DESIGN AND OPTIMIZATION OF A HUMAN–MACHINE COLLABORATIVE VIBRATION HARVESTING SYSTEM FOR *LYCIUM BARBARUM* L.

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枸杞人机协同振动采收系统设计与优化

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ABSTRACT

To address the challenges of labor-intensive and inefficient manual harvesting of Lycium barbarum L. grown on a double-layer trellis, this study proposes a human–robot collaborative system. The system consists of a hand-held high-frequency rocker-oscillator harvester and an electric receiving cart. Mechanical property measurements of fruits and branches revealed detachment forces of 1.2 to 1.8 N for mature fruits and 2.5 to 3.0 N for immature fruits, with an average bending elastic modulus of 548.9 MPa for fruit-bearing branches, providing a basis for selective harvesting. A Box–Behnken design was employed to optimize vibration frequency, harvesting duration, and inter-rod spacing, and response surface analysis identified the optimal parameters as 18 Hz, 4.5 s, and 26 mm. Next, a central composite design optimized the receiving cloth tilt angle and radius to maximize collection efficiency, defined as the ratio of fruits collected by the cart to the total number of detached fruits. Field validation demonstrated a mature fruit harvesting rate of 96.2%, a mis-harvesting rate of 4.3%, a damage rate of 3.7%, and a collection efficiency of 96.1%, with relative errors below 0.5% compared to model predictions. These results confirm the system's effectiveness and provide technical support for standardized, low-damage mechanized fruit harvesting of Lycium barbarum L..

摘要

为解决双层篱架栽培枸杞人工采摘劳动强度大、效率低下的问题，本研究提出了一种人机协作采摘系统。该系统由手持高频摇摆振动采摘机与电动接果车组成。对果实及枝条力学特性的测定结果显示，成熟果实的脱离力为 1.2 至 1.8 N，未成熟果实为 2.5 至 3.0 N，果枝的平均弯曲弹性模量为 548.9 Mpa，为实现选择性采摘提供了理论依据。研究采用 Box–Behnken 试验设计对振动频率、采摘时长及振动杆间距进行了优化，并通过响应面分析确定最佳参数为振动频率 18 Hz、采摘时长 4.5 s 以及振动杆间距 26 mm。随后，利用中心复合试验设计对接果布的倾角与半径进行了优化，以最大化接果效率，接果效率定义为接果车收集到的果实数量占脱落果实总量的比例。田间验证结果显示，成熟果实采摘率达到 96.2%，误采率为 4.3%，损伤率为 3.7%，接果效率为 96.1%，各项指标实测值与模型预测值的相对误差均低于 0.5%。上述结果表明该系统具有高效、低损伤的应用潜力，为双层篱架栽培枸杞的标准化机械化果实采摘提供了技术支撑。

INTRODUCTION

The transition toward mechanization and intelligent technologies is of great significance for improving the production efficiency of *Lycium barbarum* L. *(Torregrosa et al., 2014)*. Owing to its indeterminate inflorescences and continuous multi-cropping fruiting, harvesting operations are frequent and labor-intensive *(Chen et al., 2025)*. At present, high-cost and low-efficiency manual harvesting remains predominant, constituting a major bottleneck for high-quality development of the industry. Therefore, the development of efficient and low-damage mechanized harvesting equipment is imperative.

Vibrational harvesting is the principal method for mechanized harvesting of *L. barbarum*, with notable progress in both hardware and operational strategies. The impact of shaker design, shaking position, and duration on fruit detachment efficiency has been experimentally tested in stone fruits such as apricots *(Erdogan et al., 2003)*. Canopy shaker systems for late-season oranges have also been studied to evaluate the effect of vibration parameters on fruit motion and detachment *(Castro-García et al., 2018)*, and the application of arrayed excitation units further enhances operational efficiency *(Mei et al., 2024)*.

Additionally, a variable-pitch combing brush device has been developed to achieve effective fruit detachment with reduced damage *(Zhang et al., 2018)*. Modifications to excitation methods can effectively increase harvesting efficiency *(Chen et al., 2025)*, while batch-specific parameter optimization improves overall yield *(Liu et al., 2025)*. Simulation and field trials have validated optimal parameter combinations *(Wang et al., 2025; Wang et al., 2026)*, and studies on energy transmission have revealed optimal excitation positions and resonance frequency for vibrational harvesting of *L. barbarum (Deng et al., 2025; Su et al., 2025; Zhao et al., 2021)*.

However, existing studies have mainly focused on fruit detachment, with limited attention to the receiving system. Portable harvesters typically rely on manually spread collection mats, resulting in high labor demands and significant fruit loss. Research on blueberries has shown that soft receiving surfaces can effectively reduce impact damage *(Yu et al., 2014)*, and rigid–flexible coupled collision models further optimize harvesting parameters *(Takeda et al., 2017; Wang et al., 2022)*. Additionally, proper selection of excitation frequency can improve picking rate *(Yu et al., 2024)*. Recent studies on mechanical harvesting systems in olives provide insights for power requirements and trunk shaker optimization *(Ghonimy et al., 2023)*, and analysis of coffee fruit-peduncle systems reveals vibration transmissibility and energy transfer for efficient harvesting *(Villibor et al., 2023)*. Studies on other small berry crops indicate that integrating harvesting and receiving functions can enhance efficiency and minimize fruit damage; multiple excitations improve fruit detachment, whereas mechanical analysis and transport optimization further reduce damage *(Sim et al., 2024; Komarnicki, 2025; Lyu et al., 2024)*. Nevertheless, systematic integration studies for *L. barbarum* remain lacking.

To address this gap, the present study proposes a human–machine collaborative harvesting approach with a portable vibrational harvester and an electric receiving cart. By integrating agronomic measurement, mechanical analysis, simulation, and field trials, key operational parameters are optimized to improve efficiency and reduce fruit damage, providing systematic support for mechanized harvesting of *L. barbarum*.

MATERIALS AND METHODS

Agronomic Parameter Measurement

Key agronomic parameters of goji berries, including plant height, row spacing, layer height, and layer width, were measured and are summarized in Table 1. These data serve as a reference for the design of subsequent harvesting equipment.

Table 1

Agronomic Parameters of Standard Double-Layer Trellis Cultivation

Agronomic Parameter	Description	Mean ± SD
Plant height (m)	Height from ground to the top of the plant	1.71 ± 0.12
Plant spacing (m)	Distance between centers of adjacent plants in a row	1.32 ± 0.10
Layer 1 height (m)	Height of first fruit-bearing branch layer from ground	0.73 ± 0.06
Layer 2 height (m)	Height of second fruit-bearing layer from ground	1.51 ± 0.30
Layer 1 width (m)	Horizontal width of the first layer fruit crown	1.27 ± 0.16
Layer 2 width (m)	Horizontal width of the second layer fruit crown	1.15 ± 0.23
Row spacing (m)	Distance between centers of adjacent rows	3.19 ± 0.35

The field study was conducted on goji plants cultivated by Ningxia Zhengqi Hong Industrial Development Co., Ltd. in Guyuan City, Ningxia, China. A standard double-layer trellis system was employed, with branches pruned to droop naturally, thereby minimizing inter-branch entanglement and facilitating mechanized harvesting (Fig. 1). The overall cultivation environment is depicted in Fig. 2.

Fig. 1 - Single Goji Plant Model

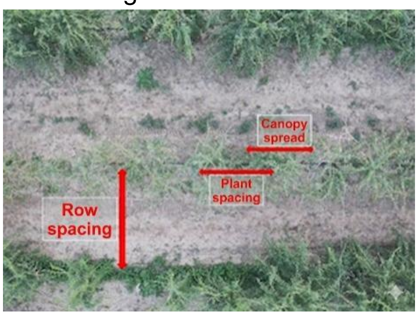


Fig. 2 - Cultivation Environment

Fruit Detachment Mechanical Parameters

The mechanical properties of goji berries at different physiological stages are crucial for designing vibration-based harvesting devices. Structural and compositional changes during maturation influence how easily the fruit detaches. The relationship between detachment force and moisture content is therefore critical for developing effective harvesting strategies.

To measure detachment force, a tensile load was applied along the peduncle at a constant speed, and the peak force at fracture was recorded. Mature fruits with 85–90% moisture content show peduncle shear forces of 1.2–1.8 N, whereas immature green fruits, despite sometimes exceeding 90% moisture, have more lignified peduncles and require higher detachment forces of 2.5–3.0 N.

As shown in Fig. 3, detachment force is negatively correlated with moisture content across all maturity stages. When moisture rises from 75% to 90%, mature fruits' detachment force decreases by ~30% to 1.2–1.8 N, while immature fruits decrease by only ~15%, remaining 2.5–3.0 N. This difference underlies the harvest-ripe, leave-unripe strategy, essential for selective mechanical harvesting and preventing damage to developing fruits.

Based on this relationship, vibration parameters can be adjusted in real time. For mature fruits with moisture above 85%, 15–20 Hz efficiently detaches them without stressing branches. Green fruits below 80% moisture require higher energy, naturally remaining attached under tuned excitation. These findings provide a theoretical basis for precise vibration control and intelligent, adaptive harvesting systems.

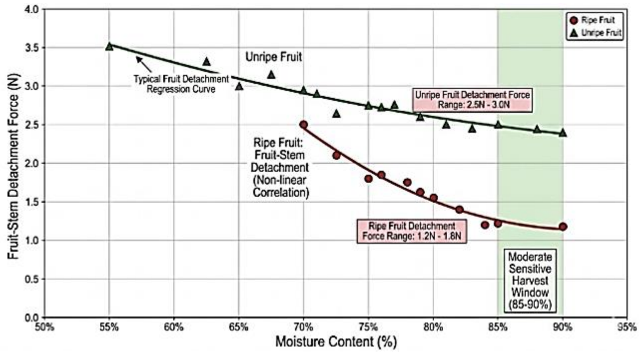


Fig. 3 - Hematic Illustration of the Relationship Between *Lycium barbarum L.* Detachment Force and Moisture Content

Analysis of Vibration Mechanisms

During operation of the portable goji harvester, the excitation rod induces forced vibrations in the "fruit–peduncle–branch" system. Statistical analysis identified three detachment modes: tensile break, fling-off, and impact detachment, with tensile break being predominant. The sequential stages of this process are illustrated in Fig. 4.

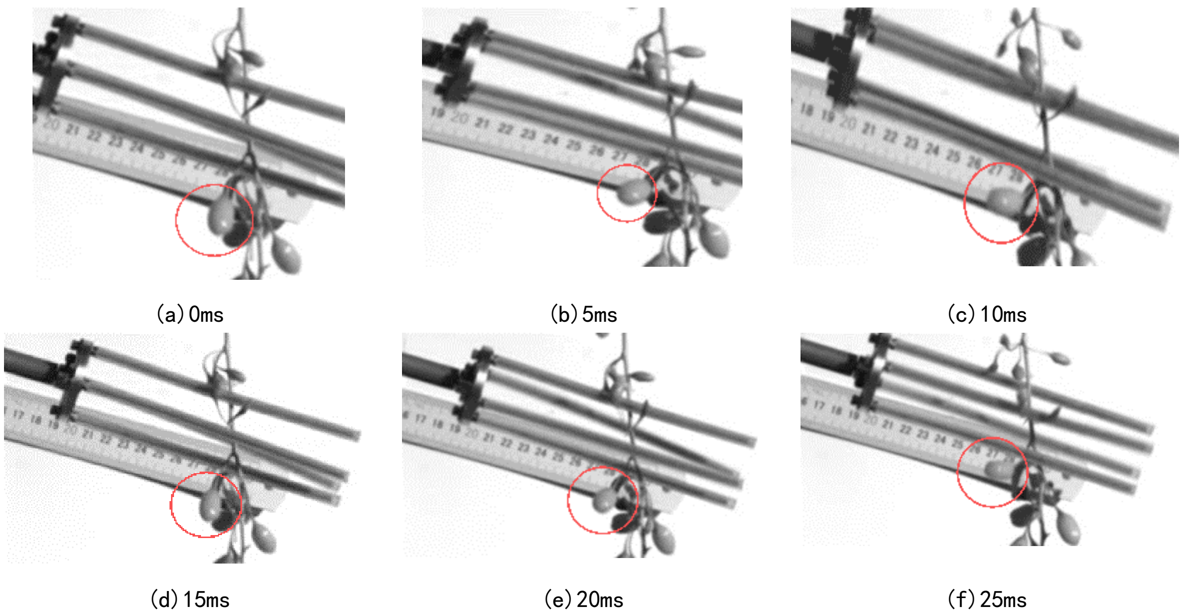


Fig. 4 - Sequence Diagram of Fruit Detachment During Vibration Harvesting

In the tensile break mode, vibration-induced tension in the peduncle generates a velocity difference between the branch and the fruit, while branch acceleration produces an inertial force exceeding the fruit–peduncle adhesion, causing detachment. As shown in Fig. 4a–f, the process follows six stages: (a) initial excitation and peduncle tensioning; (b) inertial sliding of the fruit after branch acceleration; (c) reverse branch motion and impact interaction; (d) secondary sliding after collision; (e) repeated peduncle tensioning during cyclic vibration; and (f) final fruit detachment. This sequence reveals that mature fruit removal is primarily driven by the accumulation of vibration-induced inertial force exceeding fruit–peduncle adhesion, which is essential for understanding the mechanism of selective harvesting. Notably, the repeated tensioning during cyclic vibration progressively weakens the peduncle connection, making final detachment more efficient.

A staged dynamic analysis of this vibration-induced detachment is summarized in Fig. 5, which illustrates the key mechanical interactions involved. During vibration harvesting, the fruit-bearing branch is regarded as an excitation carrier, and the fruit–peduncle system is simplified as a forced vibration system. The inertial force generated by vibration can be expressed as:

$$F_i = ma = m\omega^2 r \tag{1}$$

where F_i is the inertial force acting on the fruit (N), m is the fruit mass (kg), a is the vibration acceleration $(m \cdot s^{-2})$, ω is the angular velocity of vibration $(rad \cdot s^{-1})$, and r is the equivalent vibration radius (m).

Considering the combined effects of inertial force and gravity, the resultant tensile force acting along the fruit–peduncle connection can be described as:

$$F = \sqrt{(I\sin\theta + m\omega^2 r)^2 + (I\cos\theta - G)^2} \tag{2}$$

where F is the resultant tensile force acting on the fruit–peduncle connection (N), G is the fruit gravity (N), and θ is the angle between the peduncle and the vibration direction $(°)$. Fruit detachment occurs when $F > F_d$, where F_d is the measured fruit detachment force (N). Therefore, under appropriate vibration conditions, mature fruits with lower detachment force can be detached preferentially, while immature fruits with higher detachment force remain attached, thereby providing a clear mechanical basis for selective vibration harvesting. This principle ensures that only ripe fruits are removed during operation, leaving unripe fruits to continue maturing for subsequent harvests.

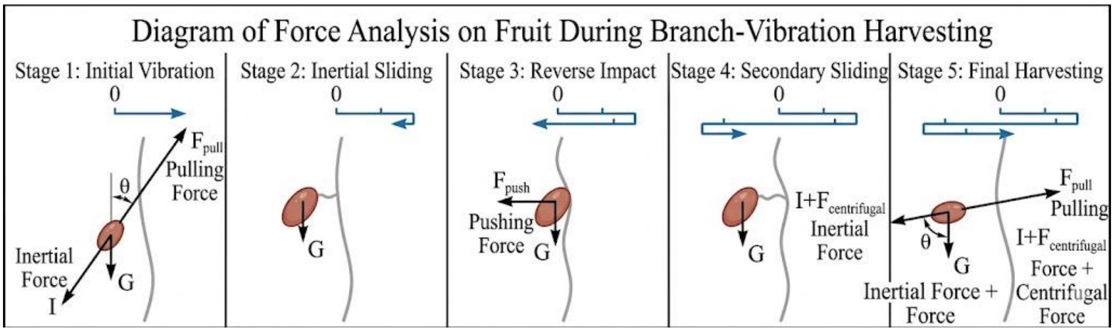


Fig. 5 - Schematic Diagram of the Dynamic Analysis of Fruit Detachment During Vibration Harvesting

During harvesting, the excitation rod applies direct vibration to fruit-bearing branches, inducing forced vibrations in the "fruit–peduncle–branch" system. Detachment forces differ among tissues: mature fruits require the least force, followed by flowers, while immature fruits and leaves require higher forces, with some overlap.

Vibration-based harvesting relies on inertial forces, and controlling vibration intensity is critical. By adjusting acceleration appropriately, mature fruits can be detached selectively while minimizing unintended detachment of other tissues. Calculated detachment accelerations rank in the order: mature fruits, immature fruits, leaves, and flowers, with minimal overlap, supporting effective selective harvesting.

Harvesting System Platform

A coordinated system was developed for mechanized Lycium barbarum L. harvesting, comprising a portable hand-held harvester and an electric fruit-collecting cart. During operation, the harvester is guided by an operator to detach fruits using the excitation rod, while the cart positions a receiving cloth beneath the branches to collect the detached fruits. The platform is mounted on a mobile chassis, manually navigated along orchard rows, with a fixed frame supporting all components.

Design of the Harvesting Device

The portable harvester improves *Lycium barbarum L.* harvesting efficiency and reduces labor through mechanized vibration. Its rocker-oscillator mechanism ensures smooth, continuous oscillation, and the harvesting head is adjustable. The oscillating rod length can be varied to control vibration amplitude and angle, enabling precise excitation at the fruit–peduncle junction (Fig. 6). Goji berries of different maturity often coexist on the same branch, requiring selective harvesting. During operation, the excitation rod acts on fruit-bearing branches, transmitting high-frequency torsional torque. Mature fruits detach when inertial force exceeds peduncle adhesion, while immature fruits remain attached, achieving selective harvesting of ripe fruits (Fig. 7).

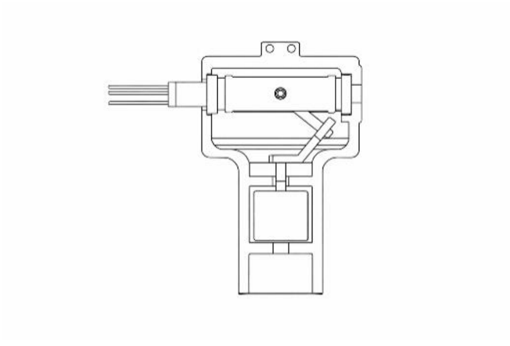


Fig. 6 - Schematic Diagram of the Hand-Held Harvesting Device Structure

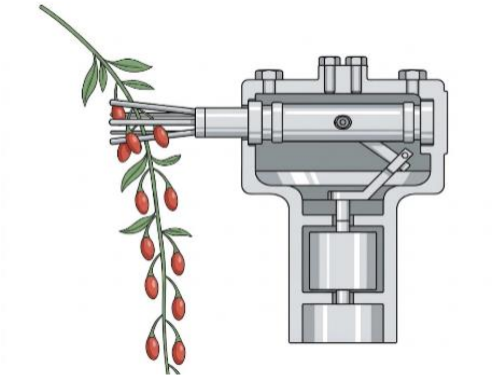


Fig. 7 - Operation Diagram of the Portable Harvesting Device

Design of the Receiving Device

A coordinated system combines a hand-held harvester with an electric collection cart. The operator vibrates fruit-bearing branches while the cart deploys a cloth to collect detached fruits, improving efficiency and reducing labor. The cart chassis fits the standardized double-layer trellis, with row spacing 3.19 m, canopy width 1.27 m, and inter-row corridor 1.92 m. Its width is 0.6 m, height 0.4 m, and length 1.6 m, allowing side-by-side operation and clearance under lower branches (first-layer branches average 0.73 m, lower traction line 0.61 m). The design lowers the center of gravity to enhance stability while accommodating 1.32 m plant spacing.

Based on its chassis dimensions, the receiving cart’s structure and workflow were designed to reduce fruit loss and labor intensity. The operator guides the cart along orchard rows using a push handle, while an electric-driven, manually assisted mechanism deploys flexible side cloths to form a semi-enclosed collection surface. The low-center-of-gravity chassis with wide wheel track ensures stability, and the worm-gear motor maintains position under impact. The canopy, tilted 20° downward with a cushioning layer, absorbs shocks and directs detached fruits into the storage basket. Fruits are collected as branches are vibrated by the hand-held harvester, and the canopy is retracted after harvesting (Fig. 9).

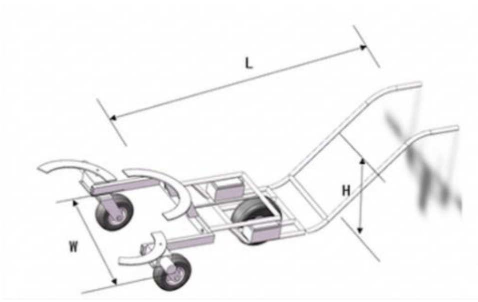


Fig. 8 - Three-Dimensional Structural Model of the Receiving Cart Chassis

Fig. 9 - Field Operation Diagram of the Receiving Cart

RESULTS

Experimental Design

To investigate the effects of vibration frequency X_1, harvesting duration X_2, and inter-rod spacing X_3 on harvesting performance, a Box–Behnken design was employed. The factor coding is summarized in Table 2.

Table 2

Factor Coding for the Portable Harvesting Device

Code	Vibration frequency X1 (Hz)	Harvesting duration X2 (s)	Inter-rod spacing X3 (mm)
1	20	5	40
0	15	3	30
-1	10	1	20

The mature fruit harvesting rate Y_1, mis-harvesting rate of immature fruits Y_2, and damage rate of mature fruits Y_3 were calculated as follows:

$$Y_1 = \frac{N_{hm}}{N_{hm} + N_{rm}} \times 100\% \tag{3}$$

$$Y_2 = \frac{N_{hi}}{N_{hi} + N_{ri}} \times 100\% \tag{4}$$

$$Y_3 = \frac{N_{dm}}{N_{hm}} \times 100\% \tag{5}$$

where N_{hm} is the number of harvested mature fruits, N_{rm} is the number of residual mature fruits, N_{hi} is the number of harvested immature fruits, N_{ri} is the number of residual immature fruits, and N_{dm} is the number of damaged mature fruits.

During each trial, the receiving device was carefully positioned precisely beneath the canopy, and the collection surface was fully deployed to ensure complete coverage of the target area and to maximize fruit capture efficiency (Fig. 10). The collection surface consists of a fixed central cloth and two motor-driven lateral arms that together envelop the trunk, forming a fully enclosed annular collection area around the base of the plant, effectively capturing all detached fruits and preventing losses. The harvester then applied controlled high-frequency excitation to fruit-bearing branches via the vibrating rods (Fig. 11), with vibration carefully tuned to avoid excessive stress. Detached fruits fell directly onto the tilted collection surface, rolled smoothly downward along the 20° slope, and gradually accumulated into the storage basket located at the lowest point. This carefully designed gravity-driven flow completely eliminates the need for manual fruit collection, minimizes handling, and effectively reduces impact damage by controlling both the distance and speed at which fruits fall before contacting the soft, cushioned collection surface.


Fig. 10 - Field Positioning of the Receiving Device


Fig. 11 - Vibration Harvesting Operation

Data Analysis

Using vibration frequency X_1, harvesting duration X_2, and inter-rod spacing X_3 as independent variables, and the harvesting rate of mature fruits Y_1, mis-harvesting rate of immature fruits Y_2, and damage rate of mature fruits Y_3 as dependent variables, trials were conducted sequentially for each treatment combination. The data are summarized in Table 3.

Table 3

Statistical Data of *Lycium barbarum L.* Vibration Harvesting Experiments

Index	X1	X2	X3	Y1/%	Y2/%	Y3/%
1	-1	-1	0	73.62	1.85	8.97
2	1	-1	0	69.34	5.2	6.5
3	-1	1	0	85.97	3.31	3.99
4	1	1	0	99.74	6.13	3.07
5	-1	0	-1	71.55	0.83	9.91
6	1	0	-1	90.16	1.77	6.6
7	-1	0	1	87.2	6.12	4.87
8	1	0	1	98.4	10.87	1.89
9	0	-1	-1	69.01	0.73	11.38
10	0	1	-1	85.88	2.6	7.12
11	0	-1	1	85.47	4.2	4.78
12	0	1	1	94.88	10.07	3.48
13	0	0	0	87.96	3.3	2.68
14	0	0	0	85.2	5.85	3.84
15	0	0	0	94.6	2.26	4.08
16	0	0	0	94.55	4.72	1.2
17	0	0	0	93.6	4.8	4.28

The experimental data were fitted using a second-order polynomial regression model, expressed as:

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} X_i X_j \tag{6}$$

Where Y represents the response variable, β_0 is the intercept coefficient, β_i, β_{ii} and β_{ij} are the linear, quadratic, and interaction coefficients, respectively, and X_i and X_j are the coded independent variables.

Based on the definitions of Y_1, Y_2 and Y_3 (Eq.3 – Eq.5), a second-order polynomial regression was applied to obtain models for each evaluation indicator, as given in Eq. 7 – Eq. 9:

$$Y_1 = 91.18 + 4.91X_1 + 8.63X_2 + 6.17X_3 - 6.02X_2^2 \tag{7}$$

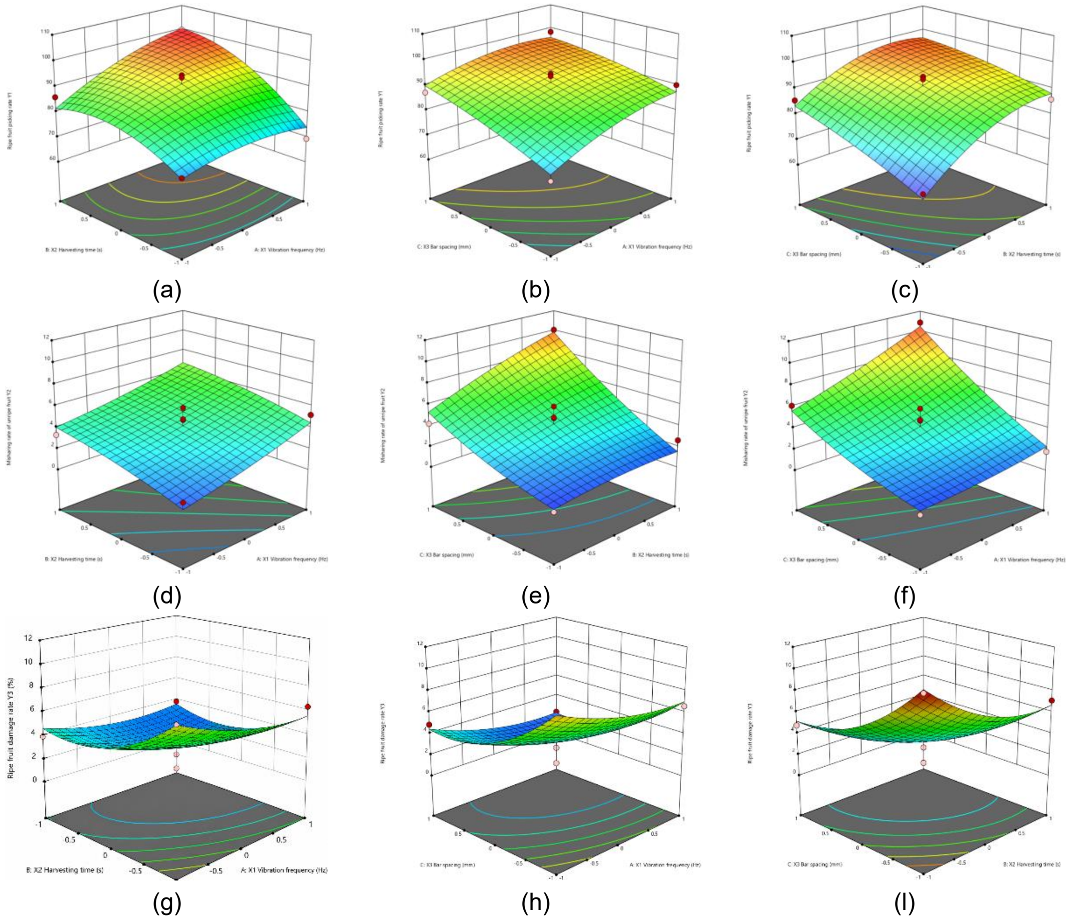
$$Y_2 = 4.19 + 1.48X_1 + 1.27X_2 + 3.17X_3 \quad (8)$$

$$Y_3 = 3.22 - 1.21X_1 - 1.75X_2 - 2.50X_3 + 1.64X_2^2 + 1.83X_3^2 \quad (9)$$

Analysis of variance (ANOVA) showed that the regression model for the harvesting rate of mature fruits Y_1 was significant $(P = 0.0095)$, with a non-significant lack-of-fit $(P = 0.3376)$ and $R^2 = 0.8980$. The model for the mis-harvesting rate of immature fruits Y_2 was highly significant $(P = 0.0083)$, with a non-significant lack-of-fit $(P = 0.5318)$ and $R^2 = 0.9020$. The model for the damage rate of mature fruits Y_3 was also highly significant $(P = 0.0025)$, with a non-significant lack-of-fit $(P = 0.7476)$ and $R^2 = 0.9321$. All three models showed good fit and high predictive reliability.

Parameter Optimization

The response surface analysis is shown in Fig. 12. Figs. 12(a–c) show the effects of harvesting duration, vibration frequency, and inter-rod spacing on the mature fruit harvest rate. Both duration and frequency initially increase the harvest rate, but saturation occurs beyond a certain threshold, indicating that most easily detached fruits have already been removed. Inter-rod spacing further improves overall harvest efficiency by reducing excitation blind zones, enhancing detachment from inner branches, and ensuring more uniform fruit removal across the canopy.



(a) (b) (c)

(d) (e) (f)

(g) (h) (l)

Fig. 12 - Response Surface Analysis

Figs 12(d–f) show the effects on mis-harvesting of immature fruits. Inter-rod spacing has the strongest influence, as wider spacing allows deeper penetration into the canopy, increasing unintended detachment. Vibration frequency and harvesting duration also contribute, with high-frequency, long-duration excitation potentially inducing peduncle fatigue.

Figs 12(g–i) illustrate effects on mature fruit damage, which exhibits a U-shaped trend. Narrow spacing leads to surface bruising, moderate spacing minimizes damage, and excessive spacing or duration causes secondary collisions, increasing peel rupture.

Multi-objective optimization identified the optimal combination as 18 Hz vibration frequency, 4.5 s harvesting duration, and 26 mm inter-rod spacing, predicting 96.47% harvest, 4.18% mis-harvesting, and 3.59% damage, balancing efficiency and fruit quality.

Based on the harvesting parameter optimization, the performance of the receiving device was further optimized. A central composite design (CCD) was used, with the receiving cloth tilt angle (20–40°) and radius (70–100 cm) as independent variables. The factor coding is summarized in Table 4.

Table 4

Factor Coding for the Lycium barbarum L. Receiving Device

Index	Tilt Angle of Receiving Cloth A_1 (°)	Radius of Receiving Cloth A_2 (cm）
1	40	100
0	30	85
-1	20	70

The collection efficiency of the receiving device Y_4 was used as the evaluation indicator, as expressed in Eq.10:

$$\eta = \frac{m_1}{m_2} \times 100\% \tag{10}$$

where m_1 is the number of fruits collected by the receiving device, and m_2 is the total number of detached fruits. Upon completion of the trials, the results are summarized in Table 5.

Table 5

Statistical Data of Lycium barbarum L. Receiving Experiments

Index	Tilt Angle of Receiving Cloth A1（°）	Radius of Receiving Cloth A2（cm）	Collection Efficiency B（%）
1	20	70	88.4
2	40	70	88.9
3	20	100	67.1
4	40	100	67.6
5	20	85	85.7
6	40	85	86.2
7	30	70	95.5
8	30	100	74.5
9	30	85	92.8
10	30	85	93.1
11	30	85	92.6
12	30	85	93.2
13	30	85	92.9

A second-order polynomial regression was applied to the experimental data to obtain the regression model for the collection efficiency of the receiving device Y4, as expressed in Eq.11:

$$\eta = 92.92 + 0.25A_1 - 10.60A_2 - 6.98A_1^2 - 7.93A_2^2 \tag{11}$$

The regression model was highly significant $(P < 0.0001)$ with a coefficient of determination $R^2 = 0.9998$, indicating an excellent fit. Response surface analysis showed that collection efficiency increased and then decreased with both tilt angle and cloth radius, revealing a single optimum within the experimental range. Optimization to maximize collection efficiency yielded a tilt angle of 29.72° and a cloth radius of 76.83 cm, corresponding to a predicted efficiency of 96.33%. For practical control, these parameters were rounded to 30° and 77 cm.

Validation experiments under these conditions produced a harvesting rate of mature fruits of 96.2%, a mis-harvesting rate of 4.3%, a damage rate of 3.7%, and a collection efficiency of 96.1%. The relative errors compared to model predictions (96.47%, 4.18%, 3.59%, and 96.33%, respectively) were all below 0.5%, confirming the reliability of the optimization and the accuracy of the model.

CONCLUSIONS

This study developed a human–machine collaborative harvesting system for double-layer trellis-cultivated goji berries, integrating a hand-held high-frequency rocker-oscillator harvester and an electric receiving cart. Mature fruits had detachment forces of 1.2–1.8 N and immature fruits 2.5–3.0 N, with the average bending elastic modulus of fruit-bearing branches being 548.9 MPa, providing a basis for selective harvesting and simulation. The harvester, equipped with a flexible silicone-coated comb head and Hall-effect speed monitoring, delivered precise excitation at 15–20 Hz. The receiving cart, with a 1.6 × 0.6 × 0.4 m chassis and side-mounted cantilever canopy, formed a ring-shaped collection area of 50–180 cm diameter with a 20° downward tilt. Response surface optimization identified operational parameters of 18 Hz vibration frequency, 4.5 s harvesting duration, 26 mm inter-rod spacing, 30° cloth tilt, and 77 cm radius. Field validation achieved a mature fruit harvesting rate of 96.2%, mis-harvesting rate of 4.3%, damage rate of 3.7%, and collection efficiency of 96.1%, with relative errors below 0.5%, demonstrating the platform’s effectiveness for high-efficiency, low-damage harvesting.

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