EXPERIMENT AND ANALYSIS OF MECHANIZED PICKING OF *CAMELLIA OLEIFERA* FRUIT BASED ON ENERGY UTILIZATION RATE

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基于能量利用率的油茶果机械化采摘试验与分析

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ABSTRACT

In order to use the resonance principle for vibratory picking of Camellia oleifera fruit, the frequency sweep tests were carried out on the fruiting branches of Camellia oleifera trees. The results showed that the acceleration response of fruit-bearing branches had good consistency. The use of fruit removal rate alone to evaluate the picking effect is not reliable, and the introduction of energy utilization to evaluate the vibration picking effect is significant. The best results were a vibration frequency of 8 Hz and an excitation time of 10 s. The fruit removal rate was 88.12% and the energy utilization rate was 36.72%. Compared with the traditional fruit shedding rate, the application of energy utilization rate to evaluate the picking effect can improve the reliability of the results and reduce the energy loss.

摘要

为了利用共振原理对油茶果进行振动采摘，对油茶树挂果枝条进行扫频试验。结果表明：挂果枝条的加速度响应具有较好的一致性。仅使用果实去除率不能准确评价采摘效果，引入能量利用率评价振动采摘效果是显著的。采用 8Hz 振动频率和 10s 激振时间的振动采摘效果最佳，此时油茶果实去除率为 88.12%，能量利用率为 36.72%。与传统果实脱落率相比，应用能量利用率评价采摘效果可以提高结果的可靠性，同时降低能量的损失。

INTRODUCTION

Camellia oleifera is unique oilseed species to China and is one of the world's four major woody oil crops, along with olive, coconut and palm *(Peng Shaofeng et al.,2021; Zhang Liwei et al.,2021)*. For those who grow Camellia oleifera, labour costs and economic efficiency are the two main issues. As *Camellia oleifera* is characterized by random spatial location and orientation of the fruit within the growing canopy and varying spatial location and orientation, manual harvesting is work intensive and inefficient. Although labour-saving *Camellia oleifera* fruit harvesting techniques plays a vital role in the development of the *Camellia oleifera* industry, no commercial *Camellia oleifera* fruit harvesting machines have been available to growers up to date. In the long run, advances in mechanized *Camellia oleifera* fruit harvesting technology will help the *Camellia oleifera* industry become more competitive and sustainable.

Research has shown that mechanical harvesting based on vibration technology is an effective technique for improving harvesting efficiency and reducing costs *(Brondino et al.,2021)*. The fruit is picked by vibration. When picking fruit by vibration, the fruit is shed by means of excitation device that provides vibration energy with the right combination of vibration parameters (frequency, amplitude and duration of vibration) *(Sargent, S.A. et al., 2020)*. The main study is the effect of vibration mode and vibration parameters on fruit drop rate and fruit damage rate *(Zhang Z. et al., 2020; Wang, W.Z. et al., 2019; Castro-Garcia, S. et al., 2018; Castro-Garcia, S. et al., 2019)*. *Wu Delin et al. (2022)* theoretically analysed the whole acceleration process of mechanical vibration picking according to different vibration positions (heights), and carried out vibration picking experiments. *He et al., (2013)* found a relationship between frequency and harvest efficiency, with higher frequencies associated with easier fruit shedding. *Guangrui Hu et al., (2020)* inserted the comb finger into the apple tree model by simulation to comb and pick apples, and determined the important parameters of

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apple in the combing and harvesting of vertical structure. *Kang et al., (2021)* optimal Camellia fruit picking parameters were obtained by designing the canopy Camellia fruit picking gear and calculating the key position acceleration. The device designed by *Gao Zicheng et al., (2019),* fruit collecting by vibrating the main branches of the *Camellia oleifera* tree through a suspended vibrating mechanical arm. The test results show that the removal rate of the device can reach 95% and the damage rate of the flower bud can be as low as 5%. *Rao Honghui et al., (2018, 2019)* used an electric rubber roller rotating *Camellia oleifera* picking actuator to achieve fruit removal rate of 86.4% by creating extrusion on *Camellia oleifera* fruit impact through upper and lower rubber roller rotation. *Wu Delin et al., (2020),* analysed the main factors affecting the shedding of *Camellia oleifera* fruits as the amplitude, vibration frequency, vibration time and clamping position of the excitation device, and designed a shaking branch type *Camellia oleifera* fruit picking device, and the removal rate of *Camellia oleifera* fruits was 89.13% under the optimal combination of vibration parameters.

In summary, the best way to mechanize the harvesting of forest fruits is vibration, and the effect of vibration on the mechanized harvesting of *Camellia oleifera* is more significant. The current research on vibration harvesting of *Camellia oleifera* is limited to the development of excitation devices, the correspondence between excitation parameters and fruit removal rate, and the evaluation of excitation effect only relying on fruit removal rate. In this paper, it is studied the acceleration response of fruiting branches in the *Camellia oleifera* canopy, using the resonance principle to conduct excitation picking tests and introducing energy utilization rate to evaluate vibration picking. The results of this study can provide a basis for understanding the vibration response characteristics of the fruiting branches of *Camellia oleifera* trees, reducing energy consumption and improving harvesting efficiency during *Camellia oleifera* fruit harvesting.

MATERIALS AND METHODS

Healthy and well-managed *Camellia oleifera* trees of the XIANGLIN 210 variety were tested in November 2020 at the 'Uncle Lei' *Camellia oleifera* site in Yongzhou, Hunan Province, China. Some of the orchard, tree and fruit characteristics are given in Table 1 and these data are taken from the mean of 100 samples. The field trials were conducted in two sessions. The first field trial is the frequency scan test of the acceleration response amplitude of hanging fruit branches in the canopy of oilseed tea trees, during which the corresponding optimum vibration frequency to the extreme value of the acceleration response was detected. The fruiting branches are relatively thin and can easily break when the vibration frequency is too high, the vibration frequency was set in the range of 0 - 20 Hz with an interval of 1 Hz, a vibration time of 8 s and an amplitude of 50 mm. 20 vibration tests were conducted with similar *Camellia oleifera* trees at each vibration frequency. The second field trial utilized the excitation frequency with the larger acceleration response in the frequency scan results for the canopy vibration picking test on Camellia oleifera.

Table 1

Basic parameters of XIANGLIN 210 Camellia oleifera

Row spacing [m]	Plant spacing [m]	Tree height [m]	Canopy height [m]	Canopy diameter [m]	Branches length [m]
3.9±0.35	2.4±0.26	2.0±0.45	1.5±0.34	2.28±0.21	0.63±0.15

Canopy vibrating camellia fruit harvester

As shown in Figure 1. A prototype "Canopy Vibrating *Camellia Oleifera* Fruit Harvester" developed and built by the research group was used in the trials.

Fig. 1 - Vibrating camellia fruit harvester used in the canopy experiment

The prototype consists of a vehicle body and a vibrating device. The vehicle body is made from a small tracked excavator with a telescopic arm, and bucket of the excavator removed and replaced by a lifting platform, telescopic rod and rack and pinion mechanism which changes in the spatial position of the vibrating device. The mini excavator is powered by a hydraulic motor, the movement of the lifting platform, telescopic rod and rack and pinion mechanism is achieved by the hydraulic motor driving the hydraulic cylinder.

Table 2

Basic parameters of the vibrating camellia fruit harvesting prototype

Number	Project		Parameters
1	Boundary dimension	Long [mm]	2300
2		Wide [mm]	1480
3		High [mm]	2180
4	Displacement distance [mm]		2400~2680
5	Rotation angle [°]		180
6	Rising height [mm]		990~1860
7	Motor rated power [KW]		1.5
8	Rotary table eccentricity [mm]		40, 50, 60, 70, 80
9	Excitation frequency [Hz]		0-50
10	Running speed [m/s]		0.3

Acceleration measurement

For the acceleration response of hanging fruit branches, the acceleration response of each test point was measured by inserting the vibration actuator of the canopy vibration *Camellia oleifera* fruit harvester into the *Camellia oleifera* tree canopy and excitation of the *Camellia oleifera* tree canopy by varying the vibration frequency. The test equipment consisted of an excitation device, an accelerometer (CA-YD-141, Jiangsu Zhongke Ceramic Piezoelectric Company, Yangzhou, China), a charge amplifier (YE5853A, Jiangsu Zhongke Ceramic Company, Yangzhou, China), and a data acquisition unit (NI cDAQ-9174, China). Data analysis software (CRAS V7.1, First Test Software Engineering Co., Ltd., Nanjing, China). The accelerometer was fixed to a small wooden block (15 mm x 15 mm x 15 mm) and the block was attached to the test points of the branch using hot melt glue.

As shown in Figure 2, the accelerometer is placed on the hanging branch (point C) at a distance of 500 mm from the excitation positions B and C. The analysis is carried out using the synthetic acceleration values. Equation as:

$$a = \sqrt{a_x^2 + a_y^2 + a_z^2} \tag{1}$$

where:

a_x, a_y and a_z are the instantaneous acceleration values for each axis at the same moment, [m/s^2].

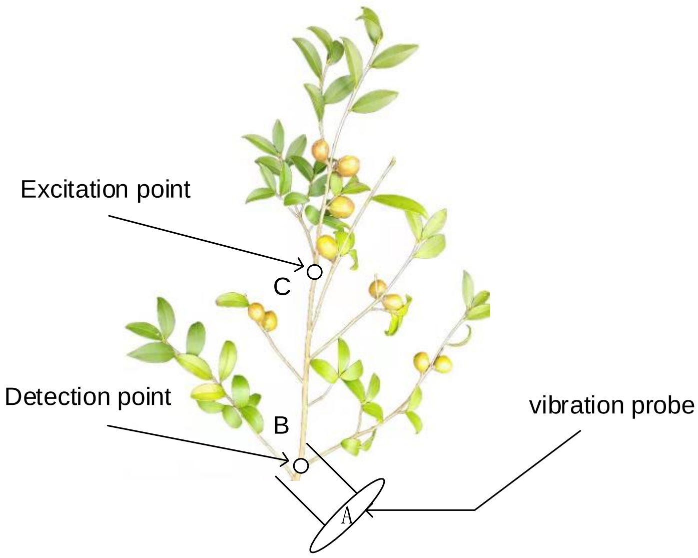

Fig. 2 - Accelerometer installation position

Determine the energy utilization rate

For the canopy vibration *Camellia oleifera* fruit process, by inserting the vibration actuator of the canopy vibration *Camellia oleifera* fruit harvester into the canopy of the *Camellia oleifera* tree, the canopy of the *Camellia oleifera* tree is stimulated by varying the vibration frequency and the vibration time, the vibration harvested *Camellia oleifera* fruit is collected after the vibration is over and the unshed *Camellia oleifera* fruit is manually removed and weighed and recorded separately. Energy utilization was introduced to collaboratively evaluate the effect of canopy vibration on *Camellia oleifera* fruit harvesting. Defined as the efficiency of fruit removal per unit amount of energy consumption during harvesting, expressed as:

$$\mu = \frac{C}{E} \tag{2}$$

where:

μ is the energy efficacy of a harvesting operation, [%/kJ];

C is the fruit removal efficiency, [%];

E is the energy consumption of the harvester, [kJ].

Fruit removal efficiency is defined as the weight of mechanically harvested fruit as a percentage of the weight of all fruit on the tree. The fruit removal efficiency can be mathematically expressed by the following equation:

$$C = \frac{M_1}{M} \times 100\% \tag{3}$$

where:

M_1 is the weight of the mechanically harvested fruit, [kg];

M is the weight of all fruit grown on the tested tree, [kg].

The energy consumption of the shaker during the harvesting operation is determined by the input power used during the total harvesting time with the following equation:

$$E = P \times t \tag{4}$$

where:

E is the shaker energy consumption in certain shaking durations, [kJ];

P is the input power to the shaker in operation, [KW];

t is the duration of harvesting, [s].

The input power of the shaker is expressed as:

$$P = \frac{P_0 \times f}{f_0} \tag{5}$$

where:

P_0 is motor rated power, [W];

f_0 is the power frequency, take 50 Hz;

f is the power frequency adjusted by the frequency converter is the motor rotation frequency, [Hz].

RESULTS

The acceleration response of the test point

The vibration response of the hanging fruit branches of the *Camellia oleifera* tree is caused by the excitation of the branches driven by the excitation device. In order to use the resonance characteristics for vibration picking of *Camellia oleifera* fruit, the acceleration response of *Camellia oleifera* tree fruit branches to the harmonic excitation of *Camellia oleifera* tree fruit branches need to be studied to obtain the acceleration-spectrum curve.

The excitation device was inserted into the canopy of the *Camellia oleifera* tree and the vibration signal was directed to the hanging branches of the tree. The accelerometer was fixed at test point C on the hanging branches. The acceleration signals a_x, a_y and a_z were recorded in three directions during the experiment, and the acceleration curve with time was intercepted after the motor had stabilized in operation. The acceleration response values in the X, Y and Z directions were different at each frequency.

Figure 3 shows that acceleration values of the three directions of the branches of *Camellia oleifera* varied greatly. Compared to the other two axes, the acceleration response value in the X direction is the largest, the acceleration response value in the Z direction is the smallest, and the acceleration response value in the Y direction is slightly larger than that in the Z direction. When the excitation frequency is 8 Hz, the acceleration value in the Z direction is only 13 m/s^2, while the acceleration values in the X and Y directions are 6.15 and 1.92 times higher respectively.

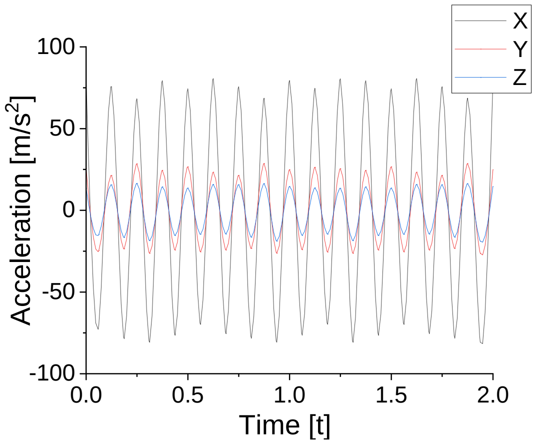

Fig. 3 - Acceleration time domain response

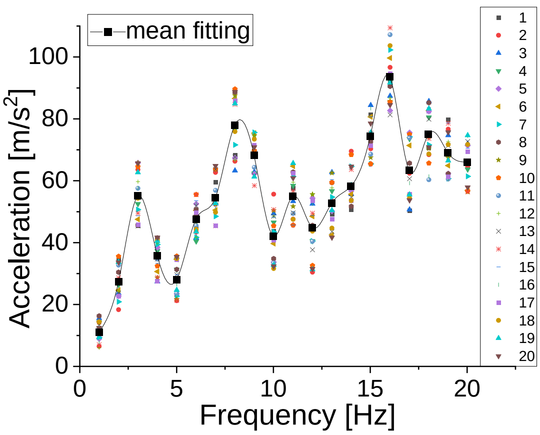

Fig. 4 - Acceleration frequency domain response

The curve of acceleration versus frequency obtained from experimental measurements is shown in Figure 4. Generally, the excitation frequency range of the crank linkage based on excitation method used in *Camellia oleifera* harvesting does not exceed 20 Hz. Moreover, the diameter of the hanging branches of the *Camellia oleifera* tree is small and the relative stiffness is low, when the excitation frequency exceeds 20 Hz, the hanging branches are extremely vulnerable to injury and even break, which causes great damage to Camellia oleifera tree. Therefore, this paper focuses on the acceleration-spectrum curve below 20 Hz.

The range of spectral curves used in this paper is from 1 to 20 Hz. This may be the different number of fruits and leaves on the different branches, as denser leaves can produce higher aerodynamic damping; This may also be the different thickness of the branches, the thinner the branch, the higher the structural damping of the branch. Fortunately, the overall trend of the measured acceleration response of the hanging branches of the *Camellia oleifera* tree with respect to frequency were similar, and the acceleration-frequency response curve of the hanging branches of the *Camellia oleifera* tree was obtained by fitting the average value of the acceleration response at the same frequency. The peak frequencies in the test frequency range are the resonant frequency that are likely to cause resonance in the fruiting tree, namely 3 Hz, 8 Hz, 11 Hz, 16 Hz and 18 Hz, and the corresponding accelerations are 55.1 m/s^2, 80 m/s^2, 55 m/s^2, 93.6 m/s^2 and 75.03 m/s^2.

Energy delivery efficiency

In the vibration harvesting tests, field trials were carried out for the test points for 3 Hz, 8 Hz and 16 Hz, where the sweep test results had a significant and abrupt change in acceleration, as the excitation frequencies. Vibration times of 5 s, 10 s and 15 s were applied respectively.

Table 3

Results of vibration picking test with 5 s vibration time

Frequency [Hz]	**3**			**8**			**16**		
Energy consumption[KJ]	0.45			1.2			2.4		
Fruit removal rate [%/KJ]	15.38	16.48	15.07	42.08	35.07	43.22	65.78	58.73	69.78
Energy utilization [%/KJ]	34.19	36.61	33.49	35.07	29.23	36.02	27.41	24.47	29.07

Table 4

Results of vibration picking test with 10 s vibration time

Frequency [Hz]	**3**			**8**			**16**		
Energy consumption[KJ]	0.9			2.4			4.8		
Fruit removal rate [%/KJ]	29.35	35.29	30.63	88.58	83.24	92.55	89.33	85.6	94.9
Energy utilization [%/KJ]	32.61	39.22	34.03	36.91	34.68	38.56	18.61	17.83	19.78

Table 5

Results of vibration picking test with 15 s vibration time

Frequency [Hz]	3			8			16		
Energy consumption[KJ]	1.35			3.6			7.2		
Fruit removal rate [%/KJ]	28.26	29.55	26.98	88.96	84.27	91.59	89.71	86.04	90.83
Energy utilization [%/KJ]	20.93	21.89	19.98	24.71	23.41	25.44	12.46	11.95	12.61

For 5 s continuous vibration, with the increase of excitation frequency, the removal rate of *Camellia oleifera* fruits showed an upward trend. However, the energy utilization rate increased first and then decreased. When the vibration frequency was 3 Hz, the average value of fruit removal rate was 15.64% and the average value of energy utilization rate was 34.76%/KJ; when the vibration frequency was 8 Hz, the fruit removal rate was 40.12% and the energy utilization rate was 33.44%/KJ; when the vibration frequency was 16 Hz, the fruit removal rate was 64.76% and the energy utilization rate was 26.98%/KJ.

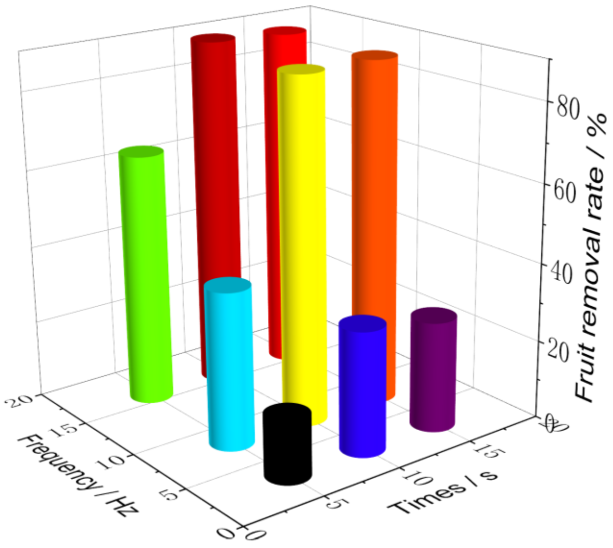

Fig. 5 - Camellia fruit removal rate

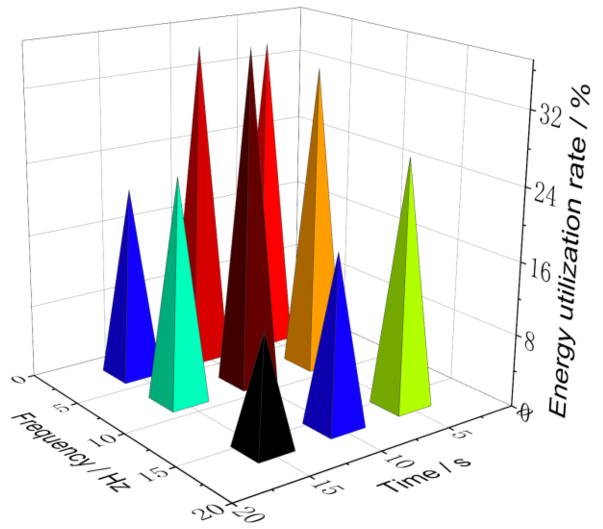

Fig. 6 - Energy utilization rate

At 10 s of continuous vibration, the fruit removal rate at an excitation frequency of 8 Hz was significantly higher than that at a vibration frequency of 3 Hz. However, the fruit removal rates at excitation frequencies of 8 Hz and 16 Hz were essentially the same; the energy utilization rate at an excitation frequency of 3 Hz was slightly lower than that at an excitation frequency of 8 Hz and much higher than that at an excitation frequency of 16 Hz. When the vibration frequency was 8 Hz, the fruit removal rate was 88.12% and the energy utilization rate was 36.72%/KJ. Compared to the vibration effect at 8 Hz, the fruit removal rate at 3 Hz decreased by 56.36% and the energy utilization increased by 1.43%/KJ, and the fruit removal rate at 16 Hz increased by 1.84% and energy utilization decreased by 17.98%/KJ.

The variation trend of fruit removal rate (Figure 5) and energy utilization rate (Figure 6) of *Camellia oleifera* at 15 s of continuous vibration were basically the same as the excitation effect at 10 s of vibration duration. When the vibration frequency was 3 Hz, the fruit removal rate was 28.26% and the energy utilization rate was 20.93%/KJ, while the fruit removal rate at a vibration frequency of 8 Hz was 3.12 times higher than that at a vibration frequency of 3 Hz, and the fruit removal rate at a vibration frequency of 16 Hz was 3.14 times higher than that at a vibration frequency of 3 Hz, and the energy utilization rate at a vibration frequency of 8 Hz was 1.17 times higher than at 3 Hz and 0.59 times higher at 16 Hz than at 3 Hz.

Vibration parameters have a great influence on the harvesting fruits. In this study, different vibration parameters were used for harvesting *Camellia oleifera* fruit to investigate the effects of two excitation parameters, vibration frequency and vibration time, on the harvesting effect of *Camellia oleifera* fruit. As the excitation frequency increased, the removal rate of *Camellia oleifera* fruits shows an increasing trend. However, when the vibration frequency reached a certain value, the removal rate of *Camellia oleifera* fruits does not keep increasing.

Only when the free vibration frequency of the *Camellia oleifera* branch reaches the resonance, the vibration amplitude is maximum and the acceleration of the *Camellia oleifera* fruit reaches the abscission condition, the *Camellia oleifera* fruit may be absconded. At 3 Hz, 8 Hz and 16 Hz excitation frequencies, the maximum values of *Camellia oleifera* fruit removal rate were 35.29%, 92.55% and 94.96% at different excitation times respectively. This indicates that 3 Hz is not the optimum excitation frequency, although in the sweep test, the *Camellia oleifera* canopy branches showed a higher acceleration response at 3 Hz. The removal rates of *Camellia oleifera* fruit at 8 Hz and 16 Hz were generally consistent and could be used as the excitation frequency for vibratory harvesting of *Camellia oleifera* fruit canopies.

Discussions

The same relationship exists between *Camellia oleifera* fruit removal rate and vibration duration, that is, with the rate increasing, the vibration duration increases. The results of the picking trials showed a common trend for the three tested excitation frequencies, with a surge in *Camellia oleifera* fruit removal rate at 10 s excitation duration relative to 5 s excitation duration, but when the excitation duration was increased to 15 s, the *Camellia oleifera* fruit removal rate was essentially the same as that at 10 s excitation duration, with a maximum *Camellia oleifera* fruit removal rate of 92.55%.

The energy utilization was similar at 5 s and 10 s, reaching 39.22%/KJ, however, when the excitation duration was extended to 15 s, the energy utilization decreased rapidly by almost 50%. The energy utilization was higher when the excitation duration was 5 s or 10 s and the removal rate of *Camellia oleifera* fruit was higher when the excitation duration was 10 s or 15 s. This indicates that an excitation duration of 10 s is the optimum vibration time for vibratory harvesting of *Camellia oleifera* canopy. From the perspective of energy utilization, the energy utilization at a vibration frequency of 8 Hz was significantly higher than at a vibration frequency of 16 Hz for different vibration durations. With the same *Camellia oleifera* fruit removal rate, choosing 8 Hz as the vibration frequency for *Camellia oleifera* fruit canopy can effectively reduce energy consumption.

The experimental results of *Camellia oleifera* canopy vibration picking showed that the best effect of *Camellia oleifera* fruit removal rate does not reach 100%, which may be caused by the following reasons:

1. When vibration picking, the maturity of camellia fruit is different. The binding force between stalk and branch of the fruit with higher maturity is smaller than that of the fruit with lower maturity. The smaller the binding force, the easier it is to fall off.

2. The distance between the camellia fruit and the excitation point is different. The inertial force generated by the fruit with a shorter distance is larger than that of the fruit with a longer distance, and the closer the distance, the easier it is to fall off. Therefore, the use of a single vibration frequency vibration picking can't make all camellia fruits obtain enough inertia force, that is, a single vibration frequency can't make all camellia fruits removed. In the next study, multiple vibration frequencies will be used simultaneously to achieve higher fruit removal rate and energy utilization rate of camellia oleifera. Future work will focus on expanding the study to include other controllable factors, including differences in camellia canopy structure and species.

CONCLUSIONS

The results of the study on the acceleration response characteristics of *Camellia oleifera* showed that the acceleration response of fruit was consistent with different test results. The acceleration responses at 3 Hz, 8 Hz, 11 Hz, 16 Hz and 18 Hz were higher, which was most likely the natural frequency of *Camellia oleifera* branches.

When the vibration result was evaluated by fruit removal rate, the vibration effect was basically the same when the excitation frequency was 8 Hz and 16 Hz, and the excitation duration was 10 s and 15 s. When the vibration frequency was 8 Hz and the vibration duration was 10 s, the optimal vibration parameters of *Camellia oleifera* canopy were 88.12% of fruit removal rate and 36.72%/KJ of energy utilization rate.

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