lycium barbarum*, reduces dependence on manual labor, and addresses the mismatch between traditional harvesting equipment and the actual cultivation pattern. It provides essential technical and equipment support for achieving continuous mechanized harvesting of *L. barbarum* and demonstrates promising prospects for practical application.

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REFERENCES

- [1] Cao Y., Chen Y., Li Y., Li C., Lin S., Lee B., Hsieh C., Hsiao Y., Fan Y., Luo Q., Zhao J., Yin Y., An W., Shi Z., Chow C., Chang W., Huang C., Chang W., Liu Z., Wu W., Tsai W., (2024). Wolfberry genome database: Integrated genomic datasets for studying molecular biology, *Frontiers in Plant Science*, vol.15, No.1310346, Lausanne/Switzerland. DOI: <https://doi.org/10.3389/fpls.2024.1310346>
- [2] Kulczyński B., Gramza-Michałowska A., (2016). Goji Berry (*Lycium barbarum*): Composition and Health Effects – a Review, *Polish Journal of Food and Nutrition Sciences*, vol.66, no.2, pp.65-75, Olsztyn/Poland. DOI: <https://doi.org/10.1515/pjfn-2015-0040>

- [3] Li Y., Hu Z., Zhang Y., Wang J., Xu J., (2024). Research progress of technology and equipment for mechanized harvest of wolfberry (枸杞机械化采收技术与装备研究进展), *Journal of Chinese Agricultural Mechanization*, vol.45, no.5, pp.16-21, Jiangsu/China. DOI: <https://doi.org/10.13733/j.jcam.issn.2095-5553.2024.05.003>
- [4] Liang X., An W., Li Y., Qin X., Zhao J., Su S., (2024). Effects of different nitrogen application rates and picking batches on the nutritional components of *Lycium barbarum* L. fruits, *Frontiers in Plant Science*, vol.15, No.1355832, Lausanne/Switzerland. DOI: <https://doi.org/10.3389/fpls.2024.1355832>
- [5] Liu Y., Fan K., Ma C., (2023). Theoretical analysis of vibration of self-propelled wolfberry picker (枸杞采收机振动采收机理分析), *Forestry Machinery & Woodworking Equipment*, vol.51, no.10, pp.39-43, Helongjiang/China. DOI: <https://doi.org/10.13279/j.cnki.fmwe.20230911.001>
- [6] Liu Y., Liu J., Zhao J., Wang F., Zhang H., Su X., Sun Y., Liu Jia., Zhao D., (2025). Effects of Different Excitation Parameters on Mechanized Harvesting Performance and Postharvest Quality of First-Crop Organic Goji Berries in Saline–Alkali Land, *Agriculture*, vol.15, no.13, pp.1377, Basel/Switzerland. DOI: <https://doi.org/10.3390/agriculture15131377>
- [7] Liu Y., Liu J., Zhao J., Zhao D., Zhang H., Su X., Feng Y., Cheng Y., Li Z., (2025). Research Progress of Theory and Equipment Related to Mechanized Harvesting of *Lycium barbarum* (枸杞机械化采收相关理论与装备研究进展), *Scientia Silvae Sinicae*, vol.61, no.5, pp.222-232, Beijing/China. DOI: <https://doi.org/10.11707/j.1001-7488.LYKX20240448>
- [8] Ma R., Zhang X., Ni Z., Thakur K., Wang W., Yan Y., Cao Y., Zhang J., Rengasamy KRR, Wei Z, (2022). *Lycium barbarum* (Goji) as functional food: A review of its nutrition, phytochemical structure, biological features, and food industry prospects, *Critical Reviews in Food Science and Nutrition*, vol.63 no.30, pp.10621-10635, Philadelphia/United States. DOI: <https://doi.org/10.1080/10408398.2022.2078788>
- [9] Ma Y., Wang Z., Li Y., Feng X., Song L., Gao H., Cao B., (2023). Fruit morphological and nutritional quality features of goji berry (*Lycium barbarum* L.) during fruit development, *Scientia Horticulturae*, vol.308, No.111555, Amsterdam/Netherlands. DOI: <https://doi.org/10.1016/j.scienta.2022.111555>
- [10] Mei S., Tang D., Shi Z., Song Z., Tian Z., Zhou R., (2024). Design and test of a Chinese wolfberry harvester using arrayed vibration units (基于阵列化振动单元的枸杞采收机设计与试验), *Transactions of the Chinese Society of Agricultural Engineering*, vol.40, no.23, pp.115-125, Beijing/China. DOI: <https://doi.org/10.11975/j.issn.1002-6819.202407252>
- [11] Mei S., Wang J., Song Z., Tang D., Shen C., (2024). Mechanism and experimental study on the fruit detachment of Chinese wolfberry through reciprocating vibration, *International Journal of Agricultural and Biological Engineering*, vol.17, no.2, pp.47-58, Beijing/China. DOI: <https://doi.org/10.25165/j.ijabe.20241702.8482>
- [12] Principal A., Ciceoi R., Luchian V., Tabacu A.F., Gutue M., Stavrescu-Bedivan M.M., (2022). Goji Berry Gall Mite Expansion in Europe, with Emphasis on Southeastern Part of Romania. *Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, Food Science and Technology*, vol.78, no.2, Cluj-Napoca/Romania. DOI: <https://doi.org/10.15835/buasvmcn-fst.2021.0028>
- [13] Skenderidis P., Kerasioti E., Karkanta E., Stagos D., Kouretas D., Petrotos K., Hadjichristodoulou C., Tsakalof A., (2018). Assessment of the antioxidant and antimutagenic activity of extracts from goji berry of Greek cultivation, *Toxicology Reports*, vol.5, pp.251-257, Amsterdam/Netherlands. DOI: <https://doi.org/10.1016/j.toxrep.2018.02.001>
- [14] Su X., Liu Y., Liu J., Zhao D., (2025). Experiment and Analysis of Vibration Response in Fruit-Bearing Branches of Wolfberry (枸杞挂果枝条振动响应分析与试验), *Scientia Silvae Sinicae*, vol.61, no.8, pp.25-31, Beijing/China. DOI: <https://doi.org/10.11707/j.1001-7488.LYKX20240470>
- [15] Wang Y., Yang C., Gao Y., Lei Y., Ma L., Qu A., (2024). Design and Testing of an Integrated *Lycium barbarum* L. Harvester, *Agriculture*, vol.14, no.8, pp.1370, Basel/Switzerland. DOI: <https://doi.org/10.3390/agriculture14081370>
- [16] Yang Q., W J., Yang J., (2025). Overview of Harvesting Machinery and Harvesting Methods of Wolfberry (枸杞采收机械与采收方式综述), *Forestry Machinery & Woodworking Equipment*, vol.53, no.3, pp.4-10, Beijing/China. DOI: <https://doi.org/10.13279/j.cnki.fmwe.2025.0026>

- [17] Yu J., Yan Y., Zhang L., Mi J., Yu L., Zhang F., Lu L., Luo Q., Li X., Zhou X., Cao Y., (2023). A comprehensive review of goji berry processing and utilization, *Food Science & Nutrition*, vol.11, no.12, pp.7445-7457, Birmingham/United Kingdom. DOI: <https://doi.org/10.1002/fsn3.3677>
- [18] Zhang W., Zhang M., Zhang J., Li W., (2018). Design and Experiment of Vibrating Wolfberry Harvester (振摇枸杞采收机设计与试验), *Transactions of the Chinese Society of Agricultural Machinery*, vol.49, no.7, pp.97-102, Beijing/China. DOI: <https://doi.org/10.6041/j.issn.1000-1298.2018.07.012>
- [19] Zhang Z., Xiao H., Ding W., Mei S., (2015). Mechanism simulation analysis and prototype experiment of Lycium barbarum harvest by vibration mode (振动式枸杞采摘机理仿真分析与样机试验), *Transactions of the Chinese Society of Agricultural Engineering*, vol.31, no.10, pp.20-28, Beijing/China. DOI: <https://doi.org/10.11975/j.issn.1002-6819.2015.10.003>
- [20] Zhao J., Ge L., Xiong W., Leong F., Huang L., Li S., (2016). Advanced development in phytochemicals analysis of medicine and food dual purposes plants used in China (2011–2014), *Journal of Chromatography A*, vol.1428, pp.39-54. DOI: <https://doi.org/10.1016/j.chroma.2015.09.006>