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INFLUENCE OF EXCITATION POSITION ON MECHANIZED PICKING EFFECT OF CAMELLIA OLEIFERA

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KEYWORDS

Camellia fruit, vibration picking, excitation height, canopy vibration.

ABSTRACT

Camellia oleifera oil is easily absorbed by the human body and has a high development prospect in the research and development of new drugs. However, the labor intensity involved in picking has limited the development of the camellia oil industry. Vibratory mechanized harvesting is considered to be an effective way to solve harvesting difficulties. In this study, the whole process of accelerating the mechanical vibration picking is analyzed theoretically, according to different vibration positions (height), and a vibration picking experiment is carried out. The ratio of the optimal excitation location to the years of growth of Camellia oleifera was found to be between 16 and 20. It was observed that with the increase of camellia growing years, this ratio gradually decreased, and its optimal vibration position showed an increasing trend. Further, when the excitation time was greater than 8 s, the fruit removal rate did not continue to increase, but the buds and leaves falling continued to decrease. This study can effectively improve the efficiency of camellia oil fruit picking and reduce the drop-off of camellia buds and leaves.

INTRODUCTION

Camellia oleifera is a unique oil species in China (Zhang & Wang, 2021). When the tree fruit is picked by vibration, the shedding of fruit is accomplished by providing vibration energy with an appropriate combination of parameters such as vibration frequency, amplitude and vibration time using a trunk or a canopy vibration device (Sargent et al., 2020). It has recently been proven that mechanical harvesting based on vibration technology is an effective technique to improve the harvesting efficiency and reduce the cost (Brondino et al., 2021; Pu et al., 2018; Zhao et al., 2021).

At present, the effects of the vibration mode and the vibration parameters on the fruit drop rate and fruit damage rate are the main subjects of study (Zhang et al., 2020; Wang et al., 2019; Castro-Garcia et al., 2018; Ortiz et al., 2021). Some authors studied the main factors affecting the removal rate of other fruits such as walnut, grape, apricot, citrus, and cherry (Zhou et al., 2016a; Zhou et al., 2016b; Torregrosa et al., 2009; Torregrosa et al., 2019). Zhou et al. (2014) studied the fruit removal efficiency of y-frame cherry trees and tested them by dividing them into four excitation zones using a hand-held vibrating screen. Xiao et al. (2021) studied the vibration harvesting of citrus. The results showed that crown vibration was the most effective method for the citrus harvest, and the vibration parameters significantly influenced the citrus harvesting efficiency. However, it was suggested that, in order to improve the harvesting efficiency, consideration should be given to adapting the tree canopy structure to position the harvesting machinery operations.

Many scholars have done much research on the picking of Camellia oleifera fruits by imitating the mechanized picking methods of other forest fruits and designed picking devices to realize the mechanized harvesting of the fruit (Zhao et al., 2011). Rao et al. (2018) designed an electric roller rotary picking actuator for camellia fruit. Wu et al. (2021) studied Camellia oleifera and found that it is a shallow root tree species, such that trunk vibration may cause it irreversible damage. A vibration shedding model of the Camellia oleifera fruit and a fruit–branch double pendulum dynamic model were established, and the main factors affecting the shedding of the fruit were found to be the amplitude, vibration frequency, and vibration time of the excitation device. A vibration picking device for the Camellia oleifera canopy was designed, and a field experiment achieved a good picking effect. These mechanized picking devices for camellia fruit in the literature are successful, and

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the corresponding optimal picking parameters were obtained using various field experiments.

Although in previous studies some scholars have proposed that the exciting location may affect the picking effect of vibration harvesting, no research has been carried out on the exciting location in the field of mechanized camellia oil harvesting. According to the previous analysis, there are differences in the biological characteristics of Camellia oleifera depending on how many years the tree has been growing. This study aims to identify the main determinants of the canopy vibration acceleration response of Camellia oleifera by theoretical analysis, and the optimum vibration position (height) of Camellia oleifera trees of different ages was determined by a field experiment. The results of this study can ensure the maximum harvest yield in the mechanized picking process of Camellia oleifera, and at the same time reduce the long-term damage to the tea trees. It can provide the basis for efficient vibration picking of Camellia oleifera fruits.

MATERIAL AND METHODS

In November 2020, an experiment was performed at "Uncle Lei's" camellia site in Yongzhou, Hunan Province, China. The healthy, well-managed oil tea variety Xianglin 210 (no signs of decline, appropriate leaf and canopy size, no water stress symptoms) was used. When camellia oil trees enter the mature stage (5–10 years old), the number of fruit produced is stable at about 200 / tree. However, the amount of camellia fruit was so small that it was not worth picking. Therefore, the representative Camellia oleifera tree shown in Table 1 is used as the research object in this study. Table 1 shows the main parameters of Xianglin 210 Camellia oleifera, and these data were averaged, with 100 samples of trees of each age.

TABLE 1. Basic parameters of Xianglin 210 Camellia oleifera.

Age (year)	Tree spacing in row (cm)	Tree spacing in column (cm)	Total tree height (cm)	Crown height (cm)	Crown diameter (cm)	Trunk diameter (cm)
9			204±15	158±8	198±18	10±1.5
8			195±14	151±11	173±14	9±1.2
7	390±15	240±12	184±9	142±14	148±16	8±0.8
6			169±12	131±9	126±21	7±1.6
5			153±8	120±12	108±13	6±1.4

*Measured on 100 samples of trees of each age.

Canopy vibration camellia fruit harvester

During the experiment, a self-made "canopy vibration camellia fruit harvester" prototype (hereinafter referred to as the prototype) was used. When the prototype is in operation, it is possible to adjust the height of the lifting mechanism, the hydraulic telescopic boom, and adjust the length of the rack and pinion steering gear, from the angle of the right to insert vibration plates into the canopy. The kinetic energy of the motor through the flexible shaft will transfer to the vibration mechanism, and the vibration components produce a horizontal vibration force in the branches. When the inertia force of the camellia fruit is greater than the binding force of the fruit stalk, the fruit will fall from the branch, thus achieving the purpose of camellia fruit picking.

The prototype (shown in Figure 1) is composed of a car body and a vibration device. The car body is a refit from a small crawler excavator. The telescopic arm and bucket of the excavator are removed and replaced with a lifting platform, telescopic rod, and a rack and pinion mechanism, which can change the spatial position of the vibration excitation device. The small excavator is powered using a hydraulic motor to move a lifting platform, a telescopic rod, a rack and pinion mechanism movement driven by the hydraulic motor, and a hydraulic cylinder. The vibration device converts the circular motion into linear motion according to the working principle of the crank-connecting rod-slider mechanism. The vibration device consists of a disk, a connecting rod, a vibrating spear, a slide rod, a pressure plate, and a support plate. The pressure plate and the support plate are provided with a U-slide groove. The slide rod is connected with the slide block through the pin and can slide between the U-shaped slide groove of the pressure plate and the support plate. The slide rod is connected with the vibration plate by a thread. The eccentric hole plays a role in regulating the amplitude. The rotary drive disk (crank) of the AC servo motor moves in a circle, and the motor speed is adjusted through the frequency converter in order to change the vibration frequency of the vibration device. The vibration time is adjusted by opening and closing the motor. The basic parameters of the prototype are shown in Table 2.

TABLE 2. Basic parameters of camellia fruit canopy vibration harvesting prototype.

Number	Item		Parameter
1		Length (mm)[a]	2300
2	Boundary dimensions	Width (mm) [a]	1480
3		Height (mm) [a]	2180
4	Elongation distance (mm)[a]		2400~2680
5	Elongation distance (°) [a]		180
6	Hoisting height (mm) [a]		990~1860
7	Rated power (kW) [b]		1.5
8	Rated speed (r/min) [b]		2840
9	Rotary disk eccentricity (mm)[a]		40, 50, 60, 70, 80
10	Excitation frequency (Hz)		0–50
11	Running speed (m/s) [b]		0.3

[a] The measurement error is less than 1%.
[b] Machine nameplate marking.

FIGURE 1. Camellia fruit canopy vibration harvester used in the experiment.
1. Vibration device 2. Telescopic rod. 3. Rack and pinion mechanism. 4. Control box. 5. Crawler excavator. 6. Lifting platform. 7. Motor. 8. Flexible shaft. 1-1. Slide rod. 1-2. Vibrating spear. 1-3. Pressure plate. 1-4. Connecting rod. 1-5. Disk. 1-6. Support plate

Dynamic model

In the process of canopy vibration harvesting, under external excitation, the Camellia oleifera canopy produces a bending vibration and torsional vibration to a certain extent in both the horizontal and vertical directions. However, the amplitude of the vertical bending vibration and torsional vibration is small. Therefore, this paper only studies the external excitation characteristics of the canopy under horizontal and transverse vibrations.

The principle of the excitation device is the crank - connecting rod - slider mechanism, which converts rotating motion into linear reciprocating motion in order to realize the excitation vibration of the reciprocating motion. The simple harmonic force that is generated is used as the excitation force for camellia oil fruit picking.

The excitation force of the vibration actuator is shown in [eq. (1)].

$$F = M\omega^2 r \cos \omega t \tag{1}$$

where:

M is the mass of the excitation device, kg;

ω is the angular velocity of rotation of the disk, rad/s;

r refers to the disk eccentricity, m,

t is the excitation time, s.

The camellia tree was considered as a cantilever beam fixed at one end, and the canopy vibration of the tree was considered as a bending vibration under the vertical external excitation. In order to simplify the model, the camellia tree was simplified as a conical table. It was assumed that the diameter and the height of each section of the camellia tree changed linearly, and the diameters at both ends were D and d respectively, regardless of the influence of the moment of inertia and shear deformation. During the vibration process, ΔX represents the transverse displacement of the camellia tree canopy, F represents the transverse force acting on the main branch, H refers to the distance between the applying point and the ground, E refers to the elastic modulus of the branches, and I(x) refers to the moment of inertia of the cross-section of the camellia tree at the distance from the ground X to the neutral axis in the direction of external force, as shown in Figure 2.

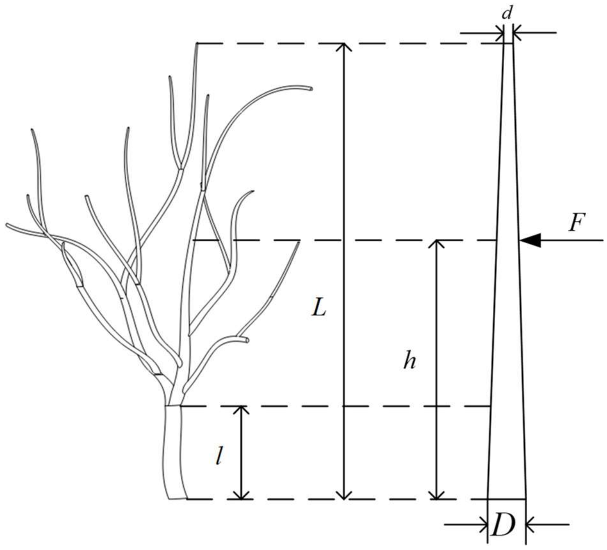

FIGURE 2. Simplified model of Camellia oleifera tree. *L* is the distance from the top of the camellia tree canopy to the ground, m; *l* is the distance from the bottom of the camellia tree canopy to the ground, m; *h* is the excitation position (height), m; *D* is the camellia root diameter, m; *d* is the top diameter of the camellia, m; *F* is the force of the excitation device, N.

When the diameter of the cross-section at *x* from the bottom is *D (x)*, it is obtained by scaling as shown in [eq. (2)].

$$D(x) = D(1 - \frac{D-d}{D} g \frac{x}{L}) \tag{2}$$

where:

D refers to the camellia root diameter, m;

d refers to the top diameter of the camellia, m, and

L refers to the distance from the top of the camellia tree canopy to the ground, m.

The moment of inertia of the cross-section at low *x* with respect to the neutral axis

$$I(x) = \frac{\pi D^4}{64} \tag{3}$$

In addition, according to material mechanics, the equation of canopy deflection is shown in [eq. (4)] and [eq. (5)].

$$x_1 = \frac{Fx^2}{6EI(x)}(3h - x) \qquad (0 \le x \le h) \tag{4}$$

$$x_2 = \frac{Fh^2}{6EI(x)}(3x - h) \qquad (h \le x \le L) \tag{5}$$

where:

F refers to the force of the excitation device, N;

h refers to the excitation position (height), m, and

E refers to the elastic modulus of the Camellia oleifera trees.

When x=l, which is the lowest camellia canopy, eqs (1) ~ (3) are substituted into [eq. (4)] to obtain [eq. (6)].

$$x_1 = \frac{32m\omega^2 r\cos(\omega t)l^2(3h-l)}{3E\pi\left[D(1-\frac{D-d}{D}g\frac{l}{L})\right]^4} \qquad \left(0 \le x \le h\right) \tag{6}$$

When $x=L$, which is the top of the camellia tree canopy, eqs (1) ~ (3) are substituted into [eq. (5)] to obtain [eq. (7)].

$$x_2 = \frac{32m\omega^2 r\cos(\omega t)h^2(3L-h)}{3E\pi\left[D(1-\frac{D-d}{D})g\frac{L}{L}\right]^4} \qquad \left(h \le x \le L\right) \tag{7}$$

According to the conclusions in Table 1, the relationships as shown in [eq. (8)] are

$$\begin{cases} L = c_1 l \\ D = c_2 d \end{cases} \tag{8}$$

where:

c_1 and c_2 are coefficients.

The mean canopy displacement of Camellia oleifera in eqs (8) ~ (10) is as shown in [eq. (9)].

$$x = \frac{1}{2}\left(x_1 + x_2\right) = \frac{K_1 m\omega^2 r\cos(\omega t)\left[K_2 L^2 h + K_3 h^2 L - K_3 h^3 - L^3\right]}{E\pi D^4} \tag{9}$$

where:

K_1, K_2, K_3, and K_4 are coefficients.

The second derivative of [eq. (9)] with respect to time t is considered to obtain the acceleration response equation as shown in [eq. (10)].

$$a = \frac{dx}{dt} = \frac{-K_1 m\omega^4 r\cos(\omega t)\left[K_2 L^2 h + K_3 h^2 L - K_3 h^3 - L^3\right]}{E\pi D^4} \tag{10}$$

According to the above formula, the factors affecting the lateral acceleration response of the Camellia sinensis canopy during the canopy vibration harvesting include the vibration parameters and biological characteristics of the tree. The excitation frequency, amplitude R, and excitation position *h* are the vibration parameters. The tree height L, root diameter D, and the elastic modulus *E* are directly related to the years of growth of the Camellia oleifera. When the frequency (and amplitude) is higher, the excitation position *h* is also higher, and when the acceleration of the forced vibration of the Camellia sinensis canopy is greater, the fruit falls off more easily. Furthermore, when the height L of the camellia tree is larger, and when the root diameter D is smaller, the elastic modulus is also smaller. Moreover, when the acceleration of the forced vibration of the camellia tree canopy is larger, the camellia fruit fall off easily.

During the vibration process, when the inertia force of the camellia fruit was greater than the binding force between the stalk and the branches, the camellia fruit fell off. However, the inertia force on the camellia fruit was constant during one operation cycle of the excitation device. According to the concept of impulse, the excitation device acts on the camellia tree canopy and must act for a certain time before the fruit can fall off. The duration of the excitation is also a very important factor in the picking effect.

During the vibration harvesting, if the acceleration is too large and the excitation time is too long, this will cause irreversible damage to the Camellia oleifera tree body, and even the branches will be broken. Due to this, the acceleration and the excitation time are kept small, and the camellia fruit is also not easy to shake off. Therefore, Camellia oleifera trees with different years of growth have different optimal vibration parameters, including the selection of the excitation frequency, amplitude, time, and location.

The excitation process

According to the above analysis, the mechanized canopy vibration picking of camellia fruits involves many factors, among which the vibration frequency of 8 Hz, amplitude of 50 mm, and vibration time of 8 s were proved to be the best vibration parameters for the Xianglin210 Camellia oleifera trees. The field experiment was divided into two parts. The first was to study the effect of the vibration position on the canopy vibration picking of the Camellia oleifera fruit. The second analyzes the effect of the vibration time on the vibration effect.

During the first field experiment, a vibration frequency of 8 Hz, amplitude of 50 mm, and vibration time of 8s were used to study the vibration position of Camellia oleifera trees with different ages. The experiment of picking Camellia oleifera fruit by canopy vibration was carried out on 5~9 year old trees. The vibration actuator of the canopy vibration harvester was inserted into the camellia tree canopy, and the canopy was excited by changing the vibration position. After the vibration, the camellia fruit dropped by the vibration were collected, and the remaining camellia fruits were manually removed and weighed respectively. The fruit removal efficiency is defined as the weight of mechanically harvested fruit as a percentage of the weight of all fruits on the tree. The fruit removal efficiency can be expressed mathematically as shown in [eq. (11)].

$$FRP=\frac{M_1}{M}\times 100\% \tag{11}$$

where:

M_1 refers to the weight of the mechanically harvested fruit, kg, and

M refers to the weight of all the fruit grown on the tested tree, kg.

During the second field experiment, the optimal vibration positions of Camellia oleifera trees with different years of growth obtained from the first field experiment were used to explore the relationship between the excitation time and the shedding of fruits, buds, and leaves. The experiment process was the same as the first field experiment. Camellia oleifera trees with the same ages were selected to collect the fallen fruits, buds, and leaves after being stimulated for a period of time, and the fruit removal rate and the quality of the buds and leaves were calculated.

RESULTS AND DISCUSSION

Results

The effects of the shaking height and the shaking time on the fruit removal percentage and defoliation are discussed below.

Effects of shaking height on fruit removal percentage

Figures 3 to 7 show the correlation between the excitation height and FRP of all observed data for five different numbers of growth years (24 sets of data were tested for each). From the figures, it is observed that the correlation between the excitation height of camellia trees and the FRP for trees of different ages is consistent, and the maximum value exists in the middle of the canopy.

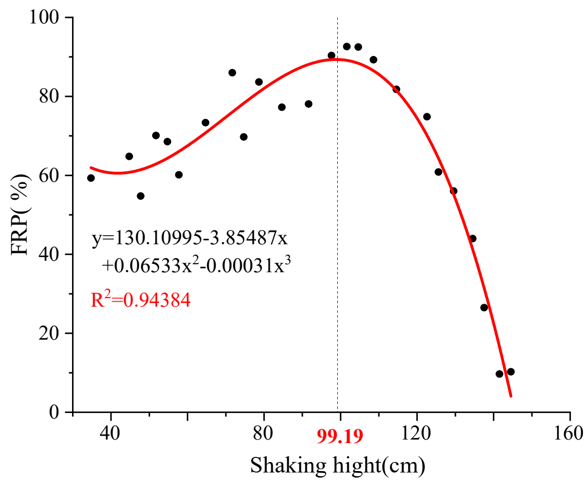

FIGURE 3. Shaking height versus FRP for 5 years.

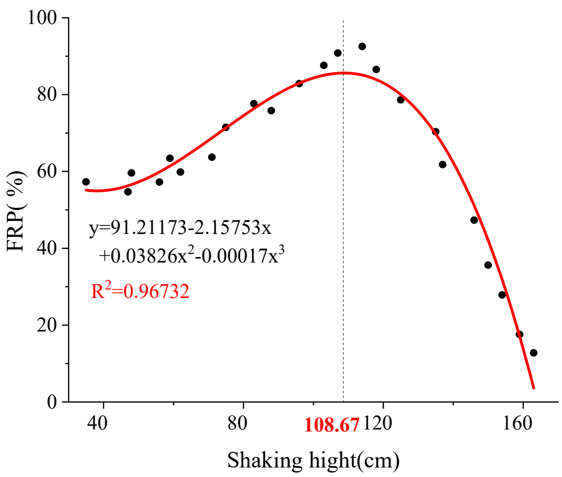

FIGURE 4. Shaking height versus FRP for 6 years.

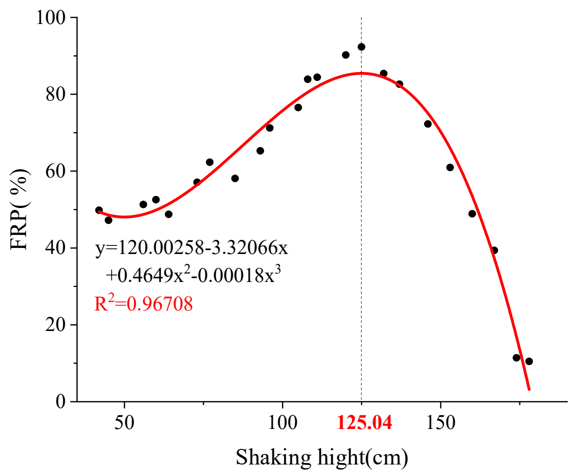

FIGURE 5. Shaking height versus FRP for 7 years.

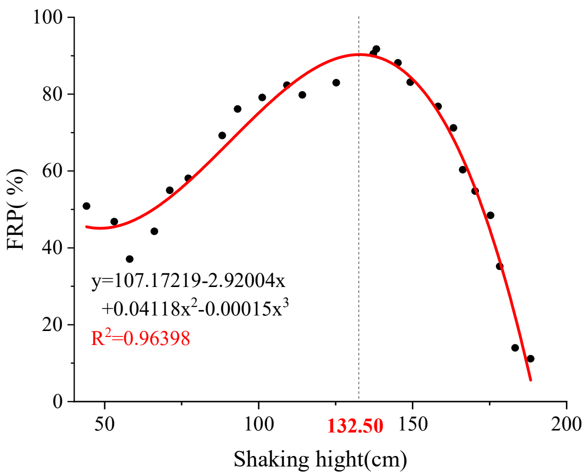

FIGURE 6. Shaking height versus FRP for 8 years.

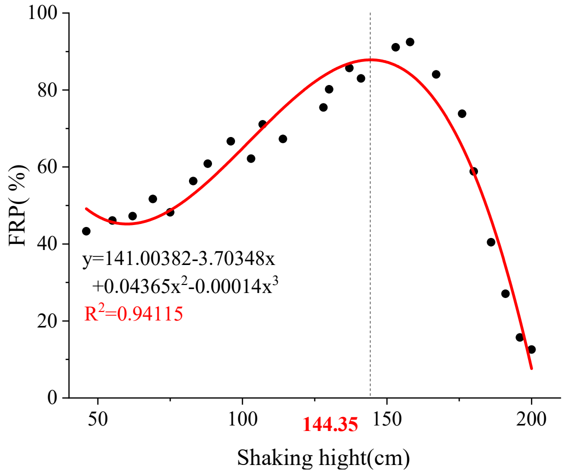

FIGURE 7. Shaking height versus FRP for 9 years.

The data of each group were fitted by a cubic polynomial. The R^2 values of the excitation height of the camellia trees and the FRP for trees aged 5, 6, 7, 8, and 9 years were found to be high and the values were 0.94384, 0.96732, 0.96708, 0.96398, and 0.94115 respectively. Therefore, for Camellia oleifera trees that have been growing for 5 years, the optimal excitation height to maximize the FRP is 99.19 cm (FRP=89.40%). For trees that have been growing for 6 years, the optimal excitation height to maximize the FRP is 108.67 cm (FRP=85.61%). For the trees that have been growing for 7 years, the optimal excitation height to maximize the FRP is 125.04 cm (FRP=85.44%), and for the trees that have been growing for 8 years, the optimal excitation height to maximize the FRP is 132.50 cm (FRP=90.30%). Finally, for the trees that have been growing for 9 years, the optimal excitation height to maximize the FRP is 144.35 cm (FRP=87.84%).

Effects of shaking time on fruit removal percentage and defoliation

Figure 8 shows the effect of the vibration time on the FRP. There is a good correlation between the FRP and the vibration time, and it shows an S-shaped trend. Blanco-roldan et al. (2009) observed similar trends in the mechanized vibration picking of olives. The Camellia oleifera trees of the five different ages had similar fruit dropping times. It was found that when the vibration time was 1~3s, the fruit removal rate increased slowly, and it increased significantly from 3~8s. However, after 8s, with the increase of time, the fruit removal rate did not change significantly, and the increase was very small, in a horizontal state. However, from Figure 9, it is observed that the time to reach the maximum fruit removal rate of Camellia oleifera is proportional to the years of growth. Further, the younger the trees are, the less time is required to reach the maximum fruit removal rate. The time to reach the maximum fruit removal rate of Camellia oleifera trees growing for 5 years was earlier than that of the trees growing for 6 years, and so on. Thus, the time to reach the maximum fruit removal rate of Camellia oleifera trees growing for 8 years was earlier than that of the trees growing for 9 years.

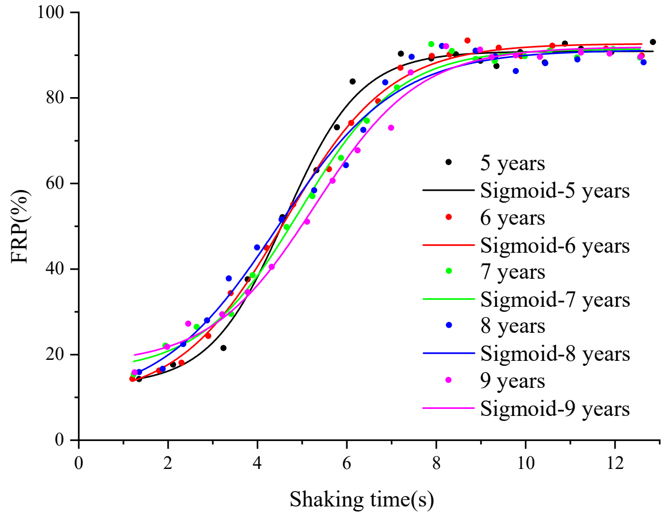

FIGURE 8. Correlation between removal yield and shaking time for Camellia oleifera trees of five ages.

Figure 9 shows the correlation between the excitation time and the bud and leaf abscission (the amount of bud abscission is much less than leaf), and the R^2 of linear fitting of Camellia sinensis growing for 5 to 9 years (0.99585, 0.99893, 0.99854, 0.99831, 0.99655) are found to be high. However, with the increase of excitation time, the total mass of the bud and leaf shedding of Camellia oleifera trees with different ages was different and this total mass was related to the ages of the trees. It is also observed that when the Camellia oleifera trees have been growing for longer, the total mass of the bud and leaf shedding is greater under the same excitation time. The reason for this phenomenon may be that when the tree has been growing for longer, the canopy is larger and the buds and leaves are more numerous. In order to provide enough nutrients to the tree, the metabolic rate of the leaves may be accelerated. Therefore, under the same excitation time, when the tree has been growing for longer, the leaves fall off more obviously. Fortunately, even though the excitation time is increased, none of the camellia branches were found to be broken during the experiment.

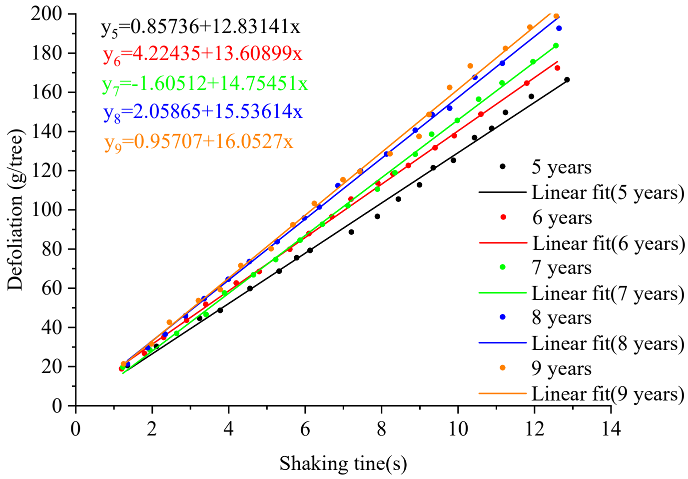

FIGURE 9. Correlation between bud and defoliation versus shaking time for Camellia oleifera trees with five years of growth.

From Figure 8 and Figure 9, when the excitation time exceeds 8s, the camellia oil fruits are not found to fall off, but the amount of buds and leaves being shed continues to rise. The excitation time of 8s ensures the fruit removal rate and effectively reduces the damage caused to the buds during the vibration process. According to the statistics, when the excitation time was 8s before, the number of buds that dropped due to vibration accounted for only 10–20% of the total number of buds, and such bud damage would not reduce the yield of camellia oil in the second year.

Discussion

The FRP is found to increase slowly initially and then to decrease rapidly with the increase of the excitation height. The reason for this trend may be that the excitation parameters such as frequency, amplitude and time that were considered in the test are the best excitation parameters for the vibration of the camellia canopy. However, the branches at the lower end of the camellia canopy are thicker, resulting in an increase in the elastic modulus. According to [eq. (10)], the entire average acceleration response of the canopy and the modulus of elasticity are in inverse proportion. Therefore, during the increased vibration height from the canopy low-end to the best vibration in the process of height, camellia tree branches of the elastic modulus were found to decrease, the average acceleration response of the canopy gradually increased, and the FRP showed a slowly increasing trend. As the height of the main branches of the camellia tree is greater than that of the side branches, this trend is particularly obvious at the top of the camellia tree canopy. Therefore, when the excitation height continues to rise from the optimal position, the effect of the excitation device and the side branches will be less and less, and only the main branches will always be vibrated by the excitation device. Moreover, the branches at the top of the canopy are thinner and softer, and more ductile. These thin branches will not transfer the excitation force effectively to the low end of the canopy. Therefore, when the excitation height continues to rise from the optimal excitation height to the top of the canopy, the FRP shows a rapidly decreasing trend.

According to the camellia trees with different years of growth and their optimal excitation positions in Fig. 7, the ratio of the optimal excitation location to the age of Camellia oleifera is found to be between 16 and 20. With the increase of growing years, this ratio gradually decreases.

The optimal excitation position is as shown in [eq. (12)].

$$H = 11.415y + 42.045 \tag{12}$$

where:

y is the camellia tree's years of growth.

The vibration picking test results of the Camellia oleifera canopy showed that the best effect of the fruit removal rate did not reach 100%. This may be due to the following reasons: (1) In the process of vibration picking, the maturity of the camellia fruit is different. The binding force between the stalk and a more mature fruit branch is much less than that of a less mature fruit. Under the action of the same excitation parameters, when the binding force is less, it is easier to shake the fruit off. (2) The distance between the camellia fruit and the excitation point is different. The inertia force generated by fruit that is closer is found to be much larger than the more distant fruit, and when the distance is less, it falls off more easily. Therefore, a single vibration frequency cannot remove all the camellia fruit. In the following study, multiple vibration frequencies were applied simultaneously in order to achieve a higher fruit removal rate and energy utilization rate of the camellia oil. Future work will focus on expanding the scope of the study to include other controllable factors, including the canopy structure and different varieties of camellia oil.

CONCLUSIONS

In this study, the influencing factors of the canopy vibration of Camellia oleifera were analyzed to understand the vibration characteristics. The analysis results showed that the excitation location (height) and the age of the camellia trees also had a significant influence on the canopy vibration response in addition to the excitation frequency, amplitude and time. In this study, different locations in Camellia oleifera trees of different ages were selected to stimulate the trees and the fruit removal rate was counted. The results showed that the best excitation positions were 99.19, 108.67, 125.04, 132.50 and 144.35 cm for the trees that had been growing for 5, 6, 7, 8 and 9 years, respectively and the harvest rate was found to be above 85%. At the same time, the linear fitting method was used to determine the relationship between the optimal vibration height and the years of growth of the Camellia oleifera trees, so that the optimal vibration location for different ages could be better and obtained more accurately. Through the correlation study between the fruit removal rate and excitation time, as well as the influence of the excitation time on canopy leaf abscission, we found that when the excitation time was more than 8 s, the fruit removal rate did not increase, but the bud and leaf separation continued to increase.

In this study, due to the limitation of the Camellia oleifera base conditions (the longest period of growth of the trees in the study is 9 years), vibration tests were only carried out on trees that had been growing for 5–9 years. Therefore, it has to be verified whether the conclusions of this study can also be applied to large and more mature Camellia oleifera trees using further field tests. In future research, it is also necessary to conduct experiments on different varieties of Camellia oleifera trees in order to obtain targeted vibration picking parameters. This can effectively improve the efficiency of fruit picking in camellia plantations.

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