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EXPERIMENTAL DESIGN OF A SYMMETRICAL ECCENTRIC VIBRATION HARVESTER FOR WALNUTS

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KEYWORDS

walnut tree, vibration harvesting, parameter optimisation.

ABSTRACT

Under the cultivation mode of walnut dwarfism and dense planting, existing walnut vibration harvesting machinery has the problems of poor adaptability and low harvesting efficiency. A vibration walnut harvester was designed, paying particular attention to the design of the trunk clamping mechanism, the symmetrical double eccentric vibration mechanism, and the hydraulic control system; determination of the optimal harvesting parameters was also undertaken. A forced vibration dynamics model of the tree was developed and the fruit shedding dynamics equation was built. The key factors influencing harvesting performance were determined, including the mass of the eccentric block, the vibration frequency, and the clamping height. In order to determine the optimal working parameters, a three-factor, three-level field performance test was conducted, resulting in a regression model for fruit picking rate and tree vibration acceleration. The test results showed that, when the mass of the eccentric block was set to 63.2 kg, the vibration frequency was 8.7 Hz and the clamping height was 83.2 mm. A walnut picking rate of 90.42% was achieved and the tree vibration acceleration reached 55.02 m/s², which meets the operational requirements for walnut harvesting. This study provides a theoretical foundation for improving the efficiency of vibratory harvesting of walnut trees.

INTRODUCTION

Walnuts are one of the four major edible dried fruits worldwide; they are distributed and cultivated in over 50 countries and regions, across six continents (Fordos et al., 2023). One of their main areas of origin is China, with a planting area of 7.45 × 106 hm^2 and a yield (dry weight) of 5.4035 × 10^6 tons, ranking it number one in the world (Fao, 2022). Harvesting is a critical step in walnut production, which is characterised by strong seasonality and high labour intensity. The labour required for harvesting accounts for 35% to 45% of the total labour used in the entire production process. At present, walnut harvesting mostly relies on manual harvesting or assisted picking with simple tools and machinery. Although various agricultural machinery brands and technical methods are available, the problems encountered by walnut harvesting machinery include: low efficiency, damage to the branches, and drawbacks in recognition systems. These result in poor applicability and a low utilisation rate (Wang et al., 2009). Therefore, as the imbalance between the growth of walnut production and labour shortage becomes increasingly prominent, there is an urgent need to develop high-performance mechanical walnut harvesting equipment.

At present, research into mechanised harvesting technology for forest fruits mainly focuses on one-time combined fruit harvesting and vibration harvesting followed by fruit collection. Mechanised vibration picking has been found to be more than three times as efficient as manual and traditional methods, especially for fruits with hard impact-resistant shells, such as walnuts, because it reduces damage during the detachment process (Camposeo et al., 2023). Studies have demonstrated that vibration-based harvesting is feasible for walnuts, with efficiencies up to three times that of manual methods (Jiao et al., 2024; Zhang et al., 2011). Research into vibration-based harvesting technology has been a key area of focus and several studies have explored the effects of parameters like vibration frequency and amplitude on harvesting performance (Du et

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al., 2019; Wang et al., 2024). Common vibration harvesting machines, such as eccentric vibration, rocker link, and pneumatic vibration types, have been the focus of various studies aimed at improving vibration harvesting systems (Fu et al., 2018; Hoshyarmanesh et al., 2017). Research has primarily concentrated on optimising the vibration parameters, such as frequency and amplitude. The diverse types of vibration harvesting machines (eccentric, rocker link, and pneumatic) suggest different approaches to achieving the desired results, each being better suited to specific operating conditions or tree types. There has also been research into the impact of canopy and tree characteristics on harvesting performance (He et al., 2019). Castro-Garcia et al. (2018) studied the fruit separation process and found that, by improving the design and management of the canopy vibration system, the risk of damage to trees and fruits during mechanical harvesting can be reduced. This suggests that future developments in harvesting technologies should take into account both mechanical and biological factors (tree health, fruit ripeness, etc.). The mechanical harvesting of fruit and nut trees, utilising technologies like limb, trunk, and canopy shakers, improves efficiency but requires careful consideration of the tree characteristics, fruit properties, and vibration techniques (Jia et al., 2025). Mechanical harvesting, employing technologies like shakers and catch frames, improves efficiency but faces challenges such as tree injury and high costs, with recent advancements in automation enhancing productivity and reducing operator dependency (De Langre, 2019).

As well as walnuts, research has spanned a variety of forest fruits, including blackcurrants, oil tea, and olives, showing that vibration harvesting is a widely used forest fruit harvesting technology. This indicates that there is a trend towards developing more generalised vibration harvesting technologies that can be adapted to different tree species and fruit types. Castro-Garcia et al. (2018) reported that they analysed the dynamic behaviour of olive trees under forced vibration using modal testing techniques, identifying primary vibration modes and damping characteristics, with the trees predominantly acting as mass-damped harmonic oscillators in these modes (Afsah-Hejri et al., 2021). Wang et al. (2024) investigated the vibration response of walnut tree trunks to excitation from harvesting devices, analysing the vibration transmission dynamics between the excitation device and the tree, the impact of damping on response attenuation, and the phase relationships between various points on the fruit tree. Wang et al. (2012) established a dynamic model of the walnut tree-harvester vibration system and designed an eccentric forest fruit vibration harvester. Wu et al. (2021) established a double pendulum dynamic model of the oil tea "fruit-branch" and designed a crown-excited oil tea fruit harvester. They proposed a method combining finite element simulation and vibration testing to determine the natural frequency and modal vibration mode of olive trees, and determined the optimal vibration parameters for harvesting through harmonic response analysis (Niu et al., 2022). While vibration-based methods show significant promise in terms of efficiency, more work is needed to optimise systems for different types of trees and canopy structures. Considering that current walnut planting in China mostly adopts the dwarfing and dense planting mode, existing fruit harvesting machines are generally large and medium sized tools which require a lot of working space; these machines are suitable for sparse orchards (He et al., 2025; Liu et al., 2023). Therefore, the adaptability of mechanised operations is poor and it is difficult to effectively solve the walnut harvesting problem by using existing models directly.

In this study, in order to investigate the optimal combination of vibration picking parameters for branches at different positions on walnut trees and guide the design of walnut vibration picking machines, a walnut vibration harvesting machine was designed, characterised by the need for only a small working space but with strong adaptability to mechanised operations. The key innovations included a specially designed trunk clamping mechanism, a symmetrical double eccentric vibration system, and a hydraulic control system. Through a three-factor, three-level field test, optimal parameters were determined, thus enhancing harvesting efficiency and providing a theoretical and technical foundation for improving vibratory harvesting practices.

MATERIAL AND METHODS

Figure 1 shows that the study is divided into three modules, which build upon each other. The process begins with the conception phase, where the theoretical analysis and mechanisms of the harvesting machine are defined. This is followed by the design phase, which involves creating the machine’s structure, components, and control systems. Next, the design undergoes experimental verification, where key parameters are tested and optimised for real-world conditions. Finally, the testing results are used to refine and finalise the design, ensuring optimal performance. Each phase informs and improves the next, leading to a continuously refined walnut harvesting machine.

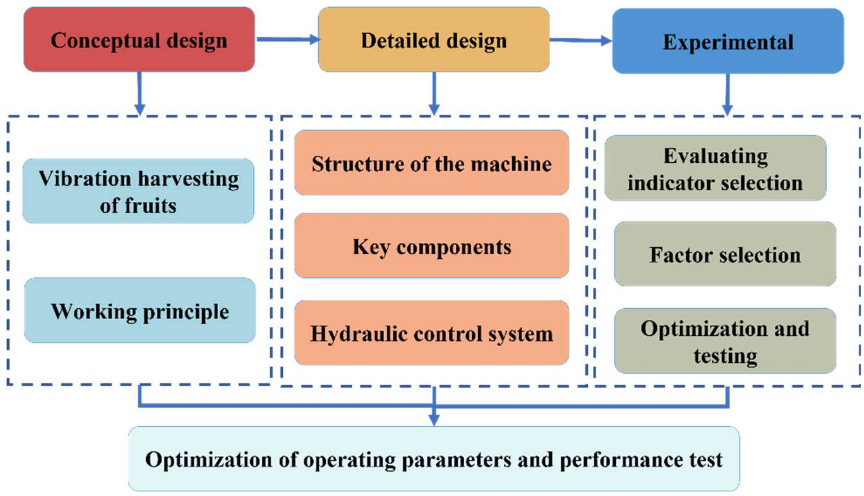


FIGURE 1. Material and method flow chart.

A preliminary bench test design was created, using the clamping mechanism identified in Module 1 as a key component of the entire harvesting device. Evaluation indicators and factors for harvesting performance were determined and the data from these tests were optimised using response testing. The final optimisation results were validated and evaluated for performance.

Structure and working principle of the whole structure

The symmetrical eccentric vibration walnut harvester consists of a power plant, a vibration mechanism, an adaptive truss, a directional adjustment mechanism, and a clamping mechanism, as shown in Figure 2. Specifically, the power plant features a hydraulic pump, oil tank, and corresponding oil circuit. The directional adjustment mechanism comprises a frame, truss, suspension chain, and hydraulic lifting cylinder. The clamping mechanism includes an activity clamp block, a symmetrical eccentric vibration mechanism, and a swing rod (a parallel four-bar mechanism). The harvester is attached to the tractor using a three-point suspension system, with power input from the tractor through a power input shaft. The truss is hinged to the frame by a hydraulic lifting cylinder, while the vibration harvesting device is suspended by a hooking chain, allowing for easy positional adjustments during its operation. The clamping mechanism, operated by a hydraulic cylinder, tightens around the walnut trunk, while the vibration source from the symmetrical eccentric vibration mechanism excites the trunk.

FIGURE 2. Structure of symmetrical eccentric vibration harvesting machine for walnuts.

The working principle of walnut harvesting machinery relies on the use of mechanical vibrations to dislodge mature walnuts from the tree trunk. The machinery is equipped with a vibration mechanism, typically consisting of an eccentric block, which generates rapid, high-frequency oscillations. This vibration mechanism is mounted on a clamping device that grips the walnut tree trunk. When activated, the vibrations are transmitted through the trunk, creating a shaking force that detaches the walnuts from their branches by disrupting their attachment to the stems. A hydraulic control system regulates the position and clamping force of the harvesting device, ensuring optimal contact with the tree trunk while preventing damage. Thus, the biggest advantage of this machine is its strong working mobility, allowing it to efficiently move from one tree to another. Depending on the design, the system can be either tractor-mounted, leveraging the tractor for power and mobility, or a standalone unit with an integrated mobile base. This versatility makes the machinery adaptable to various orchard layouts and operational requirements.

Design of harvesting device

The harvesting machine utilises symmetrical double eccentric vibration as its core mechanism for fruit picking, with the vibration harvesting device serving as the central component of the system (Zhou et al., 2014). The symmetrical eccentric vibration mechanism comprises a hydraulic motor, pulley, belt, transmission gear, symmetrical double eccentric block, and cover plate. The clamping mechanism includes a hydraulic clamping cylinder, a moving-end clamping arm, a fixed-end clamping arm, and a rubber pad. During operations, the clamping mechanism grips the tree trunk by coordinating the actions of the hydraulic cylinder, moving arm, and fixed arm. The vibrations generated by the high-speed rotation of the symmetrical double eccentric block are transmitted through the vibration arm to the clamping mechanism and, subsequently, to the tree trunk. The vibration harvesting device is suspended from the harvesting machine via a suspension chain connected through swinging rods and lifting ears, allowing for the self-excited vibration of the device. The design of the vibration harvesting device must ensure that the clamping force and clamping height range of the mechanism align with actual production requirements. This optimisation is critical to achieving efficient and effective harvesting, whilst maintaining the integrity of the tree and minimising fruit damage (Zhang et al., 2023).

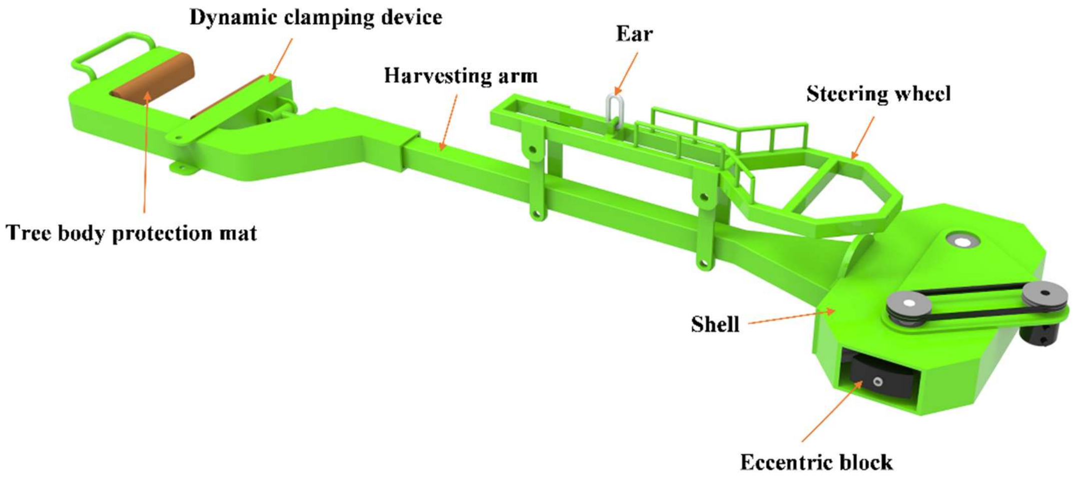
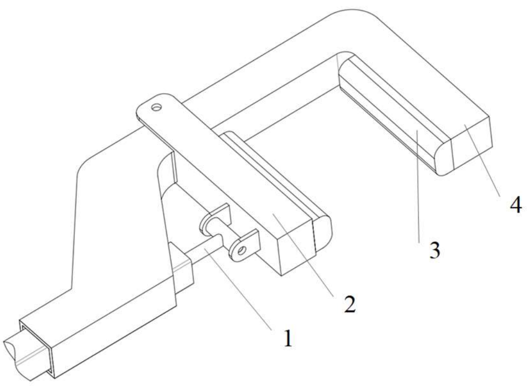


FIGURE 3. Structure of symmetrical eccentric vibration harvesting device for walnuts.

Design of clamping mechanism

As shown in Figure 4, the clamping mechanism comprises a hydraulic clamping cylinder, a movable clamping arm end, a fixed clamping arm end, and rubber pads. The piston rod of the hydraulic clamping cylinder is attached to the movable end of the clamping arm, enabling the clamping mechanism to secure the tree trunk by adjusting the hydraulic cylinder, in coordination with the fixed arm end. In order to protect the tree trunk and ensure clamping force during operation, rubber pads are installed on the contact surfaces of the fixed and movable clamping arms, reducing the risk of tree damage while maintaining a firm grip.



1. Hydraulic clamping cylinder; 2. Movable clamping arm end; 3. Rubber pads; 4. Fixed clamping arm end.

FIGURE 4. Structural diagram of the clamping mechanism.

In order to reduce the weight of the vibration device and improve harvesting mobility, a compact one-way hydraulic clamping cylinder was designed, as shown in Figure 5. The cylinder diameter was 60 mm and the piston rod had a diameter of 30 mm. In addition, considering that the diameters of walnut tree trunks typically range between 80 mm and 250 mm, the piston rod stroke was designed to be 300 mm, to ensure that the clamping mechanism could adapt to trunks with different diameters.

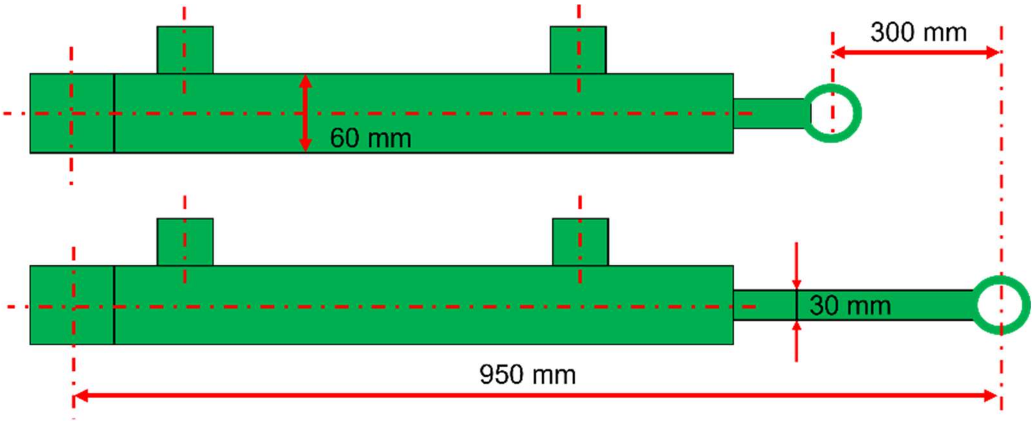


FIGURE 5. Structural diagram of the clamping mechanism.

When the pressure oil entering the left and right-hand chambers was the same, due to the presence of the piston rod, the effective working area was different, resulting in a difference in thrust between the two directions of the hydraulic clamping cylinder. The thrust in each direction can be calculated using the following equations:

$$F_1 = (p_1 A_1 - p_2 A_2)\eta = \frac{\pi}{4}\left[D^2 p_1 - (D^2 - d^2) p_2\right]\eta \quad (1)$$

$$F_2 = (p_1 A_2 - p_2 A_1)\eta = \frac{\pi}{4}\left[D^2 - d^2) p_2\right]\eta \quad (2)$$

in which

F_1 - force of the pressure oil entering the rodless chamber, N;

F_2 - force of the pressure oil entering the rod chamber, N;

P_1 - pressure in the high-pressure chamber, MPa;

P_2 - pressure in the return oil chamber, N;

A_1 - effective working area of the rodless chamber piston in the hydraulic cylinder, mm^2;

A_2 - effective working area of the piston with a rod chamber in the hydraulic cylinder, mm^2;

D - diameter of the hydraulic cylinder, mm;

d - diameter of the piston rod, mm;

η - mechanical efficiency of the hydraulic cylinder, %.

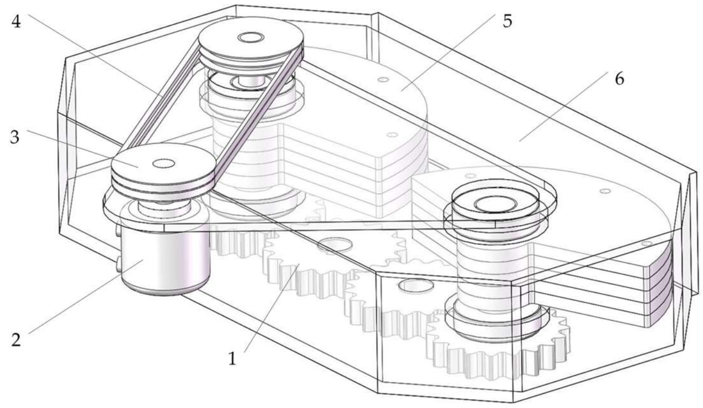
These equations account for the difference in effective working area caused by the piston rod, resulting in unequal thrust, despite the identical oil pressure in both chambers.

The hydraulic cylinder designed for the vibration harvesting device operates at a high chamber pressure (P_1) of 7 MPa and a return chamber pressure (P_2) of 6 MPa. When the mechanical efficiency (η) was 95%, the thrust in the direction of the piston rod (F_1) was 8550 N, and the thrust in the opposite direction (F_2) was calculated to be 2565 N.

Therefore, the maximum clamping force exerted by the device, which was used to grip the tree trunk, was 8550 N. Preliminary experiments have shown that walnut tree trunks with diameters less than 400 mm can safely withstand a maximum clamping force of approximately 9000 N, suggesting that our clamping mechanism design operated well within the safety limits. This indicates that the designed clamping mechanism can effectively grip tree trunks without causing mechanical damage, making it fully suitable for harvesting walnuts.

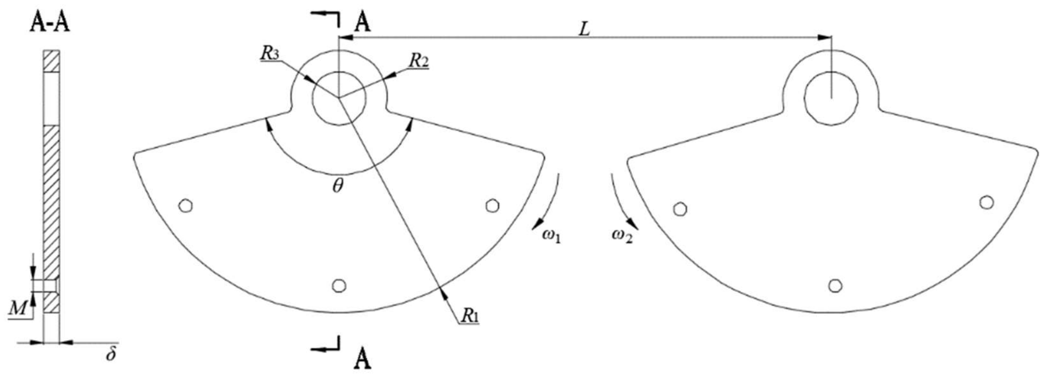
Design of vibration mechanism

Vibration was achieved by installing adjustable weight-rotating eccentric blocks on two axes. During operations, the eccentric block rotated at high speed around the axis, generating an excitation force. Eccentric blocks are typically categorised into three types: disc, fan, and heavy hammer. The disc type has a simple structure but generates a smaller excitation force and the manufacturing process is relatively complex. The fan type provides an excitation force between the two and is relatively simple to manufacture, so it is widely used. Therefore, the eccentric block designed in this study was fan-shaped, consisting of two overlapping fan-shaped blocks. These blocks were driven by the same motor, rotating at the same speed but in opposite directions, driven by a belt, pulley, and transmission gear system. Each eccentric block group consisted of 2-5 sub-blocks, with the specific number depending on the operational requirements. The number of sub-blocks for both eccentric blocks should be consistent. Two sets of symmetrical arrangements formed a symmetrical double eccentric vibration mechanism (Figure 6a). According to the operational requirements and design experience of the vibration acquisition device, the fan-shaped eccentric block had the specifications outlined below (Figure 6b). The vibration mechanism was capable of modulating the amplitude of the excitation force through the addition or reduction of eccentric blocks, thereby accommodating walnut trees of varying ages.



1. Transmission gear; 2. Hydraulic motor; 3. Belt pulley; 4. Belt; 5. Eccentric block; 6. Cover plate.

(a) Perspective schematic of vibration mechanism.



(b) Dimensions of the symmetrical double eccentric block.

FIGURE 6. Clamping mechanism structure diagram.

The fan had an angle of 150°, the radius of the large circle was 200 mm, the radius of the small circle was 45 mm, and the radius of the inner hole was 25 mm. The thickness was 15 mm and the central distance between the symmetrical eccentric blocks was 460 mm. The eccentricity of the fan-shaped eccentric block was calculated as follows:

$$e = \frac{38.197 \sin\theta (R_1^3 - R_2^3)}{\theta R_1^2 + (180 - \theta) R_2^3 - 180^{\circ} R_3^2} \tag{3}$$

$$m = \frac{\pi}{180}\left[\theta R_1^2 + (180^{\circ} - \theta) R_2^2 - 180^{\circ} R_3^2\right]\delta\rho \tag{4}$$

in which

e - eccentricity, mm;

m - weight of the eccentric block, kg;

ρ - eccentric block density, kg/m^3.

Based on [eq. (3)], it can be concluded that the eccentric distance e of the eccentric block was 25.65 mm. In addition, the eccentric block material used in this study was steel with a density of 7.85 × 10^3 kg/m^3. Combining [eq. (4)], the mass m of the eccentric block was approximately 8.00 kg and the calculation of the excitation force F of the eccentric block was calculated as follows:

$$F = me\omega^2 \tag{5}$$

Where:

ω is the angular velocity of the eccentric block (rad/s).

The relationship between rotational speed and angular velocity is:

$$\omega = \frac{2\pi n}{60} \tag{6}$$

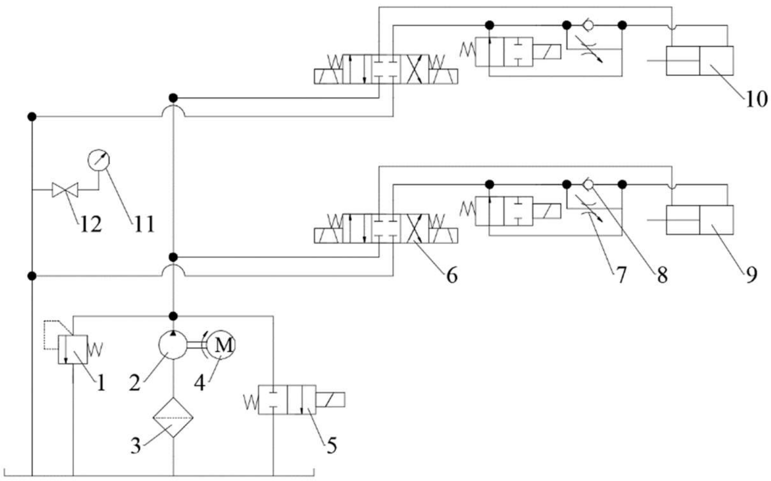
Where:

n is the working speed of the eccentric block (r/min).

The eccentric block speed of the designed picking machine could be adjusted, with a speed range of 600-1500 r/min. By combining eqs. (5) and (6), the maximum excitation force F of a single eccentric block was calculated to be 2250 N. For a symmetrical double eccentric vibration mechanism, a maximum of 10 eccentric blocks could be symmetrically arranged in two sets, resulting in a maximum excitation force of 22,500 N.

Design of hydraulic control system

In order to meet the clamping operation requirements of the harvester, a control system consisting of an engine, hydraulic pump, hydraulic motor, and hydraulic cylinder was developed. The hydraulic system primarily comprised a hydraulic pump, filter, one-way valve, hydraulic lifting cylinder, and hydraulic clamping cylinder. The operating principle of the hydraulic control system is depicted in Figure 7. The hydraulic pump displacement was dynamically adjusted by modulating the engine speed, allowing the pump to adapt to the real-time movements of the harvesting machine. This approach improved the energy utilisation efficiency of the system. The hydraulic pump served as the power source for the hydraulic lifting cylinder and the hydraulic clamping cylinder. The pump's output oil flowed through the one-way valve's oil port, to supply each hydraulic cylinder. These cylinders drove the harvesting device by adjusting the clamping degree and the height of the walnut trunk. A pressure gauge monitored the inlet flow pressure of the hydraulic motor. When the hydraulic motor's load exceeded its pressure threshold, a speed-regulating valve adjusted the flow rate to automatically compensate for load variations, ensuring accurate clamping and achieving closed-loop control. Pilot-operated relief valves and hydraulic control check valves provided system protection and control over the opening and closing functions, while the filter facilitated oil return filtration. During operations, each executing component functioned independently. The solenoid valve was activated and the hydraulic pump, powered by the engine, supplied the required hydraulic oil flow to the entire hydraulic control system.



1. Overflow valve; 2. Hydraulic pump; 3. Filter; 4. Motor; 5. Electromagnetic valve; 6. Electromagnetic directional valve; 7. Speed control valve; 8. Check valve; 9. Hydraulic lifting cylinder; 10. Hydraulic clamping cylinder; 11. Pressure gauge; 12. Switch.

FIGURE 7. Principles of the hydraulic control system.

Results and analysis of the factors affecting walnut harvesting

Forced vibration dynamics model of the tree body

Vibration harvesting involves the use of machinery to clamp and secure fruit trees to a rigid structure, followed by the induction of simple harmonic vibrations via a vibration device, which transfers energy to the fruit and induces accelerated motion. When the inertial force acting on the walnut tree exceeds the bonding force between the fruit and its stalk, the fruit naturally detaches from the tree. In order to investigate the factors influencing vibration during the harvesting of walnut trees, we developed a dynamic model of a walnut tree and analysed the key factors that affected vibration throughout the process.

The growth characteristics of fruit trees adhere to the Euler–Bernoulli beam theory, where the length of the tree trunk exceeds its cross-sectional dimension by five times. In this study, we simplified the trunk to a beam model with a uniform cross-section, where one end was fixed and the other was free, with a concentrated mass at the free end. The coordinate system (x, y) was defined with the root of the tree trunk representing the origin (O); a unit length of the beam was used for force analysis. Analysing the forces acting on a simplified beam model provided a deeper understanding of the mechanical characteristics of the fruit tree during the vibration harvesting process.

In vibration harvesting operations, walnut trees and harvesting machines constitute a continuous vibration system (Láng, 2006; San et al., 2018). For analytical and theoretical purposes, walnut trees are modelled as cantilever beam structures with a fixed end. The clamping mechanism of the harvesting machine is rigidly attached to the tree, enabling the walnut tree and harvesting device to be treated as a unified system. In the horizontal plane, the coordinate system is defined with the origin (O) being at the centre of the clamping position, the x-axis represents the horizontal motion direction and the y-axis represents the vertical motion direction of the vibration system. The mechanical properties of the tree are represented by an equivalent elastic coefficient (k) and an equivalent damping coefficient (c). The walnut tree harvesting device is further simplified into a single-degree-of-freedom vibration system and so a dynamic model of a symmetric double eccentric vibration harvesting system for the walnut tree was established, as shown in Figure 8.

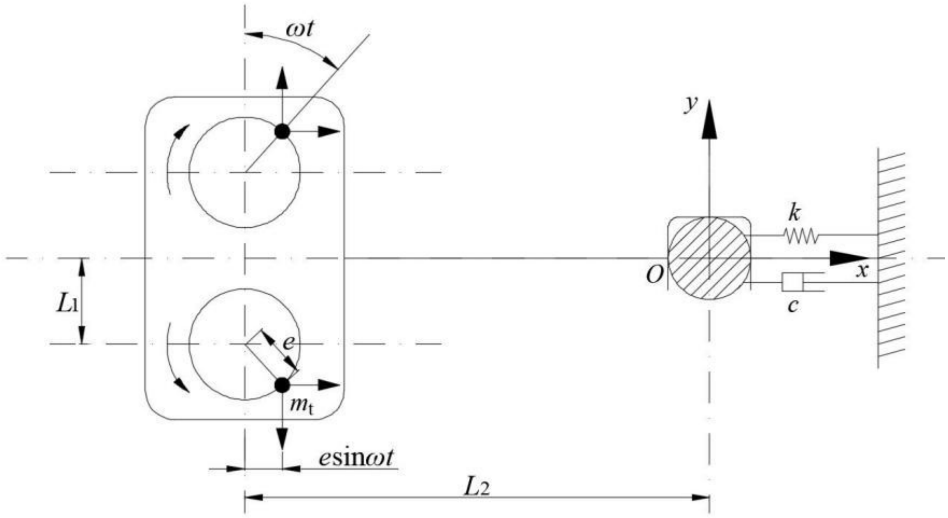


FIGURE 8. Principles of the hydraulic control system.

In Figure 8, m_t is the total mass of a single eccentric block (kg), e is the eccentricity of the eccentric block (m), ω is the angular velocity of the eccentric block (rad/s), T is time (s), L_1 is the distance between the centre of rotation of the eccentric block and the x-axis (m), L_2 is the distance between the centre of rotation of the eccentric block and the walnut tree (m), k is the equivalent elastic coefficient (constant), and C is the equivalent damping coefficient (also a constant).

During its operation, the two sets of eccentric blocks rotated at equal speeds but in opposite directions. Force analysis of the harvesting system revealed that the eccentric forces generated in the x-direction were equal in magnitude and direction. In contrast, the eccentric forces in the y-direction wee equal in magnitude but opposite in direction, causing their cancellation and resulting in a net force of zero in the y-direction. The differential equation governing the system's vibrations is as follows:

$$M_t \ddot{x}_1 + c\dot{x}_1 = 2m_t e\omega^2 t \sin \omega t \tag{7}$$

in which

M_t - total mass of the harvesting system, kg;

x_1 - x-direction displacement of the walnut tree from the origin, m.

When the excitation frequency approached the natural frequency of the tree, the harvesting efficiency was at its highest. A high damping ratio meant that vibration energy dissipated faster, thereby reducing potential damage to the trees. The dynamic equation assumes that the system is a linear system, without considering the nonlinear characteristics of trees or the interaction between the soil and the roots.

According to [eq. (7)], the calculation for the amplitude A and phase difference θ_1 of the system can be derived as follows:

$$\begin{cases} A = \dfrac{m_t e\omega^2 \cos\theta_1}{\sqrt{(k - M_t\omega^2)^2 + c^2\omega^2}} \\ \theta_1 = \arctan \dfrac{c\omega}{k - M_t\omega^2} \end{cases} \tag{8}$$

The walnut trunk vibration model was simplified to a cantilever beam structure with one end fixed (Theckes et al., 2011; Wang et al., 2025), as shown in Figure 9.

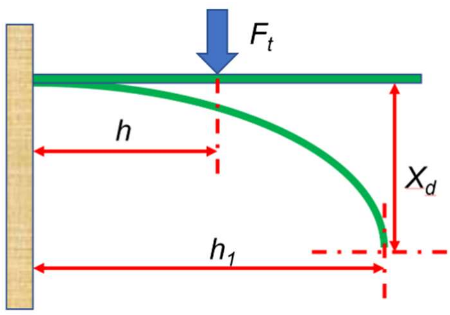


FIGURE 9. Principles of the hydraulic control system.

F_t is the excitation force (N), h is the clamping height (m), h_1 is the trunk height (m), and X_d is the trunk deformation (m). According to the deformation equation of a cantilever beam (Yu et al., 2023), the static deformation X_d of the tree trunk under harmonic force can be calculated as follows:

$$X_d = \frac{F_t h^2 (3h_1 - h)}{6EJ} \tag{9}$$

in which

E - elastic modulus of the tree trunk, MPa;

J - moment of inertia of the curved section of the tree trunk, m^4.

Walnut harvesting is a complex and dynamic process, accompanied by vibration energy transmitted to the fruit along various branches of the walnut tree. For ease of analysis, it is assumed that there is no relative displacement between the trunk, branches, and fruits; the relationship between the trunk vibration displacement x_1, branch vibration displacement x_2, and fruit vibration displacement x_3 is as follows (Wu et al., 2020):

$$x_1 = x_2 = x_3 = X_d \sin(k\omega t) \tag{10}$$

in which

K is a constant.

According to Maxwell's divergent hypothesis, the response at j caused by excitation at i is equal to the response at i caused by the excitation at j, and the energy transmitted by tree branch vibration should satisfy $\boldsymbol{Q}_i^j = \boldsymbol{Q}_j^i$. However, in the actual vibration process, due to the elastic and damping forces of the trunk and branches themselves (as well as external air resistance), the energy transmitted by the trunk and branches during the vibration process is less than the energy input by the vibration device. From this, it can be concluded that the energy Q transmitted to the walnut during the vibration process has the following relationship:

$$Q = Q_F - Q_{c1} - Q_{k1} - Q_{c2} - Q_{k2} - Q_a \tag{11}$$

in which

Q_F - total energy input to the vibration device, J;

Q_{c1} and Q_{c2} - damping energy consumed inside the trunk and branches, J;

Q_{k1} and Q_{k2} - energy consumed by the trunk and branches to resist the elastic recovery force, J;

Q_a - energy consumed by air resistance, J.

Taking into account the energy changes of the walnut trunk branch fruit system during vibration, the following formula is obtained from the kinetic energy theorem:

$$Q = \frac{1}{2}M_1(\frac{dx_1}{dt})^2 + \frac{1}{2}M_2(\frac{dx_2}{dt})^2 + \frac{1}{2}M_3(\frac{dx_3}{dt})^2 \frac{1}{2}I_c(\frac{d\alpha}{dt})^2 \tag{12}$$

in which

M_1, M_2, and M_3 - equivalent total masses of the trunk, branches, and fruit, respectively, kg;

I_c - moment of inertia of the walnut, kg/m^2;

α - swing angle of walnuts (°).

By combining eqs. (9), (10), and (11), the angular velocity of walnut swing can be calculated using [eq. (13)].

$$\frac{d\alpha}{dt} = \sqrt{\frac{2Q}{I_c} - \frac{(M_1 + M_2 + M_3)}{I_c}[\frac{k\omega F_t h^2 (3h - h)\cos(k\omega t)}{6EJ}]} \tag{13}$$

By taking the derivative of [eq. (14)], the angular acceleration of walnut swing can be obtained as:

$$\frac{d^2\alpha}{dt^2} = \frac{k^3\omega^3(M_1 + M_2 + M_3)\left[\frac{F_t h^2 (3h_1 - h)^2}{6EJ}\right]\sin(k\omega t)\cos(k\omega t)}{\sqrt{2I_{cQ} - I_c(M_1 + M_2 + M_3)[\frac{k\omega F_t h^2 (3h_1 - h)\cos(k\omega t)}{6EJ}]}} \tag{14}$$

Main influencing factors of walnut fruit vibration shedding

We established a coordinate system with the origin O' located at the junction of the walnut stem and branch, the x' direction horizontal and y' direction vertical. The dynamic analysis is shown in Figure 10. During the vibration process, walnuts are subjected to their own gravity, inertial force, and stem tension. According to the d' Alembert principle, the inertial force can be decomposed into a normal inertial force F_{In}, which causes the walnut to generate axial tension along the stem, and a tangential inertial force F_{It}, which generates a moment at the connection between the stem and the branch. In addition, acceleration a is decomposed into normal acceleration a_n and tangential acceleration a_t; gravity can also be decomposed into normal and tangential gravity, G_n and G_t.

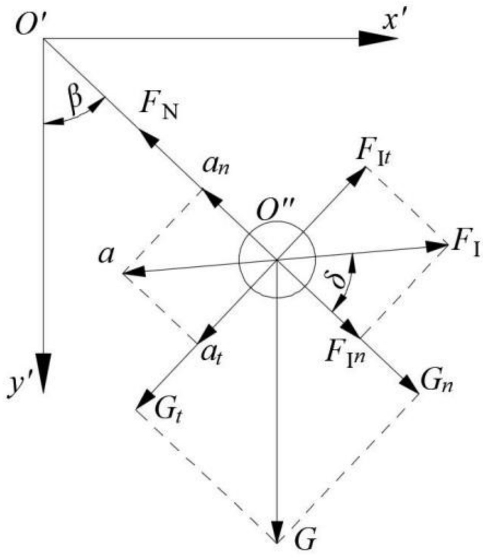


FIGURE 10. Dynamics analysis of walnut harvesting.

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn. Figure 10 shows the normal inertia force F_{In} and the tangential inertia force F_{It} of the walnut, which can be calculated as follows:

$$\begin{cases} F_{In} = m_w a_n = m_w R''(\dfrac{d\alpha}{dt})^2 \\ F_{It} = m_w a_t = m_w R''(\dfrac{d^2\alpha}{dt}) \end{cases} \tag{15}$$

in which

m_W - mass of the walnut, kg;

R'' - distance between the centre point of the walnut and the branch connection, mm.

When the walnut vibrates and falls off, the main considerations are the component force G_n of the walnut fruit's gravity on the fruit stem and the component force F_{In} of the inertial force on the fruit stem. Therefore, the fruit falling off should meet the conditions:

$$G_n + F_{In} > F_N \tag{16}$$

F_N is the connection force between the walnut stem and the branch (N). Therefore, when the walnut fruit falls off, the instantaneous acceleration obtained by the fruit should satisfy:

$$a = \sqrt{a_n^2 + a_t^2} > \frac{F_N - G_n}{m_w \cos\delta} \tag{17}$$

Where:

δ is the angle between the inertial force and the axis direction of the fruit stem (°).

By combining [eq. (15)] and [eq. (17)], the following can be obtained:

$$a = \frac{R''}{I_c}\sqrt{\left\{2Q-(M_1+M_2+M_3)\left[\frac{k\omega F_t h^2(3h_1-h)\cos(k\omega t)}{6EJ}\right]^2\right\}^2 + \frac{k^3\omega^3 R''(M_1+M_2+M_3)^2\left[\frac{F_t h^2(3h_1-h)\cos(k\omega t)}{6EJ}\right]^4 \sin^2(k\omega t)\cos^2(k\omega t)}{2Q-(M_1+M_2+M_3)\left[k\omega F_t h^2(3h_1-h)\cos(k\omega t)\right]}} > \frac{F_N - G_n}{m_W \cos\delta} \tag{18}$$

According to [eq. (18)], the main factors affecting walnut fruit shedding are excitation force, vibration frequency, and clamping height. Of these, [eq. (5)] shows that the magnitude of the excitation force is related to the mass and frequency of the eccentric block. Therefore, the mass of the eccentric blocks, vibration frequency, and clamping height are key factors affecting the shedding of walnut fruits. In the actual walnut harvesting process, selecting appropriate eccentric block mass, vibration frequency, and clamping height has a significant impact on the harvesting effect (Lin & Sun, 2021; Zhou et al., 2020).

Experimental conditions and testing indicators

Experimental conditions

Performance testing of a symmetrical eccentric vibration walnut harvesting machine was conducted at the Luoke Township Walnut Plantation in Yecheng County, Xinjiang Uygur Autonomous Region. The soil of the walnut garden is mainly sandy loam and loam, with relatively low surface moisture content. The test adhered to the national standard ‘General Provisions for the Determination of Test Conditions for Agricultural Machinery’, GB/T 5262-2008. Ten-year-old walnut trees were selected as test subjects. The plantation features a row spacing of 8 m and a plant spacing of 5 m. The trunks of the trees tested had an average diameter of approximately 20 cm, at a height of 80 cm above the ground, while the trees averaged 6.5 m in height, with a crown width of 4.5 m. Before the experiment, a plastic cloth was laid under the tree to receive fallen fruit. The dimensions of the cloth were larger than the maximum transverse diameter of the tree crown, in order to facilitate accurate statistics of harvest rate data. The vibration time for all experiments was one minute. The choice of a one-minute vibration duration in this study was based on preliminary experiments, which indicated that this duration provided stable and consistent fruit detachment under the tested conditions, particularly for trees with high fruit maturity. It is important to note that no visible damage to the trees was observed during or after the one minute vibration, indicating that this duration did not impose significant stress on the trees under the tested parameters.

Three walnut trees were selected for each experiment and a total of 41 fruit trees were harvested, taking the average as the experimental result. Each walnut tree was only harvested by vibration once and then the fruit harvesting rate and acceleration of the tree vibration were calculated. Given the significant influence of tree size and maturity on harvesting efficiency, the study carefully selected walnut trees with uniform size and maturity. Figure 11 shows the experimental field setup.

FIGURE 11. Photos of walnut mechanical harvesting experiment.

The objective of the experiment was to examine the effects of the structural and operational parameters of the harvesting machine on walnut harvesting performance. The primary goal was to identify the optimal combination of parameter values that would facilitate the efficient operation of the symmetrical eccentric vibration walnut harvesting machine (Niu et al., 2022). The experiment, based on a combination of institutional design and theoretical analysis, considered the mass of the eccentric blocks, vibration frequency, and clamping height as the key experimental factors. The fruit harvesting rate and excitation force were chosen as the evaluation indicators (Leone et al., 2015). The mass of the eccentric blocks was calculated for one set of blocks.

Fruit harvesting rate

The fruit harvesting rate was determined using the counting method. After the vibration of each tree, for a set duration of 10 seconds, the number of fallen fruits was collected and recorded. Subsequently, any remaining fruits on the tree were manually knocked down and the total number of fallen fruits was recounted. The net harvest rate was then calculated using the following equation:

$$P_c = \frac{N_1}{N_1 + N_2} \tag{19}$$

in which

P_c - fruit harvesting rate, %;

N_1 - number of fruits harvested by vibration, in pieces;

N_2 - number of fruits that did not fall off during vibration.

Excitation force

The excitation force refers to the amplitude of the harmonic alternating force exerted by the vibration mechanism on the main trunk of the walnut tree. The equation for its calculation is as follows:

$$F_1 = m_1 a_1 \tag{20}$$

in which

m_1 - equivalent mass of the walnut tree, kg;

a_1 - vibration acceleration of the walnut tree, m^2/s.

Because of the consistent size of the walnut trees used in this study, it can be assumed that the equivalent mass m_1 of each walnut tree used in the experiment is the same. Therefore, it can be inferred that the excitation force of walnut trees can be characterised by the vibration acceleration (a_1) (Dean et al., 2017; Láng, 2006). The vibration acceleration of walnut trees was measured using a vibration sensor (model WTVB01-485, Shenzhen Weite Intelligent Technology Co., Ltd.). Before testing, the sensor was fixed onto the tree trunk 80 cm above the ground and the specific fixing position was maintained at the fixed end of the mechanical support device. The sensor was connected to the computer through a data cable and real-time vibration related data was collected and stored using relevant data processing software. During the experiment, the sensor directly obtained the acceleration in three directions and the average acceleration in the X direction during the mid-vibration period was selected as the result.

The on-site data collection process is shown in Figure 12. Additionally, a set of vibration sensors was installed on the fixed end of the clamping arm of the harvesting machine's clamping mechanism during this experiment, to monitor the vibration parameters of the vibrating harvesting machine. The sensor was located on the tree, at a height of 120 mm from the ground, near the clamping limit end.

FIGURE 12. Method for measuring vibration data of walnut trees.

Setting of influencing factors

Using eccentric block mass (x_1), vibration frequency (x_2), and clamping height (x_3) as the experimental factors, and the fruit harvesting rate (y_1) and tree vibration acceleration (y_2) as the evaluation indicators, the experimental factor codes are shown in Table 1.

TABLE 1. Experimental factors and levels.

No.	Factor		
	Eccentric block weight (kg)	Vibration frequency (Hz)	Clamping height (mm)
1	48	12	100
0	64	10	80
-1	80	8	60

RESULTS AND DISCUSSION

Experimental plan and results

The field performance test of the harvesting machine was conducted using a three-factor three-level combination method (Lin & Sun, 2021). The experimental design scheme and results are shown in Table 2.

TABLE 2. Experimental plan and results.

No.	Factors			Fruit harvesting rate, y_1, (%)	Acceleration of tree vibration, y_2 (m/s^2)
	Eccentric block weight, x_1 (kg)	Vibration frequency, x_2 (Hz)	Clamping height, x_3 (mm)		
1	-1	-1	0	79.46	23.81
2	1	-1	0	69.90	32.32
3	-1	1	0	84.16	45.44
4	1	1	0	88.74	77.42
5	-1	0	-1	75.45	35.49
6	1	0	-1	83.50	76.98
7	-1	0	1	57.04	36.63
8	1	0	1	76.93	47.37
9	0	-1	-1	79.72	36.95
10	0	1	-1	81.87	71.46
11	0	-1	1	46.13	27.56
12	0	1	1	90.43	62.91
13	0	0	0	80.82	41.89
14	0	0	0	82.87	43.73
15	0	0	0	88.69	44.76
16	0	0	0	86.60	44.61
17	0	0	0	86.75	41.84

Regression analysis was performed on the experimental data presented in Table 3, using Design Expert 13.0 software. The results of the variance analysis for the fruit harvesting rate and tree vibration acceleration are presented in Table 2 and Table 3, respectively.

TABLE 3. Variance analysis of fruit harvesting rate.

Source of variance	Sum of squares	Fd	Mean square	F	P
Model	2053.44	9	228.16	12.71	0.0015**
x_1	186.53	1	186.53	10.39	0.0146*
x_2	674.27	1	674.27	37.55	0.0005**
x_3	312.56	1	312.56	17.41	0.0042**
x_1x_2	0.58	1	0.58	0.032	0.8623
x_1x_3	35.02	1	35.02	1.95	0.2053
x_2x_3	443.94	1	443.94	24.72	0.0016**
x_{12}	48.05	1	48.05	2.68	0.1459
x_{22}	18.07	1	18.07	1.01	0.3492
x_{32}	307.03	1	307.03	17.10	0.0044**
Residual	125.69	7	17.96		
Lack of fit	84.55	3	28.18	2.74	0.1774
Error	41.14	4	10.29		
Sum	2179.14	16			

Note: * * indicates extremely significant impact (P < 0.01). * indicates significant impact (0.01 ≤ P<0.01); the same applies below.

A *P*-value less than 0.01 indicates that the regression model is highly significant. According to Table 3, the vibration frequency (x_2), clamping height, interaction term, and the squared term (x_3) have a significant impact on the fruit harvesting rate. Additionally, the eccentric block mass (x_2x_3) also significantly affects the fruit harvesting rate. The eccentric block mass (x_1) is a direct parameter that affects the vibration force and has a significant impact on the recovery rate, indicating that changes in mass will significantly alter the shedding effect of walnuts. The vibration frequency (x_2) has a significant impact on recovery rate but its influence is greater than that of the eccentric block mass. The clamping height (x_3) has a significant impact on the recovery rate but its degree of influence is between the mass of the eccentric block and the vibration frequency. Based on these results, the most influential factors were identified and the regression equation between the fruit harvesting rate and the coded factor values was established.

$$y_1 = 85.15 + 4.83x_1 + 9.18x_2 - 6.25x_3 + 10.54x_2x_3 - 8.54x_3^2 \quad (21)$$

TABLE 4. Variance analysis of acceleration of tree vibration.

Source of variance	Sum of squares	Free degree	Mean square	F	P
Model	4180.94	9	464.55	80.39	<0.0001**
x_1	1074.62	1	1074.62	185.95	<0.0001**
x_2	2332.62	1	2332.62	403.64	<0.0001**
x_3	269.18	1	269.18	46.58	0.0002**
x_1x_2	137.71	1	137.71	23.83	0.0018**
x_1x_3	236.39	1	236.39	40.91	0.0004**
x_2x_3	0.17	1	0.17	0.030	0.8670
x_{12}	0.64	1	0.64	0.11	0.7497
x_{22}	4.13	1	4.13	0.71	0.4260
x_{32}	121.09	1	121.09	20.95	0.0026**
Residual	40.45	7	5.78		
Lack of fit	32.32	3	10.77	5.30	0.0705
Error	8.13	4	2.03		
Sum	4221.40	16			

Note: * * indicates extremely significant impact ($P < 0.01$). * indicates significant impact ($0.01 \leqslant P<0.01$); the same applies below.

According to Table 4, the eccentric block mass (x_1), the vibration frequency (x_2) and the clamping height (x_3) have a significant impact on the acceleration of tree vibration. The impact of the eccentric block mass and the vibration frequency on the acceleration of tree vibration are the same, while the impact of the clamping height on the acceleration of tree vibration is slightly smaller than that of the eccentric block mass and the vibration frequency. Based on these findings, the most influential factors were identified and the regression equation between tree vibration acceleration and the coded factor values was established.

$$y_2 = 43.37 + 11.59x_1 + 17.08x_2 - 5.8x_3 + 5.87x_1x_2 - 7.69x_1x_3 + 5.36x_3^2 \quad (22)$$

By analysing the regression coefficients of [eq. (21)] and [eq. (22)], it can be concluded that the primary and secondary factors influencing the fruit harvesting rate are vibration frequency, clamping height, and eccentric block mass, while the primary and secondary factors affecting tree vibration acceleration are vibration frequency, eccentric block mass, and clamping height. Regarding interaction effects, the only significant interaction term influencing the fruit harvesting rate is x_2x_3 (vibration frequency × clamping height), while the significant interaction terms influencing tree vibration acceleration are x_1x_2 (eccentric block mass × vibration frequency) and x_1x_3 (eccentric block mass × clamping height).

According to Figure 13a, the fruit harvesting rate initially decreases but then increases, as vibration frequency and clamping height are increased. As shown in Figure 13b, the vibration acceleration of the tree body rises with increases in both the mass of the eccentric block and vibration frequency. In Figure 13c, the vibration acceleration of the tree body increases with the mass of the eccentric block but it first decreases and then increases with increasing clamping height.

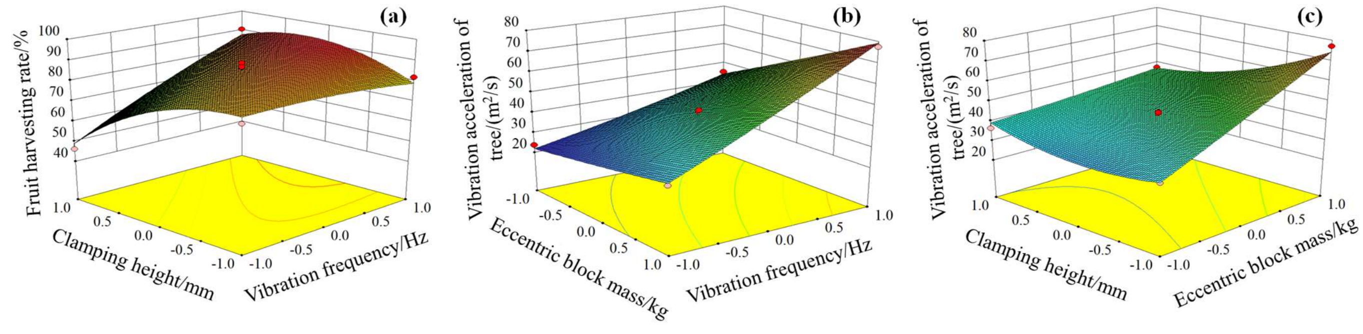


FIGURE 13. Index of response surface of factors.

Optimisation of work performance parameters

For vibration harvesting devices, it is essential to ensure high fruit harvesting efficiency while minimising tree vibration acceleration as much as possible. This is because higher tree vibration acceleration increases the likelihood of tree damage and raises the power consumption of the harvesting machine. Therefore, the optimal operational performance of the harvesting machine aims to achieve higher fruit harvesting efficiency at lower tree vibration accelerations. This study utilised the Design Expert 13.0 software optimisation module to perform constrained objective optimisation on the regression model of vibration harvesting for walnut harvesters. The goal was to identify optimal operational performance parameters. More specifically, this study considers maximising the fruit harvesting rate and minimising tree vibration acceleration as the optimisation objectives. Performance index objective functions were established and solved as follows:

$$F = \begin{cases} \min y_1(x_1, x_2, x_3) \\ \min y_2(x_1, x_2, x_3) \\ 6 \le x_1 \le 10 \\ 8Hz \le x_2 \le 12Hz \\ 60mm \le x_3 \le 100mm \end{cases} \tag{23}$$

The optimal parameter combination was found to be: an eccentric block mass of 63.2 kg, a vibration frequency of 8.7 Hz, and a clamping height of 83.2 mm. To verify the accuracy of the experimental results, field validation experiments were conducted under this parameter combination. For the convenience of parameter adjustment during practical operations, the eccentric block mass was set to 63 kg, the vibration frequency was 8 Hz, and the clamping height was set to 83 mm. The trunks of the tested trees had an average diameter of approximately 20 cm, at a height of 80 cm above the ground. Under these parameter conditions, the walnut picking rate reached 90.42% and the tree vibration acceleration was 55.02 m/s², indicating that walnut picking performance was at its most effective.

DISCUSSION AND ANALYSIS OF RESULTS

This study investigated the impact of vibration parameters on walnut harvesting efficiency, focusing on vibration frequency, amplitude, and clamping height as the key factors influencing fruit detachment. The optimal vibration parameters were determined by using a three-factor, three-level response surface analysis. A systematic comparison between walnut and other forest fruit harvesting technologies revealed that, despite shared core principles and parameter optimisation strategies, differences in fruit characteristics, tree structures, and cultivation practices necessitate distinct approaches to mechanical design, vibration transmission, and damage control.

The vibration harvesting device developed in this study has the advantages of being a simple structure and lightweight, which is in line with the current walnut planting mode in China. The dwarfing and dense planting mode is commonly used in walnut planting and the use of this lightweight machine can significantly improve the adaptability of mechanised walnut harvesting operations in China. Furthermore, the number of eccentric blocks is manually adjustable, enabling the vibration mechanism to modulate the amplitude of the excitation force by adding or removing eccentric blocks. This adaptability ensures compatibility with walnut trees of varying ages and varieties.

Vibration-based harvesting relies on vibrational separation, where mechanical energy transmitted to the tree structure induces fruit detachment through inertial forces. Optimisation of the frequency, amplitude, and duration directly affects harvesting efficiency and damage rates. For example, olive harvesting emphasises harmonic optimisation, while walnut studies focus on energy attenuation during vibration transmission (Leone et al., 2015; Niu et al., 2022). Dynamic properties of the trees, such as natural frequency, damping ratio, and vibration modes, are critical in determining harvesting effectiveness. Modal testing in olive trees refines vibrator parameters to enhance efficiency and reduce damage, while walnut studies improve energy transfer by analysing vibration attenuation. Future research should continue to investigate the biomechanical properties of walnut trees, establish vibration transmission models and optimise parameters, to improve mechanical harvesting efficiency, and reduce damage to the tree body.

The mechanised harvesting of walnuts can improve harvesting efficiency, reduce labour costs, optimise working parameters, and reduce equipment wear and tear. Optimisation of the parameters is easy to implement in practical operations because existing harvesting equipment only requires simple adjustments, such as replacing eccentric blocks or adjusting vibration frequency and clamping height. Therefore, for large-scale walnut plantations, optimised parameters can significantly reduce operating costs and improve harvesting efficiency, with is of high economic value. Besides this, prolonged vibration times could potentially lead to cumulative stress or damage in the long term, as highlighted in prior research. Therefore, future studies should focus on optimising the vibration duration by exploring shorter intervals and evaluating their effects on both fruit detachment efficiency and tree health. Additionally, the interplay between vibration duration, frequency, and amplitude should be further investigated, to achieve a balance between harvesting efficiency and minimal tree impact.

CONCLUSIONS

This study introduces a symmetrical eccentric vibration walnut harvesting machine, incorporating an innovative vibration harvesting system that integrates a clamping mechanism, a symmetrical double eccentric vibration mechanism, and a hydraulic control system. Comprehensive analysis and calculations of the key components and transmission system demonstrate that the harvesting machine achieves a maximum clamping force of 8550 N, for securely gripping the walnut tree trunk, and a maximum excitation force of 22,500 N on the tree body, meeting the design requirements.

(1) A forced vibration dynamic model was developed for the walnut tree body, to examine the primary factors influencing walnut fruit shedding. Through theoretical analysis, eccentric block mass, vibration frequency, and clamping height were identified as the primary parameters influencing walnut fruit harvesting efficiency. A dynamic equation describing the shedding process was established to quantify these effects.

(2) The experimental results indicated that the optimal operational parameters were achieved at an eccentric block mass of 63.2 kg, a vibration frequency of 8.7 Hz, and a clamping height of 83.2 mm. Under these conditions, the walnut harvesting rate reached 90.42% and the tree vibration acceleration was 55.02 m/s², demonstrating superior harvesting performance while adhering to the operational requirements of walnut harvesting.

This study addresses a significant academic gap by providing a vibration harvesting device that meets the performance requirements for efficient walnut harvesting. Furthermore, the findings improve the adaptability of mechanical harvesting devices to walnut trees of varying heights, offering valuable insights for the design and optimisation of future mechanical forestry fruit harvesting systems.

AUTHORS' CONTRIBUTION

Conceptualisation and writing—review and editing, funding acquisition, Liu J.; Investigation, Yang L.L.; Methodology, Ma W.Q.; Formal analysis, Mai Hemujiang Batuer; Data curation and Methodology, Shen X.H. All authors have read and agreed with the published version of the manuscript.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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