Design and experiment optimize of the vibration harvesting machine of *Lycium barbarum* L.

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Abstract

The primary method for harvesting *Lycium barbarum* L. (*L. barbarum*) is manual labor, making it one of the most labor-intensive fruit crops in the Northwest region of China. Due to the decrease of labor supply and the increase of labor cost, the cost of harvesting has become a major hindrance to the development of the *L. barbarum* industry. Therefore, it is important to achieving mechanized harvesting of *L. barbarum*. In this study, a vibration harvesting machine was designed. Plackett-Burman experiment was conducted to assess the correlation between the picking rate of ripe fruit and various parameters. It was found that the significant factors were vibration amplitude, vibration frequency, and spacing of the vibrating rods. Based on the response surface methodology (RSM), parameter experiment was conducted to analyze the impact of these factors on picking rate of ripe fruit, picking rate of unripe fruit, and damage rate of ripe fruit. The optimal harvesting parameters were determined to be: vibration amplitude of 44mm, spacing of the vibrating rods of 24mm, and vibration frequency of 9Hz. The verification experiment showed that the picking rate of ripe fruit was 86.44%, the picking rate of unripe fruit was 6.81%, and the damage rate of ripe fruit was 5.54%. This study provides a design basis for realizing mechanized harvesting.

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Introduction

L. barbarum, commonly known as goji berry, is a deciduous shrub in the Solanaceae family. Its fruits are rich in polysaccharides, fatty acids, carotenoids, and phenolic compounds, offering various nutritional benefits such as liver and kidney nourishment, vision enhancement, immune system strengthening, and anti-aging effects (Xiao *et al*., 2022; Ma *et al*., 2022; Zhao *et al*., 2021, Zhao and Chen 2021). China stands as the world's largest producer of *L. barbarum*, with the primary cultivation regions situated in the northwest. However, due to the lack of suitable harvesting machinery, manual labor remains the predominant method for harvesting, resulting in slow harvesting efficiency and high labor costs. The high cost of harvesting is a significant impediment to the growth of the *L. barbarum* industry (Chen *et al*., 2022a; Chen *et al*., 2021b; Zhao and Chen 2020). Consequently, achieving mechanized harvesting has become a crucial goal for the industry to reduce costs and improve efficiency. Vibration harvesting is an efficient method widely applied in the mechanized harvesting of various fruits, such as olives, coffee, and citrus (Du *et al*., 2020; Villibor *et al*., 2019; Castro-Garcia *et al*., 2018; Du *et al*., 2022; Cerruto *et al*., 2012). Chen *et al*. (2021a) designed a longitudinal vibratory compliant picking mechanism for berry shrub, conducting indoor vibration harvesting experiment with blueberries. The vibration frequency during the experiment was 5-6Hz, and the result demonstrated an average picking rate of 95.5%. Xing *et al*. (2020) investigated apple vibration harvesting, revealing that as frequency and amplitude increased, the influence of tree characteristics on fruit harvesting decreased, the fruit removal rate reached 91.43% when the amplitude was 14.3 mm and the frequency was 20 Hz. Zhang *et al*. (2020) employed different vibration methods and systems, finding that the best fruit picking rate could reach 97%. Zhou *et al*. (2014) studied cherry vibration harvesting, noting that the excitation position had a certain impact on harvesting effectiveness. Under optimal excitation parameters, the fruit picking rate reached 97%. Various methods for *L. barbarum* harvesting currently exist, including vibration, combing, pneumatic, and vibration-combing methods, with vibration harvesting demonstrating the best results, achieving a picking rate of over 90% (Xu *et al*., 2018; Zhang *et al*., 2016; He *et al*., 2017; Chen *et al*., 2021c). Handheld vibration harvesting devices have become relatively mature; however, they still require manual operation, and research on large-scale mechanized harvesting is lacking (Chen *et al*., 2019; Zhang *et al*., 2018a). Zhang *et al.* (2018b) designed a vibration harvester, the vibration frequency was 12Hz and amplitude was 40mm, the experiment results showing the picking rate of ripe fruit was 93.52%, the picking rate of unripe fruit was 5.72%, and the damage rate of ripe fruit was 2.54%. Chen *et al*., (2022b) designed a swing harvester, with the best parameters: the swing angle of 49.58°, the swing radius of 72.53 mm, and the swing frequency of 11.21 Hz. The experiment results showing the picking rate of ripe fruit was 94.18%, the picking rate of unripe fruit was 3.18%, and the damage rate of ripe fruit was 5.06%. Due to their small size and light weight, handheld harvesters can often provide a higher vibration frequency, whereas large-scale harvesting machines with greater mass may not have too high frequency during harvesting (Chen *et al*. 2021a; Chen *et al*. 2022b; Xu *et al*., 2018; Zhang *et al.* 2018b). Handheld picking falls under semi-mechanized harvesting and offers improved efficiency compared to manual harvesting. However, further reducing labor and production costs necessitates the design of large-scale harvesting machines for full mechanization. To address the challenge of mechanized harvesting of *L. barbarum*, this study conducted measurements on the standardized hedge cultivation mode for *L. barbarum*. In order to achieve efficient harvesting, we designed a vibration harvesting machine and analyzed the parameters affecting the picking rate of ripe fruit through Plackett-Burman experiment. Subsequently, we conducted parameter experiment on the primary three influencing factors using the RSM, assessing their impact on the picking rate of ripe fruit, the picking rate of unripe fruit, and the damage rate of ripe fruit. Solve the optimization objective formula of three evaluation indexes to obtain the optimal parameter combination, and verification experiments were conducted to demonstrate the feasibility of mechanized harvesting, providing a basis and reference for related research.

Figure 1. Standardized hedge cultivation mode.

Materials and Methods

Condition of experiment

All *L. barbarum* shrubs used in the experiment were planted in Ningxia Zhengqi Hong Industry Development Co., Ltd., located in Guyuan City, Ningxia Hui Autonomous Region (36°17’32.9”N, 106°6’41.5”E). The experimental variety was Ningqi No. 7, with a tree age of 3 to 4 years. As shown in Figure 1, the shrubs in the experimental field were cultivated using a standardized hedge cultivation mode. This cultivation method increases tree height and prevents fruit rot caused by branches touching the ground. As shown in Figure 2, manual pruning of branches was carried out to allow them to naturally droop, reducing interweaving of branches while facilitating mechanized harvesting. Healthy *L. barbarum* shrubs without disease or pest infestations and with no significant defects were selected for the experiments. Prior to the experiments, agronomic measurements were taken on the shrubs, including parameters such as plant height, plant spacing, layer height, and layer width, as shown in Table 1. These measurements served as reference data for the design of the subsequent harvesting machine.

Figure 2. *L. barbarum* branches.

Table 1. Agronomic parameters of hedgerow cultivation mode.

Agronomic parameters	Explain	Average value	Standard deviation
Plant height (m)	Height of *L. barbarum* shrub	1.78	0.12
Plant spacing (m)	Distance between adjacent *L. barbarum* shrubs in the same row	1.29	0.10
First layer height (m)	The maximum height of the first layer of *L. barbarum* branches	0.67	0.06
Second layer height (m)	The maximum height of the second layer of *L. barbarum* branches	1.61	0.30
First layer width (m)	The maximum width of the first layer of *L. barbarum* branches	1.24	0.15
Second layer width (m)	The maximum width of the second layer of *L. barbarum* branches	1.22	0.24
Height of the first layer lead (m)	Height of the traction line of the first layer of branches	0.64	0.05
Height of the second layer lead (m)	Height of the traction line of the second layer of branches	1.26	0.04
Row spacing (m)	Row spacing of *L. barbarum* shrubs	3.18	0.35

Vibration Vibration harvesting machine

The vibration harvesting machine, as shown in Figure 3, is equipped with a gearbox that increases the crank's torque through gear transmission, thereby enhancing the harvesting capacity of the machine and preventing it from getting stuck due to excessive branches. Below the vibrating rod plate, there are sliders and guides that enable it to move back and forth. The clamping rods plate is fixed on the mounting plate and cannot move. The clamping rods and vibration rods could be installed at different positions on the plate to adjust the parameters of the harvesting machine. When the harvesting machine is in operation, place the clamping rods and vibration rods near the root of the branches to prevent damage caused by contact between the rods and the fruits. The motor drives the crank in a rotary motion through the gearbox transmission. Via the crank-slider mechanism, the rotary motion of the crank is converted into the reciprocating vibration of the vibrating rods. Due to the fixed installation, the clamping rods will not move, while the vibrating rods vibrates back and forth, two types of rods work together to apply torque to the branches during harvesting, causing the branches to swing back and forth. When the inertial force acting on the fruit exceeds the binding force between the fruit and its stem, the fruit detaches, achieving vibration harvesting.

Plackett-Burman experiment

Due to the numerous adjustable parameters of the harvesting machine, the Plackett-Burman experiment was employed to conduct correlation test, thereby identifying the parameters significantly affecting the harvesting performance. Since the primary objective of harvesting is to collect ripe fruits, the picking rate of ripe fruit serves as the evaluation criterion for the experiment. The formula for calculating the picking rate of ripe fruit (I_1) is as follows:

$$I_1 = \frac{n_1}{n_1 + n_2} \times 100\% \quad (1)$$

where, n_1 is the amount of ripe fruit picked, n_2 is the amount of ripe fruit unpicked.

To analyze the parameters significantly affecting the picking rate of ripe fruit in the vibration harvesting machine, as shown in Table 2, eight factors were selected and designed for experiment. Among these factors, the vibration amplitude (X_1) could be adjusted by altering the crank's diameter. The vibration frequency (X_2) could be controlled by changing the rotation speed of the DC motor. The distance from the vibrating rod to the first ripe fruit (X_3) could be adjusted by varying the machine's height. The spacing of the clamping rods (X_4) could be adjusted by changing the installation position of clamping rods on clamping rod plate. The spacing of the vibrating rods (X_5) could be adjusted by changing the installation position of vibrating rods on vibrating rod plate. The vertical spacing between the clamping rods and the vibrating rods (X_6) could be adjusted by changing the mounting positions of the clamping rods and vibrating rods. The diameters of the clamping rods and the vibrating rods (X_7) could be controlled by adding plastic tubes of different thicknesses to the rods, and the duration of vibration (X_8) could be controlled by manipulating the motor switch. Due to the large number of parameters, and to reduce the number of experiments while improving efficiency, a Plackett-Burman experiment was designed. This experiment included eight real parameters and three virtual parameters, with each parameter having two levels represented in a coded form as +1 and -1. The experiment design and result analysis were conducted using Design-Expert 12 software. A total of 12 groups of experiments were conducted, and each group was repeated 5 times, and the average of 5 tests is taken as the result of this group. The experiments were conducted on July 10, 2022, at the location and under the conditions mentioned earlier.

Parameter experiment

The primary design requirement for the harvesting machine is to achieve the harvesting of ripe fruits without causing damage, and to avoid harvesting unripe fruits, so as to prevent any adverse impact on future yields. In order to enhance the harvesting efficiency and optimize harvesting parameters to obtain the best parameter combination for the harvesting machine, parameter optimization experiment was designed and conducted. The time of parameter experiment was July 12th, 2022, at the same location and under the same conditions as previously described. The primary objective of these parameter experiment for the harvesting machine was to evaluate the comprehensive harvesting effectiveness. Three key indexes, the picking rate of ripe fruit (I_1), the picking rate of unripe fruit (I_2), and the damage rate of ripe fruit (I_3), were selected as the main indexes for assessing the harvesting machine's performance. Maturation of fruits could lead to changes in color and hardness, manifested as a change in color from green to red and hardness from hard to soft. When ripe fruits are damaged by collision, the damaged area will form a soft and flat surface. A total of 17 groups of experiments were conducted, and each group was repeated 5 times in the parameter experiment. As shown in Figure 3, during the test, the vibration harvesting machine is

Table 2. Plackett-Burman experiment factor coding.

Symbol	Parameters	Low-level (-1)	High-level (+1)
X_1	Vibration amplitude (mm)	30	60
X_2	Vibration frequency (Hz)	4	10
X_3	Distance from the vibrating rod to the first ripe fruit (mm)	0	50
X_4	Spacing of the clamping rods (mm)	10	20
X_5	Spacing of the vibrating rods (mm)	5	40
X_6	Vertical spacing between the clamping rods and the vibrating rods (mm)	30	70
X_7	Diameters of the clamping rods and the vibrating rods (mm)	5	10
X_8	Vibration duration (s)	3	10
X_9, X_{10}, X_{11}	Virtual parameters	-	-

positioned to one side of the plant row, with the clamping rods and vibrating rods inserted into the branch. The fallen fruit from the vibrating branch fall into the collection device, and the branch will not repeat the test. After the test, mature and damaged fruits were manually judged and counted. The average of 5 tests is taken as the result of this group, each group of experiments calculates three key indexes. The formulas for calculating the picking rate of unripe fruit (I_2) and the damage rate of ripe fruit (I_3) are as follows:

$$I_2 = \frac{n_3}{n_3 + n_4} \times 100\% \quad (2)$$

$$I_3 = \frac{n_5}{n_1} \times 100\% \quad (3)$$

where n_3 is the amount of unripe fruit picked, n_4 is the amount of unripe fruit unpicked, and n_5 is the amount of damaged ripe fruit picked.

Parameter optimization and experimental verification

In order to further optimize the parameters, obtain the optimal harvesting parameters and conduct experimental verification. Using Design-Expert 12 software, optimization was conducted for three evaluation indexes: picking rate of ripe fruit (I_1), picking rate of unripe fruit (I_2), and damage rate of ripe fruit (I_3). The optimization objective formula is as follows (4), and due to the primary goal of the vibration harvesting machine being to improve the picking rate of ripe fruit, the weight allocation ratio for the three evaluation indexes was chosen empirically as 4:3:3.

$$I = \begin{cases} \max I_1(X_1, X_2, X_5) \\ \min I_2(X_1, X_2, X_5) \\ \min I_3(X_1, X_2, X_5) \\ 40\text{mm} \leqslant X_1 \leqslant 60\text{mm} \\ 20\text{mm} \leqslant X_5 \leqslant 40\text{mm} \\ 5\text{Hz} \leqslant X_2 \leqslant 10\text{Hz} \end{cases} \quad (4)$$

Results and Discussion

Plackett-Burman experiment

The experimental design and results of the Plackett-Burman experiment are presented in Table 3, and the analysis of test results displayed in Table 4. The analysis revealed that vibration amplitude (X_1), vibration frequency (X_2), and spacing of the vibrating rods (X_5) had a significant impact on the picking rate of ripe fruit

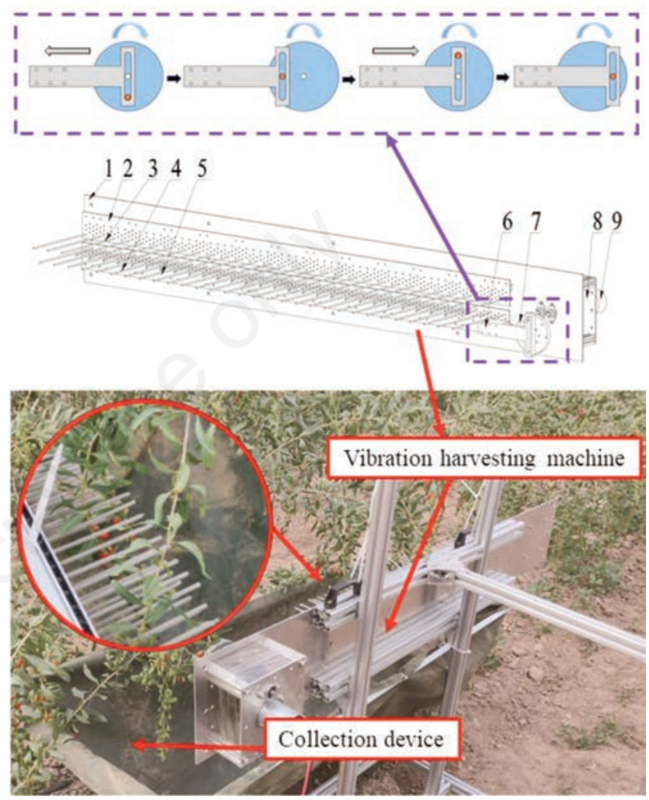

Figure 3. Vibration harvesting machine. 1. Mounting plate; 2. clamping rod plate; 3. clamping rods; 4. vibrating rods; 5. vibrating rod plate; 6. transmission piece; 7. crank; 8. gearbox; 9. DC motor.

Table 3. Plackett-Burman test 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}	I1/%
1	1	1	-1	1	1	1	-1	-1	-1	1	-1	21.74
2	-1	1	1	-1	1	1	1	-1	-1	-1	1	7.23
3	1	-1	1	1	-1	1	1	1	-1	-1	-1	37.63
4	-1	1	-1	1	1	-1	1	1	1	-1	-1	35.9
5	-1	-1	1	-1	1	1	-1	1	1	1	-1	3.16
6	-1	-1	-1	1	-1	1	1	-1	1	1	1	7.56
7	1	-1	-1	-1	1	-1	1	1	-1	1	1	32.31
8	1	1	-1	-1	-1	1	-1	1	1	-1	1	73.02
9	1	1	1	-1	-1	-1	1	-1	1	1	-1	86.57
10	-1	1	1	1	-1	-1	-1	1	-1	1	1	69.86
11	1	-1	1	1	1	-1	-1	-1	1	-1	1	11.11
12	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	10.1

($p < 0.05$). In contrast, distance from the vibrating rod to the first ripe fruit (X_3), spacing of the clamping rods (X_4), vertical spacing between the clamping rods and the vibrating rods (X_6), diameters of the clamping rods and the vibrating rods (X_7), and duration of vibration (X_8) did not significantly influence the picking rate of ripe fruit. During the experiment, it was observed that vibration amplitude and vibration frequency were the primary factors affecting vibration intensity, thereby significantly influencing the picking rate of ripe fruit. The distance from the vibrating rod to the first ripe fruit had minimal impact on the intensity of branch vibration. Additionally, due to the irregular growth of branches, it was challenging to make precise adjustments in practical experiments. The spacing of the clamping rods should not be too large because, in actual harvesting, if the vibration amplitude is smaller than the spacing of the clamping rods, the branches will not come into contact with the clamping rods during vibration, rendering the clamping rods ineffective. Similarly, the spacing of the vibrating rods should not be too large because smaller amplitude will lead to insufficient contact time between the vibrating rods and the branches. This results in the vibrating rods being unable to induce branch vibration, significantly reducing the picking rate of ripe fruit. Therefore, the spacing of the vibrating rods works in coordi-

Table 4. Analysis of test results.

Items	Sum of squares	Degree of freedom	Mean square	p
Model	8888.27	8	1111.03	0.0372
X_1	1377.52	1	1377.52	0.0346
X_2	3086.42	1	3086.42	0.0117
X_3	101.68	1	101.68	0.3904
X_4	68.12	1	68.12	0.4725
X_5	2502.45	1	2502.45	0.0157
X_6	760.18	1	760.18	0.0714
X_7	27.63	1	27.63	0.6377
X_8	964.28	1	964.28	0.0540
Residual	304.14	3	101.37	
Cor total	9192.41	11		

Table 5. Codes of factors.

Codes	X_1/mm	X_5/mm	X_2/Hz
-1	40	20	5
0	50	30	7.5
1	60	40	10

Table 6. Experiment schemes and results.

No.	X_1	X_5	X_2	I_1/%	I_2/%	I_3/%
1	-1	-1	0	55.41	1.44	4.88
2	1	-1	0	87.50	6.92	9.82
3	-1	1	0	20.10	0.34	1.25
4	1	1	0	57.82	4.65	6.56
5	-1	0	-1	35.50	0.42	0.92
6	1	0	-1	39.07	3.16	4.76
7	-1	0	1	65.80	2.83	5.65
8	1	0	1	83.15	8.73	12.16
9	0	-1	-1	42.86	5.71	5.26
10	0	1	-1	25.35	0.82	1.82
11	0	-1	1	94.37	4.00	5.22
12	0	1	1	32.05	4.53	4.00
13	0	0	0	61.49	1.08	1.01
14	0	0	0	62.72	2.20	1.89
15	0	0	0	54.46	2.95	3.28
16	0	0	0	74.85	2.44	3.91
17	0	0	0	64.25	1.64	1.74

nation with the vibration amplitude to influence the harvesting effectiveness by affecting the amplitude of branch vibration. The vertical spacing between the clamping rods and the vibrating rods should not be too small, as an excessively small spacing could lead to branch breakage, impacting future yields. The diameter of the clamping rods and vibrating rods had minimal influence on harvesting efficiency. During vibration harvesting, the majority of ripe fruits detach within 3 seconds of vibration, and an extended vibration duration does not significantly affect the picking rate of ripe fruit. Conversely, it reduces harvesting efficiency, the finding consistent with research conducted by Ortiz and Torregrosa (2013).

Parameter experiment

Based on the results of the Plackett-Burman experiment, further parameter experiment was conducted using vibration amplitude (X_1), vibration frequency (X_2), and spacing of the vibrating rods (X_5) as factors. The value ranges for each factor were determined through pre-tests and Plackett-Burman experiment: vibration amplitude ranging from 40 to 60 mm, vibration frequency ranging from 5 to 10 Hz, and spacing of the vibrating rods ranging from 20 to 40 mm. A combination experiment was employed, with factor coding as shown in Table 5. The experimental design and results are presented in Table 6. And the experimental design and result analysis were conducted using Design-Expert 12 software.

Regression analysis

Based on the experiment results described above, a regression equation was obtained using Design-Expert 12 software, with the picking rate of ripe fruit as the response function and the coded value of each factor as independent variables. The regression equation is as follows:

$$I_1 = 63.55 + 11.34X_1 - 18.10X_5 + 16.57X_2 + 1.41X_1X_5 + 3.45X_1X_2 - 11.20X_5X_2 - 0.562X_1^2 - 7.78X_5^2 - 7.11X_2^2 \quad (5)$$

Performing variance analysis on the regression equation yields the results shown in Table 7. The results indicate that the regression model was $p = 0.0038$ (< 0.05), indicating statistical significance. The factor X_1, X_2, X_5 and the interaction term X_2X_5 have a significant impact on the picking rate of ripe fruit ($p < 0.05$), while the other factors are not significant. The lack of fit term has a p-value greater than 0.05, indicating that there is no lack of fit factors present in the regression equation.

Similarly, a regression equation was derived with the picking rate of unripe fruit as the response function and the coded value of each factor as independent variables. The regression equation is as follows:

$$I_2 = 2.06 + 2.3X_1 - 0.9663X_5 + 1.25X_2 - 0.2925X_1X_5 + 0.79X_1X_2 + 1.35X_5X_2 + 0.6477X_1^2 + 0.6277X_5^2 + 1.08X_2^2 \quad (6)$$

Performing variance analysis on the regression equation yields the results shown in Table 8. The results indicate that the regression model was p=0.0039 (<0.05), indicating statistical significance. The factor X_1, X_2, X_5 and the interaction term X_2X_5 have a significant impact on the picking rate of unripe fruit (p<0.05), while the other factors are not significant. The lack of fit term has a p-value greater than 0.05, indicating that there is no lack of fit factors present in the regression equation.

Similarly, a regression equation was derived with the damage rate of ripe fruit as the response function and the coded value of each factor as independent variables. The regression equation is as follows:

$$I_3 = 2.37 + 2.58X_1 - 1.44X_5 + 1.78X_2 - 0.0925X_1X_5 + 0.6675X_1X_2 + 0.555X_5X_2 + 2.53X_1^2 + 0.732X_5^2 + 0.977X_2^2 \quad (7)$$

Performing variance analysis on the regression equation yields the results shown in Table 9. The results indicate that the regression model was p=0.0171 (<0.05), indicating statistical significance. The factor X_1, X_2, X_5 and X_1^2 have a significant impact on the damage rate of ripe fruit (p<0.05), while the other factors are not significant. The lack of fit term has a p-value greater than 0.05, indicating that there is no lack of fit factors present in the regression equation.

Table 7. ANOVA of the picking rate of ripe fruit I_1.

Sources	Sum of squares	Degree of freedom	Mean square	F	p
Model	6907.7	9	767.52	9.35	0.0038
X_1	1028.99	1	1028.99	12.53	0.0095
X_5	2621.6	1	2621.6	31.93	0.0008
X_2	2197.51	1	2197.51	26.76	0.0013
$X1X_5$	7.92	1	7.92	0.0965	0.7651
$X1X_2$	47.47	1	47.47	0.5782	0.4719
X_2X_5	501.98	1	501.98	6.11	0.0427
X_1^2	1.33	1	1.33	0.0162	0.9023
X_5^2	255.15	1	255.15	3.11	0.1213
X_2^2	212.97	1	212.97	2.59	0.1513
Lack of fit	358.99	3	119.66	2.22	0.2284
Pure error	215.74	4	53.94		
Total	7482.43	16			

Response surface analysis of test results

Analyzing the impact of each factor on the picking rate of ripe fruit, the response surface is shown in Figure 4. From Eq. (4) and Table 7, it could be observed that the spacing of the vibrating rods has the greatest influence on the picking rate of ripe fruit, followed by vibration frequency, while vibration amplitude has the least impact. The interaction between the spacing of the vibrating rods and vibration frequency has a significant effect. As depicted in Figure 4, as vibration amplitude and vibration frequency increase, the picking rate of ripe fruit gradually rises. However, due to structural constraint, it becomes challenging to further increase vibration amplitude and frequency, and doing so could have adverse effects on other evaluating indexes. Conversely, as the spacing of the vibrating rods increases, the picking rate of ripe fruit gradually decreases. This is because the spacing of the vibrating rods could affect vibration intensity of branch. When the spacing of the vibrating rods is large and the vibration amplitude is small, the contact time between vibrating rods and branches could be reduced, thus affecting the vibration amplitude at the location of branch excitation. Consequently, the vibration intensity of the branch decreases, resulting in a lower picking rate of ripe fruit.

Analyzing the impact of each factor on the picking rate of unripe fruit, the response surface is shown in Figure 5. From Eq. (5) and Table 8, it could be observed that the factors affecting the picking rate of unripe fruit are vibration amplitude, vibration frequency and spacing of the vibrating rods from high to low, and the interaction between spacing of the vibrating rods and vibration frequency has a significant influence. As shown in Figure 5, with the increase of vibration amplitude and frequency, and with the decrease of the spacing of the vibrating rods, the picking rate of unripe fruit gradually increases, which is caused by the greater vibration intensity. Because the vibrating rods hardly touch unripe fruits, almost all the unripe fruits fall off due to the excessive vibration intensity. Analyzing the impact of each factor on the damage rate of ripe fruit, the response surface is shown in Figure 6. From Eq.n (6) and Table 9, it could be observed that the factors affecting the damage rate of ripe fruit, from highest to lowest impact, are vibration amplitude, vibration frequency, and spacing of the vibrating rods, with no significant interaction effects between these factors. Compared to the ANOVA results of the other two evaluation indexes (picking rate of ripe fruit and picking rate of unripe fruit), the *p*-value of the ripe fruit damage rate model is relatively larger.

Table 8. ANOVA of the picking rate of unripe fruit I_2.

Sources	Sum of squares	Degree of freedom	Mean square	F	p
Model	81.74	9	9.08	9.28	0.0039
X_1	42.46	1	42.46	43.38	0.0003
X_5	7.47	1	7.47	7.63	0.028
X_2	12.45	1	12.45	12.72	0.0091
$X1X_5$	0.3422	1	0.3422	0.3497	0.5729
$X1X_2$	2.5	1	2.5	2.55	0.1543
X_2X_5	7.34	1	7.34	7.5	0.0289
X_1^2	1.77	1	1.77	1.81	0.221
X_5^2	1.66	1	1.66	1.7	0.2341
X_2^2	4.87	1	4.87	4.97	0.0609
Lack of fit	4.76	3	1.59	3.03	0.156
Pure error	2.09	4	0.5232		
Total	88.59	16			

Table 9. ANOVA of the damage rate of ripe fruit I_3.

Sources	Sum of squares	Degree of freedom	Mean square	F	p
Model	134	9	14.89	5.55	0.0171
X_1	53.04	1	53.04	19.78	0.003
X_5	16.68	1	16.68	6.22	0.0414
X_2	25.45	1	25.45	9.49	0.0178
$X1X_5$	0.0342	1	0.0342	0.0128	0.9132
$X1X_2$	1.78	1	1.78	0.6645	0.4418
X_2X_5	1.23	1	1.23	0.4594	0.5197
X_1^2	26.94	1	26.94	10.04	0.01571
X_5^2	2.26	1	2.26	0.8412	0.3896
X_2^2	4.02	1	4.02	1.5	0.2605
Lack of fit	13.1	3	4.37	3.08	0.153
Pure error	5.68	4	1.42		
Total	152.78	16			

This may be because the three factors could directly affect the excitation intensity, and the relationship between two evaluation indexes and excitation intensity is closer. The reason for ripe fruit damage is due to the contact between the vibration rods and the fruit, and the collision between the fruit and the collection device. Therefore, the effect of the three factors on the damage rate of ripe fruit is relatively inconspicuous. As shown in Figure 6, as vibration amplitude and vibration frequency increase, the damage rate of ripe fruit gradually increases. This is because when the excitation intensity of the picking machine is high, the vibrating rods are more likely to contact with ripe fruits, resulting in impact damage. Conversely, as the spacing of the vibrating rods increases, the damage rate of ripe fruits gradually decreases. This is because an increased spacing between the vibrating rods reduces the contact time between the vibrating rods and the branches, leading to reduced contact with ripe fruits.

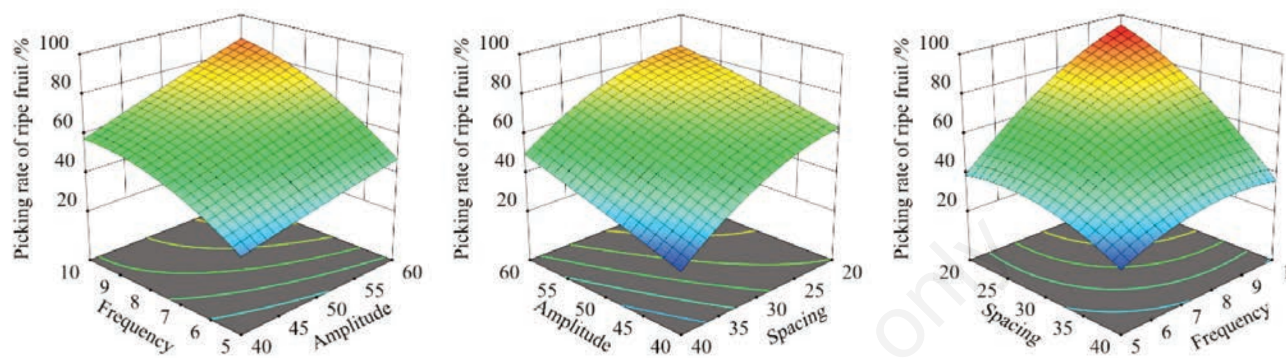

Figure 4. Response surface and contour plots of the picking rate of ripe fruit.

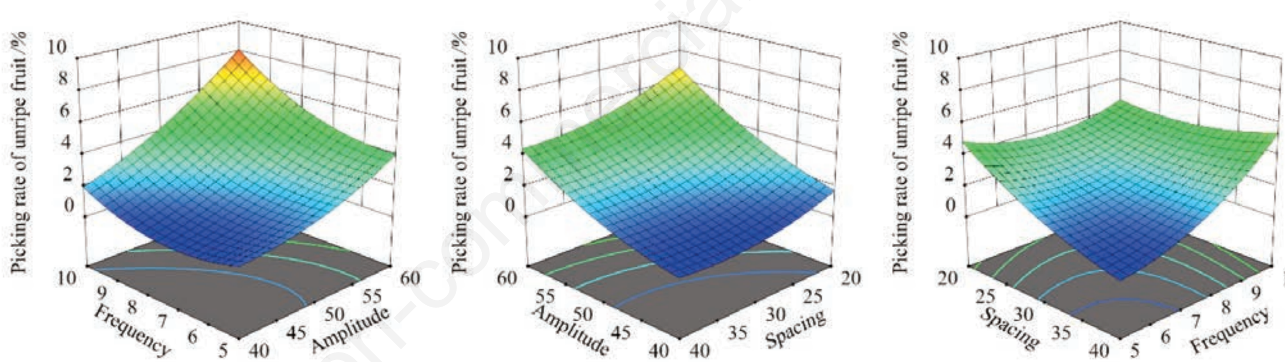

Figure 5. Response surface and contour plots of the picking rate of unripe fruit.

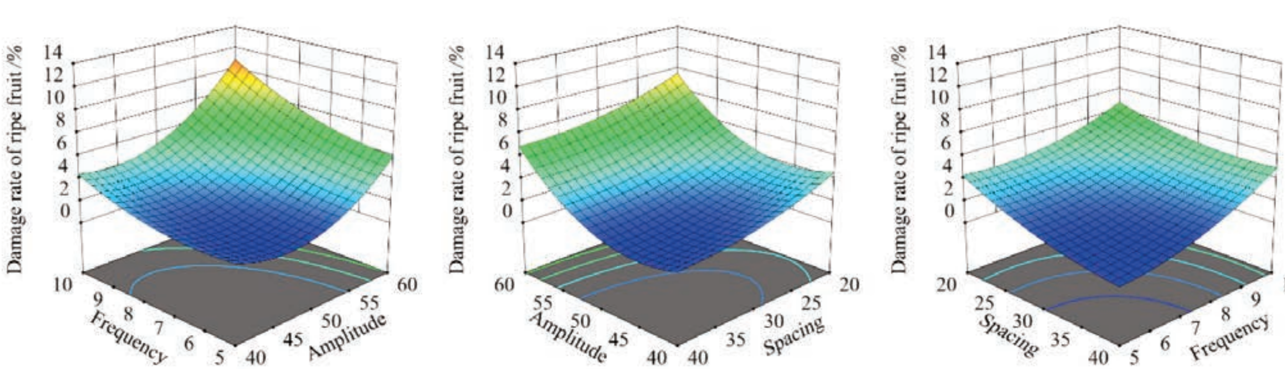

Figure 6. Response surface and contour plots of the damage rate of ripe fruit.

Parameter optimization and experimental verification

Solving the Formula (4) yielded the optimal parameter combination for each factor: vibration amplitude of 44 mm, spacing of the vibrating rods of 24 mm, and vibration frequency of 9 Hz. Conduct a new verification experiment using optimized parameters to validate their effectiveness. The verification experiment was conducted on July 15, 2022. To eliminate random errors during the experiments, the test was repeated 10 times. The results of the verification experiment indicated that 235 ripe fruits were harvested, 51 ripe fruits were not harvested, 29 unripe fruits were harvested, 426 unripe fruits were not harvested, and 18 ripe fruits were damaged. After calculation, it was obtained that the picking rate of ripe fruit of 86.44%, the picking rate of unripe fruit of 6.81%, and the damage rate of ripe fruit of 5.54%.

In some excellent large-scale vibration equipment of other fruits, its optimal picking rate can reach over 90% (Chen *et al*. 2021a; Zhang *et al*. 2020). However, due to the infinite inflorescence characteristics of *L. barbarum*. Excessive vibration intensity of the harvester could lead to an increase in the picking rate of unripe fruit, while insufficient vibration intensity results in a low picking rate of ripe fruit. Therefore, the design and parameters of the harvester need to consider multiple evaluation indexes. Compared to handheld harvesters of *L. barbarum*, large-scale harvesters face a more complex situation, which usually reduces the harvesting effect. However, the 86.44% of picking rate of ripe fruit could basically meet the harvesting needs. This article focuses on the characteristics of infinite inflorescence and designed a large-scale vibration harvesting machine suitable for *L. barbarum*, provides a foundation and reference for the realization of mechanical harvesting.

Conclusions

This study measured various parameters of the standardized hedge cultivation mode for *L. barbarum*, including plant height, plant spacing, layer height, and layer width, which serve as reference data for the subsequent design of the harvesting machine. Based on the principle of vibration harvest, a vibration harvesting machine was designed, with the picking rate of ripe fruit as the evaluation criterion. Through a Plackett-Burman experiment, eight factors, including vibration frequency, vibration amplitude, spacing of the clamping rods, and spacing of the vibrating rods, were analyzed. The experiment result indicated that vibration frequency, vibration amplitude, and spacing of the vibrating rods had significant impacts.

Using response surface methodology, parameter experiment was conducted for these three factors. The analysis included their effects on picking rate of ripe fruit, picking rate of unripe fruit, and damage rate of ripe fruit. The optimal parameter combination was determined to be: vibration amplitude of 44 mm, spacing of the vibrating rods of 24 mm, and vibration frequency of 9 Hz. The verification experiment showed that the picking rate of ripe fruit was 86.44%, the picking rate of unripe fruit was 6.81%, and the damage rate of ripe fruit was 5.54%. This research provides a foundation and reference for the realization of mechanical harvesting.

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