Journal of Agricultural Engineering

https://www.agroengineering.org/

The influence of branch inclination angles on the dynamic response of the olive tree to trunk shaking

Pedro Sánchez Cachinero,[1] Fernando Aragon-Rodriguez,[2] Sergio Tombesi,[3] Rafael R. Sola-Guirado[1]

[1]University of Cordoba, Campus de Rabanales, Córdoba, Spain
[2]Miguel Hernández University, Campus de Orihuela, Orihuela, Alicante, Spain
[3]Catholic University of Sacred Heart, Piacenza, Italy

Please cite this article as doi: 10.4081/jae.2025.1670

Submitted: 16 December 2024
Accepted: 6 May 2025

The influence of branch inclination angles on the dynamic response of the olive tree to trunk shaking

Pedro Sánchez Cachinero,[1] Fernando Aragon-Rodriguez,[2] Sergio Tombesi,[3] Rafael R. Sola-Guirado[1]

[1]University of Cordoba, Campus de Rabanales, Córdoba, Spain
[2]Miguel Hernández University, Campus de Orihuela, Orihuela, Alicante, Spain
[3]Catholic University of Sacred Heart, Piacenza, Italy

Corresponding author: Rafael R. Sola-Guirado, University of Cordoba, Campus de Rabanales, Ctra. Nacional IV km 396, 14014, Córdoba, Spain. E-mail: ir2sogur@uco.es

Contributions: RRSG, conceptualization; RRSG, PSC, methodology, manuscript original drafting and review; PSC, FAR, formal analysis and investigation; FAR, ST, manuscript review and editing; RRSG, ST, resources and supervision.

Conflict of interest: the authors declare no competing interests, and all authors confirm accuracy.

Availability of data and materials: the datasets generated during the current study are available from the corresponding author on reasonable request.

Funding: this work is part of the research Project "Optimisation of vibration technology for improving the efficiency of mechanised harvesting of fruit trees" (1381058-R) that has been co-financed by the Operational Programme FEDER 2014-2020 and by the Consejería de Economía, Conocimiento, Empresas y Universidad de la Junta de Andalucía.

Abstract

Traditional and intensive olive groves account for a large part of today's olive orchards and their harvesting is based on trunk shakers. The vibration parameters set in these machines and the biomechanical properties of the olive tree influence the detachment process. Tree geometry and morphology are fundamental factors influencing the propagation of vibration. Understanding the effect of tree geometry on vibration propagation can provide useful indications for tree training and pruning. The aim of this work is to study the effect of branch inclination on the vibration response when a trunk shaker is applied, as there is no experimental information on this variable in the literature. We randomly selected 80 olive trees from an intensive olive orchard, and the acceleration of the trunk and one of the main branches was recorded for each tree when forced vibration was applied using a trunk shaker. Two triaxial MEMS accelerometers were used to measure the vibration and, in addition, the location of each sensor, the trunk and branch diameters and the branch angle were measured. It was observed that in all cases there was an amplification of acceleration from the trunk to the branch: the mean acceleration transmissibility value was 139.5%. The highest acceleration values occurred in branches with an inclination between 30 and 60 degrees, which also had the highest acceleration transmissibility, with an increase of 13.8-16.8% and 6.3-10.5%, respectively. In addition, the highest relative kinetic energy ratio was higher in branches with an inclination between 30 and 60 degrees.

Key words: trunk shaker; acceleration; vibration; branch angle; harvesting.

Introduction

In many fruit tree species such as almond, orange, pistachio and olive, new plantations are using higher tree densities in order to reduce the initial unproductive period and optimise the use of machines, in particular for harvesting (Pérez-Ruiz *et al.*, 2018) and pruning (Dias *et al.*, 2022). However, both traditional and intensive orchards are still very widespread compared to high-density ones. In the case of the olive, more than 70% of orchards are traditional (tree density lower than 180 tree/ha) and 25% are intensive (tree density between 180 and 800 tree/ha) (IOC, 2023). For these kinds of orchard, mechanical harvesting is mostly carried out using trunk shakers.

Trunk shakers apply a forced vibration to the tree trunk which is transmitted to the bearing branches in order to detach fruits. The vibration parameters set in these machines influence the detachment process and are specific for each type of fruit tree due to the inherent biomechanical differences of each tree in its dynamic response (Sola-Guirado *et al.*, 2024) . Some authors have developed mathematical models to characterise the dynamic behaviour of a tree against vibration, discretising the trunk and branches in a mass-spring-damper system (Murphy and Rudnicki, 2012; Xue *et al.*, 2018), or studying factors such as energy dissipation in branches due to different viscous and aerodynamic damping effects (Théckès, Boutillon and De Langre, 2015). Other authors propose computational analysis of the tree against the forced vibration of the machinery (Hoshyarmanesh *et al.*, 2017; Sanchez-Cachinero *et al.*, 2022). However, all these models have a certain degree of uncertainty linked to the assumptions and simplifications they present. Experimental tests in the field are therefore more predictive for determining the influence of tree geometry parameters on the mechanical behaviour of trees.

Within the same orchard, there are important variations in the response of individual trees to the same type of excitation. This can be attributed to the geometry and morphology of the tree that, although trained to a specific system, shows wide variability in terms of branch inclination, direction, stiffness, etc. Thus, tree geometry can play a pivotal role, determining the propagation of vibrations through the tree. For example, in the pistachio, the energy required to detach fruit is greater in trees with long branches (Ma *et al.*, 2022) and larger trunks (Homayouni *et al.*, 2022). In cherries, branch bifurcations have a negative impact on the efficiency of transmitted vibration (Du *et al.*, 2012). In olive trees, leaf distribution and leaf density can dampen applied vibration to a greater or lesser extent (Sola-Guirado *et al.*, 2022), but branch flexibility is also influenced by and related to the age of the crop (Lodolini *et al.*, 2018). In citrus trees, the amount and distribution of fruit on the branch modifies vibration transmissibility (Castro-Garcia *et al.*, 2020). Therefore, certain operations such as pruning, which intervenes to change tree morphology, can affect the efficiency of mechanical harvesting.

It is well known that the intensity of pruning influences the dynamic response of the tree, particularly in the case of olive trees. For example, to improve the efficiency of mechanised harvesting, some authors propose pruning to eliminate secondary branches (Camposeo *et al.*, 2023) and to eliminate branch suckers (Tombesi *et al.*, 2017) as this modifies the efficiency of vibration transmission. There are numerous studies that relate vibration parameters to harvesting efficiency and the damage generated, leaving to one side the study of a tree's morphological variables. The influence of branch angle on vibration transmission has been poorly studied and is limited to laboratory studies or computational models and, in the case of the olive tree, such studies are scarce (Chen *et al.*, 2021; Du *et al.*, 2012; Xiaoqiang *et al.*, 2015). The aim of this study is to study a large number of olive branches experimentally and to obtain information on their dynamic response as a function of different sets of established angles. The innovation of this study lies in advancing the understanding of the behaviour of olive branches at different inclinations when subjected to trunk-induced forced vibrations. The current scientific literature on this topic is sparse, yet maximizing vibration transmission is crucial for optimizing the efficiency of mechanized harvesting. This research aims to fill this gap by investigating how branch inclination affects vibration transmission, thus informing better tree training practices.

Materials and Methods

Olive orchards

The experiment was carried out in an olive orchard located on the experimental plot of the Rabanales Campus belonging to the University of Cordoba, Spain. (37°56'07.9" N; 4°42'58.9" W). The trees were 20-year-old 'Hojiblanca' variety, spaced 4 m on the row, with 8 m between rows with form of an open vessel and three or four main branches. In the intensive olive orchards, common pruning was carried out, eliminating suckers, dry branches and low branches that make mechanised harvesting difficult. The average canopy volume, measured by measuring stick and tape measure, was 53.45 m^3 (SD=12.33). Harvesting took place in the second week of November 2022, under the same conditions of weather, fruit maturity and time of the day (Figure 1).

Figure 1. Orchard and trunk shaker used in the experiment.

Trunk shaker

Harvesting was performed with an orbital trunk shaker (Crispe, Ibros, Spain) which had an eccentric mass of 60 kg and an eccentricity of 118 mm. The eccentric mass was controlled by a rotary motor (VM4D-128, Veljan, Hyderabad, India). This motor was in turn driven by a variable displacement piston pump of 100 cm^3 (A10V100 EK, Rexroth, Lohr am Main, Germany) with a theoretical flow rate of 200 l/min to 2000 rpm. The pump was driven by the power take-off of a tractor (6420, John Deere, IL, USA) at a working speed of 540 rpm when the tractor engine speed was set to 2200 rpm. The trunk shaker head was suspended at the end of the frame with silent-blocks and metal chains. To give greater flexibility in gripping, the shaker head allowed a rotational movement to attach trunks in a position perpendicular to the plane of the clamp. The clamps were fitted with 55 SH (shore scale A) hardness rubber pads to protect the tree from possible bark damage. In order to carry out the study, a displacement of 102 cm^3 was set for the vane engine, generating a frequency of 17 Hz. This frequency has the maximum acceleration value and is very close to the natural frequency of the first mode found in intensive olive orchards with the same tree architecture (Zhang *et al.*, 2022; Castro-Garcia *et al.*, 2008).

Field test

Eighty trees were randomly selected, avoiding the border rows of the plot and the initial and final trees of each row. The selected trees had good physiological and sanitary conditions for harvesting, as well as an adequate fruit load (yield: M=35.3 kg, SD=12.3). Acceleration in the trunk and in one of the main branches was recorded simultaneously for each of the selected trees (Figure 2), with a total of 80 branches tested. Vibration recording was carried out with 2 triaxial MEMS accelerometers, (Gulf Coast Data Concepts LLC, X200-4, Waveland, MS). The position of each sensor, both trunk and branch, and the diameters of the trunk and branch where each sensor was located were measured with a tape measure and callipers. In addition, the angle of the branch was measured with respect to the horizontal of the tree, parallel to the ground, using a protractor. Three groups of angles were considered for the study, which included horizontal branches from 0° to 30°, inclined branches from 30° to 60° and vertical branches from 60° to 90°. The branches selected had similar morphological characteristics, without significant differences (ANOVA, $p>0.05$; Kruskal-Wallis, $p>0.05$), with the aim of locating the sensor at similar lengths and diameters for each tree (Table 1). This allows the variables of branch length and diameter, which affect vibration, to be controlled so that the effect of branch angle can be isolated. The position of the trunk-branch sensor pair and the diameters of the trunk-branch sensors were similar for the different angle groups, with no significant differences between them (ANOVA, $p>0.05$; Kruskal-Wallis, $p>0.05$).

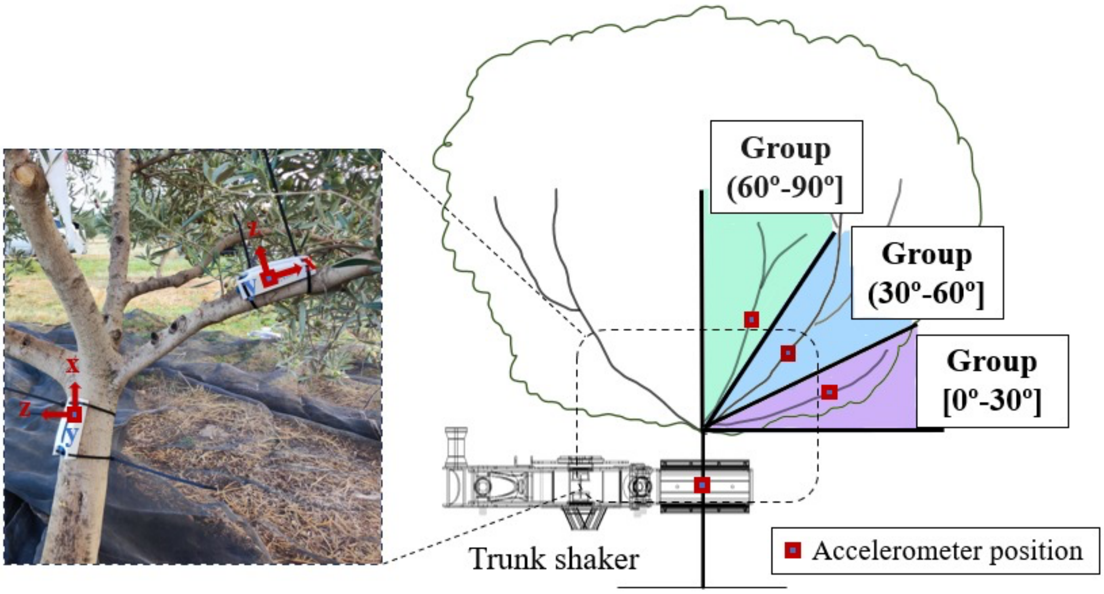

Figure 2. Real position (left) and schematic (right) of the acceleration sensors on the tree.

Table 1. Geometrical characteristics of the accelerometer position.

	Group of branch angles		
	0º-30º	30º-60º	60º-90º
Trunk height (m)	0.73 ± 0.14	0.70 ± 0.14	0.75 ± 0.17
Trunk diameter (m)	0.13 ± 0.03	0.13 ± 0.02	0.12 ± 0.03
Branch length (m)	0.48 ± 0.14	0.48 ± 0.13	0.45 ± 0.13
Branch diameter (m)	0.06 ± 0.02	0.07 ± 0.03	0.06 ± 0.02

Mean values ± SD.

Vibrational analysis

Five seconds of the stable period were selected for analysis of the vibration signals using the free software R (R Core Team version 4.1.0, Vienna, Austria) and studying the following parameters:

- Acceleration RMS (A_{RMS}) (m/s^2): root mean square acceleration RMS (vector sum) in the three axes (x, y, z) of the accelerometers in the time domain during vibration time (equation 1).

$$A_{RMS} = \sqrt{{A_{RMS_x}}^2 + {A_{RMS_y}}^2 + {A_{RMS_z}}^2} \qquad \text{(Eq. 1)}$$

Where A_{RMSx} is the acceleration RMS in the in the x-axis; A_{RMSy} is the acceleration RMS in the in the y-axis and A_{RMSz} is the acceleration RMS in the in the z-axis.

- Acceleration transmissibility (A_{TRANS}) (%): rate, in percentage, between the A_{RMS} of the different sample points measured in trees along each path: Trunk-Branch (equation 2).

$$A_{TRANS} = \frac{A_{RMS_{Branch}}}{A_{RMS_{Trunk}}} \cdot 100 \qquad \text{(Eq. 2)}$$

Where A_{RMS} *Branch* is the vector sum of the acceleration RMS values of the three axes on the branch and A_{RMS} *Trunk* is the vector sum of the acceleration RMS values of the three axes on the trunk.

- Relative kinetic energy ratio (RKER): Ratio of input kinetic energy to output kinetic energy along the tree. A variable that measures the change in dynamic response at a specific location compared to a reference point, using terms of velocities and study diameters. Assuming uniform mass density (ρ_{wooden}) and that the sections have a circular area without any irregularities (Du *et al.*, 2012) (equation 3).

$$RKER = \frac{E_{branch}}{E_{trunk}} = \frac{\frac{1}{2} \cdot m_{branch} \cdot v_{branch}^2}{\frac{1}{2} \cdot m_{trunk} \cdot v_{trunk}^2} = \left(\frac{Ø_{branch} \cdot v_{branch}}{Ø_{trunk} \cdot v_{trunk}}\right)^2 \qquad \text{(Eq. 3)}$$

Where E_{branch} and E_{trunk} are the energies of the branch and the trunk; m_{branch} and m_{trunk} are the masses of the branch and the trunk; v_{branch} and v_{trunk} are the velocities of the branch and the trunk and $Ø_{branch}$ and $Ø_{trunk}$ are the diameters of the branch.

- Frequency (Hz): number of cycles per second. Windowed scalograms were used for the analysis. They provide information analogous to the Fourier transform, but unlike the Fourier transform, where the time domain is lost, they allow the frequency component to be found in a time domain. For each scale and central time, it is defined as the square root of the integral of the squared modulus of the wavelet transform with respect to the time (equation 4).

$$WS_{windowrad}(tc, s) = \left(\int_{tc-windowrad}^{tc+windowrad} [f(t, s)]^2 \, dt\right)^{1/2} \qquad \text{(Eq. 4)}$$

Where *tc* is the central time; *s* is the scale and *t* is the time.

- Vibration time (s): time elapsed from the beginning of the initial transient period (start of the unbalance mass) to the final transient period (stop of the unbalance mass).

Statistical analysis

Both parametric and non-parametric methods were used in results analysis, depending on the nature of the variables studied. In each case, the test performed is indicated. The software used for the statistical analysis was IBM SPSS Statistics 25 (IBM Corporation; SPSS Statistics 25, New York, USA).

Results

The recorded accelerations showed mean vibration times of 8.5 s (SD=1.6), with an initial transient period of 1.5-2 s and a final transient period of 0.5-0.7 s (Figure 3, left). The analysed frequency obtained a mean value of 16.3 Hz (SD = 0.83), close to the established value of 17 Hz, with a small decrease in frequency. Frequency increased in the initial transient period, while the final transient period was shorter, corroborating the acceleration signal versus time. In the windowed scalograms, low amplitude values were observed at higher frequencies associated with the different harmonics (Figure 3 right).

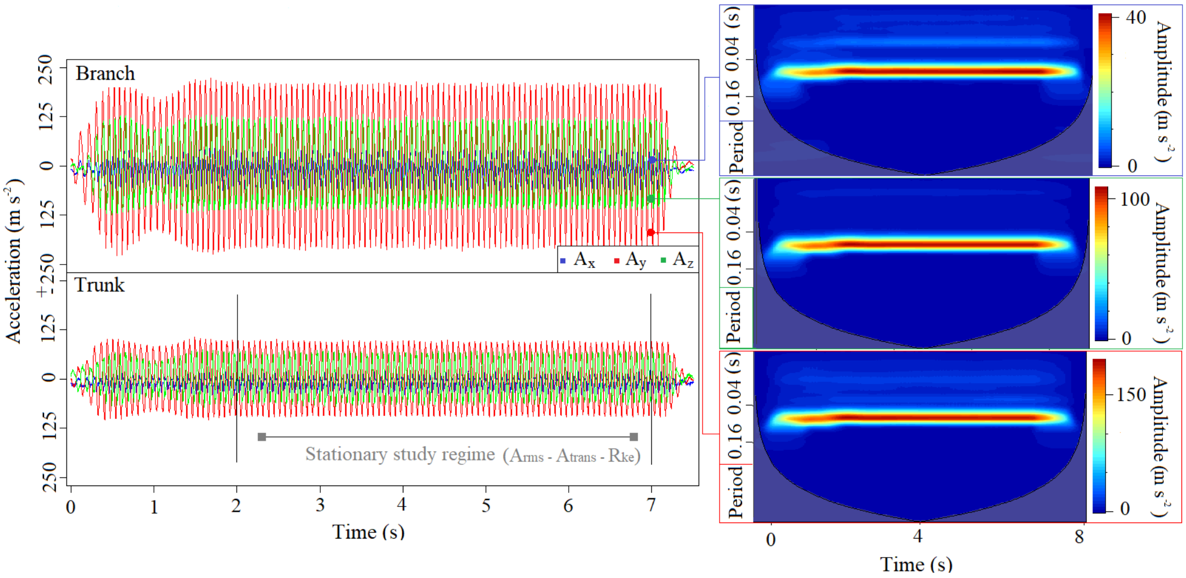

Figure 3. Time-domain acceleration signals for the branch and trunk in the three axes (left) and the windowed scalograms corresponding to the three axes of the branch (right).

Mean A_{RMS} for all registered data, in the time domain were 116.8 m/s^2 (SD = 19.2) and 162.9 m/s^2 (SD = 32.8) in the trunk and in the branch, respectively, producing an average increase of 39.5% of A_{RMS} of the branch relative to the trunk. The mean A_{RMS} values of the trunk decomposed for each of the x, y and z axes were 26.2 m/s^2 (SD = 10.8), 79.7 m/s^2 (SD = 19.2) and 77.3 m/s^2 (SD = 22.7). This indicates that the trunk shaker was working in the yz plane, transverse to the trunk, transmitting vibration vertically to the trunk and the direction of tree growth (x-axis). There was no difference in the frequency applied to the trunk (Kruskal-Wallis, $p>0.05$); therefore, having established an eccentricity which defines the amplitude of the vibration, the A_{RMS} of the trunk also showed no differences (ANOVA, $p>0.05$) (Table 2). This indicates that the branch angle groups were not influenced by these variables. It was verified that the records obtained present in a coherent pattern, with a proportional relationship between trunk diameter and branch diameter. While the records obtained for branch length of the sensor versus branch diameter show an inverse correlation (Pearson's correlation coefficient, $p<0.05$), the relationship between branch diameter and trunk diameter was not influenced by these variables.

Table 2. Vibration parameters obtained according to branch inclination.

	Group of branch inclinations		
	0º - 30º	30º - 60º	60º - 90º
Frequency (Hz)	16.25 ± 0.83 ^{a}	16.51 ± 0.84 ^{a}	16.26 ± 0.82 ^{a}
Trunk A_{RMS} (m/s^2)	110.14 ± 18.01 ^{a}	116.43 ± 18.11 ^{a}	120.90 ± 19.66 ^{a}
Branch A_{RMS} (m/s^2)	149.82 ± 24.41 ^{a}	174.98 ± 33.79 ^{b}	153.84 ± 32.00 ^{ab}
A_{TRANS} (%)	137.24 ± 18.58 ^{ab}	145.82 ± 22.43 ^{a}	131.95 ± 16.23 ^{b}

Mean values ± standard deviation; [a,b]Differences between letters in the same row indicate significant differences (ANOVA, $p<0.05$, *post-hoc* pairwise Student's *t*-test with Holm correction, $p<0.05$; Kruskal–Wallis, $p<0.05$, *post-hoc* Mann–Whitney U test with Holm adjustment, $p<0.05$).

The 30-60° angle group had significantly (ANOVA, $p<0.05$; *post-hoc* pairwise Student's *t*-test with Holm correction, $p<0.05$) higher (+16.8%) values of A_{RMS} (M = 175.0 m/s^2, SD = 33.8) than the group of 0-30º (M = 149.8 m/s^2, SD = 24.4) (Figure 4). The mean A_{RMS} of the 60-90º group (M = 153.8 m/s^2, SD = 32.0), was between that the other two groups without significant differences (ANOVA, $p<0.05$; *post-hoc* pairwise Student's *t*-test with Holm correction, $p>0.05$). The 0-30º group was the most compact group, with the lowest variability (CV = 16.3%), compared to the other groups, which presented higher variability with similar values between them (CV = 19.3% and 20.8%, respectively).

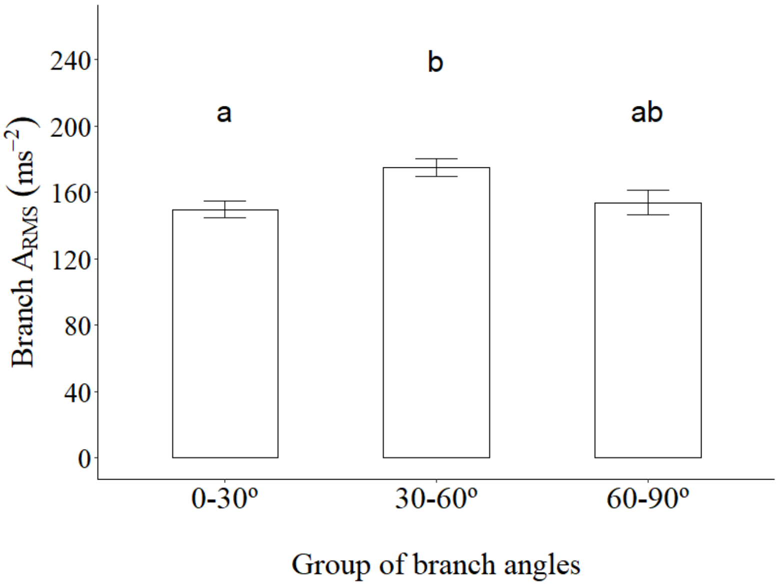

Figure 4. Acceleration RMS measured in tree branches according to the group of branch angles (mean and standard error). Differences between letters indicate significant differences (ANOVA, $p < 0.05$; *post-hoc* Student's *t*-test with Holm correction, $p < 0.05$).

The decomposition of the A_{RMS} values for each group of angles and axes can be seen in Table 3. It is observed that there is no significant difference in the magnitude of the acceleration for each of the axes in the group of more horizontal branches (0-30º) (ANOVA, $p>0.05$; Kruskal-Wallis, $p>0.05$). However, the x-axis is lower in the more vertical branches (30-60º and 60-90º group) in which the acceleration has a higher value on the y- and z-axis (ANOVA, $p<0.05$, *post-hoc* pairwise Student's *t*-test with Holm correction, $p<0.05$; Kruskal-Wallis, $p<0.05$, *post-hoc* Mann-Whitney U test with Holm adjustment, $p<0.05$). As with the A_{RMS} value of the branch in Table 2, higher acceleration values are shown in the 30-60° group compared to the rest, increasing by 16.5-32.7% in the y-axis and 2.8-29.7% in the z-axis.

Table 3. A_{RMS} values for each of the branch axes and group of branch inclinations.

	Group of branch inclinations		
	0º - 30º	30º - 60º	60º - 90º
A_{RMS} on x-axis (m/s^2)	81.83 ± 30.11 1a	69.80 ± 29.42 1a	50.41 ± 28.49 1b
A_{RMS} on y-axis (m/s^2)	87.18 ± 27.82 1a	115.67 ± 36.30 2b	99.31 ± 31.95 2ab
A_{RMS} on z-axis (m/s^2)	77.88 ± 34.42 1a	101.03 ± 37.57 2b	98.30 ± 30.24 2ab

Mean values ± standard deviation; [a,b]Differences between letters in the same row and numbers in the same column indicate significant differences (ANOVA, $p<0.05$, *post-hoc* pairwise Student's *t*-test with Holm correction, $p<0.05$; Kruskal-Wallis, $p<0.05$, *post-hoc* Mann-Whitney U test with Holm adjustment, $p<0.05$).

The range of acceleration transmissibility values (A_{TRANS}) was between 107.8 and 174.9%, so in all cases there was an amplification of the acceleration produced in the trunk to the branch (Figure 5). The maximum amplification occurred in the 30-60° branch angle group (M = 145.8%, SD = 22.4) and the minimum in the 60-90° group (M = 132.0%, SD = 16.2), with significant differences between the two groups (Kruskal-Wallis, $p<0.05$, *post-hoc* Mann-Whitney U test with Holm adjustment, $p<0.05$). This difference was a mean value of 13.8%. The 0-30° angle group had intermediate values with respect to the other groups (M = 137.2%, SD = 18.6), with no significant differences with the other groups (Kruskal-Wallis, $p<0.05$, *post-hoc* Mann-Whitney U test with Holm adjustment, $p>0.05$). Although the 30-60° group had the highest values, it also had higher variability (CV = 15.4%) and amplitude (107.8-174.9%) than the 0-30° and 60-90° groups, which had similar variability values (CV = 13.6% and 12.3%, respectively).

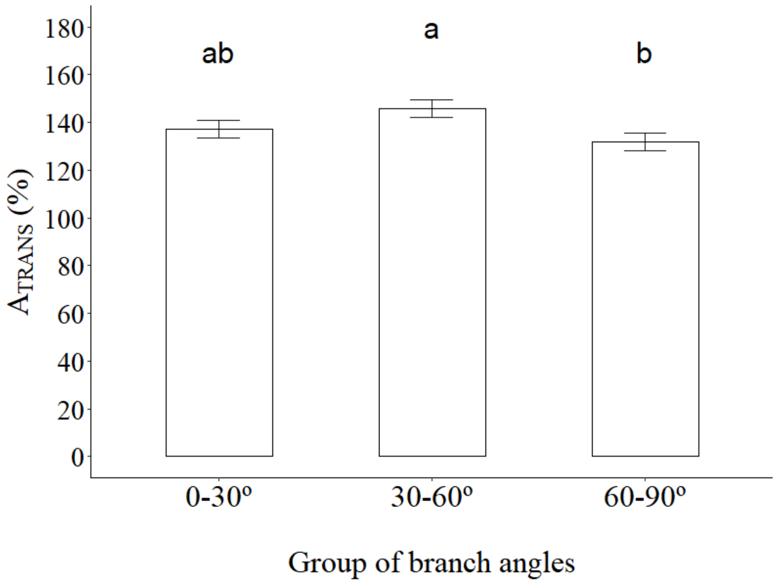

Figure 5. Acceleration transmissibility according to the group of branch angles (mean and standard error). Differences between letters indicate significant differences (Kruskal-Wallis, $p<0.05$, *post-hoc* Mann-Whitney U test with Holm adjustment, $p<0.05$).

The 30-60° angle group had the highest RKER values (M = 0.565, SD = 0.284) showing significant differences with the 0-30° group (M = 0.396, SD = 0.197) (+42.7%) (Kruskal-Wallis, $p<0.05$, *post-hoc* Mann-Whitney U test with Holm adjustment, $p<0.05$), while the 60-90° group (M = 0.487, SD = 0.267) showed no differences with the rest of groups (Kruskal-Wallis, $p<0.05$, *post-hoc* Mann-Whitney U test with Holm adjustment, $p>0.05$) (Figure 6). The RKER results show a similar division to those obtained for branch acceleration.

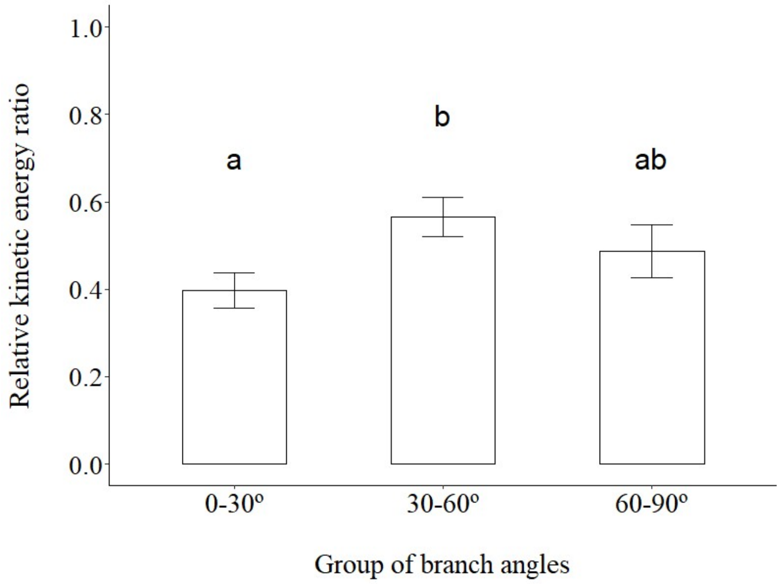

Figure 6. Relative kinetic energy ratio at the three proposed angle groups (mean and standard error). Differences between letters indicate significant differences (Kruskal-Wallis, $p<0.05$, *post-hoc* Mann-Whitney U test with Holm adjustment, $p<0.05$).

Discussion

Resultant acceleration values of 70-100 m/s^2 have been reported in olive trees on the trunk, using frequencies between 24 and 27 Hz, with a vibration time of 5-7 seconds (Leone *et al.*, 2015). These values are slightly lower than those obtained in this study, however, in our experiment, trees had a smaller crown volume, which could have affected the vibration, decreasing the mass damping and therefore increasing the acceleration. The similar acceleration obtained in the y and z axis in the trunk indicates a good adjustment of the perpendicularity in the work of the trunk shaker, with the axis of action normal to the plane. This fact minimises the shearing forces that cause debarking and may also be influenced by the diameter of the trunk, the thickness of the bark and the grip height of the clamp (Ghonimy *et al.*, 2025). Both grip height and trunk diameter were similar in the trees tested. In relation to transmissibility accelerations, other authors report values in olive groves of 130-170%, depending on whether the location of the second point was on the cross or branch of the tree, for 21 Hz, and 117-160% for frequencies of 15.5 Hz (Sola-Guirado *et al.*, 2023), which are in the range of the present study. Average transmissibility of acceleration between trunk and branch are usually higher values than those between the trunk and the shaker, with values of 196% for 3.5 Hz and 240%

for 7 Hz, since the dynamic response recorded in the trunk is minimal compared to that recorded in the branch. This is due to the rapid damping of the shocks generated by the canopy shaker (Sola-Guirado *et al.*, 2023). In citrus fruits, accelerations are 61-177 m/s^2 in trunks and 121-430 m/s^2 in branches, depending on their location and morphology, for frequencies of 14.4-22.6 Hz, with an average acceleration amplification of 88% (Torregrosa *et al*., 2010). This acceleration transmissibility value is just over double the average value obtained in this study (39.5%) and, although there are many factors involved, such as the mass and stiffness of the wood, the position on the branch relative to the application point of vibration is a key factor. Homayouni *et al.* (2022) have shown that the position of the accelerometer on the branch results in a greater wave amplitude as it approaches the end of the branch, and this is enhanced as the diameter of the branch decreases, facilitating the increase in dynamic response (Sola-Guirado *et al.*, 2019). Whereas in other crops, such as nuts, values have been recorded for pistachio branches of 40–120 m/s^2at frequencies of 15-20 Hz (Homayouni *et al.*, 2022) and in stone pine branches, values of 51.2-78.4 $m/s^2$for frequencies of 16-19 Hz with vibration times of 6 seconds (Castro-García *et al.*, 2012). The results in terms of relative kinetic energy ratio report values similar to those obtained for pistachio harvesting by trunk shaker (0.2-1.2) depending on the positions studied and the vibration patterns selected (Ma *et al.*, 2022). This variable is linked to the ratio of diameters of the selected points; therefore, the values can certainly be increased if they have similar magnitudes (Du *et al.*, 2012). On the other hand, through simulations and using modal analysis, it has been observed that the optimum range of vibration frequency for harvesting in olive groves is between 18.7-29.0 Hz (Niu *et al.*, 2022). However, experimental studies have shown that frequencies close to 1020 cycles/min (17 Hz) with high amplitudes, around 100 mm, which are very similar to the conditions of this study, produce high levels of fruit detachment (~80%) when using trunk shakers (Ferguson *et al.*, 2010). These parameters are similar to those obtained by Homayouni *et al.* (2022) in pistachios, with similar amplitudes and frequencies, which use scalograms for vibration analysis.

The branch angle can influence the dynamic behaviour of trees by maximising or minimising the amplitude of vibrations (Kovacic *et al.*, 2018). In our study, it was found that angles between 30-60° have the highest vibration transmission. According to the decomposition of the acceleration in the different axes of the branch (Table 3), it is observed that the branches with the greatest inclination (60-90°) have a similar pattern to that carried out in the trunk by the trunk shaker. As the branches become more horizontal, this decomposition varies until it reaches a similar value in all directions (0-30°), decreasing the total magnitude of the acceleration. This effect may be due to a rotation of the branch that causes part of the energy transmitted by the vibration to be absorbed in deforming the branch, decreasing the amplification of the acceleration. It has been observed that horizontal branches act as flexible elements that absorb and dissipate energy, decreasing vibration transmission and contributing to the structural stability of the tree (Camposeo *et al.*, 2023; James, 2014). However, in the branches with an intermediate inclination (30-60°) the maximum value of the vectorial sum of the acceleration is reached as the acceleration increases in the longitudinal direction of the branch, in accordance with the more inclined branches, and the acceleration in the transversal plane, that is to say, in the diameter of the branch, in accordance with the rest. These branches better capture the transverse component of the vibration, since the waves generated by the vibration propagate both longitudinally and transversely. This behaviour may be due to a change in the stiffness or the mass to stiffness ratio of the branch due to its inclination, affecting the modes of vibration and it is natural frequency, which may be closer to the frequency of the forced vibration, causing a greater amplitude of the oscillation due to resonance effects (Chau *et al.*, 2022; Zhuo *et al.*, 2022). Tous (2011) and Lavee (2010) indicate that harvesting with a trunk shaker is improved with straight olive trees and with 2 or 3 main branches with narrow insertion angles. Other authors suggest that horizontal branches do not transmit acceleration as well as those with a certain angle, which transmit vibrations more effectively. In the case of the olive, this angle is between 35-40° (Nasini and Proietti, 2014). The results obtained in these studies are close to those found in our work. It should also be taken into account that the trees used in our experiment provided branches with different changes of direction and irregularities in their wood, factors that affect the mass, stiffness and damping terms of the tree structure and, therefore, affect its dynamic response. In addition, there are other crops where the role of branch angle in vibration behaviour has been evaluated. In apple trees, it has been observed that the growth angle of the tree branch is an important factor affecting dynamic behaviour (Bu *et al.*, 2021). In almond trees, it has been determined that for the use of trunk shakers it is important to have a branching angle that should not exceed 45°, and that branches should be erect and relatively stiff (Carbó and Connell, 2017). Other authors have quantified the distribution and dissipation of vibration response applied to cherry branches, in which the vibration recorded was amplified in branches with acute angles between nodes and in lateral branches of a shorter length (Homayouni *et al.*, 2022). Xiaoqiang *et al.* (2015) reported that straight branches and a higher angle facilitate vibration transmission in Chinese hickory trees.

Pruning influences different productive and management aspects of a crop. In apple orchards, plantations have been formed with branch angles of 5º with respect to the horizontal of the ground in order to facilitate the work of a harvesting robot (Bloch *et al*., 2018). In cherries, planting has been designed at an angle of 55° to the horizontal of the ground for harvesting by hand-held shaker (Zhou *et al.*, 2014). In the case of olive trees, the timing and type of pruning can affect the vegetative growth and yield of trees in high density olive orchards (Dias *et al.*, 2022; Londolini *et al.*, 2023). However, in turn, tree shape and structure are fundamental considerations when adapting machinery to achieve an efficient harvest (Castillo-Ruiz *et al.*, 2017; Dias *et al.*, 2020). Several authors opt for young branches with greater flexibility because they are better suited to harvesting olive groves with straddle harvesters (Lodolini *et al.*, 2018; Tombesi and Farinelli, 2014). To improve the transmission of acceleration when using trunk shakers, the tree should be formed as a free vase, with an open centre, short main branches with few forks, and short branches, avoiding pendulous ones (Nasini and Proietti, 2014). The crown should not be dense and closed; it should also be opened by pruning to avoid a reduction in acceleration transmission to the branch and, subsequently, to the fruit (Connor *et al.*, 2014). This pruning must be carried out annually (Tous, 2011). In addition, according to our data, training should facilitate the branch angle being in the right range, to increase the dynamic response generated by the trunk shaker and make mechanised harvesting more effective. Therefore, proper pruning management facilitates the interaction of the harvesting machinery with the tree, both at the level of accessibility and geometry and in the efficiency of vibration transmission, optimising the operation of mechanised harvesting and achieving high values of fruit detachment (Messina *et al.*, 2025).

Future improvements of the study could be aimed at pruning a plot with established branches between the 30-60° angle group and analysing the performance of the trunk shaker in terms of harvesting efficiency and dynamic response. The use of LIDAR allows the identification of the different angles of inclination of the tree structure, which facilitates the generation of an optimal vibration to maximise harvesting efficiency, based on a previous database. Other future lines of research could focus on the study of this variable in citrus or nut crops, as these are the most common crops for trunk shakers.

Conclusions

In this work we have evaluated and quantified the contribution of branch inclination on the vibration response of olive trees when a trunk shaker is used for harvesting. The acceleration produced at the trunk and branches, the associated acceleration transmissibility and the relative kinetic energy ratio have been determined for different groups of branch inclination angle: 0-30° (horizontal branches), 30-60° (inclined branches) and 60-90° (vertical branches). The results obtained in the vibration analysis show that the 30-60° angle branch group has increased vibration transmission according the three terms studied, in comparison with the 0-30° group and the 60-90° group. The 30-60° group recorded 13.8-16.8% higher values than the others for the branch acceleration variable, and 6.3-10.5% for the acceleration transmission variable between the trunk and branch points. The relative kinetic energy ratio variable shows the same trend of results as the two previous ones, with increases in the 30-60° group between 16.0-42.7%. The vibration analyses carried out show that the horizontal branches, with the greatest parallelism to the ground, have the greatest difficulty in transmitting vibration. The implications of these findings are substantial for the field of agricultural engineering. By understanding the optimal branch inclinations for vibration transmission, growers can adopt better tree training practices that enhance the efficiency of mechanized harvesting. This not only improves yield but also reduces the physical strain on the trees and the machinery

References

Bloch, V., Degani, A., Bechar, A. 2018. A methodology of orchard architecture design for an optimal harvesting robot. Biosystems Engineering. 166:126–137.

Bu, L., Chen, C., Hu, G., Zhou, J., Sugirbay, A., Chen, J. 2021. Investigating the dynamic behavior of an apple branch-stem-fruit model using experimental and simulation analysis. Computers and Electronics in Agriculture. 186:106224.

Camposeo, S., Vicino, F., Vivaldi, G. A., Pascuzzi, S. 2023. Re-shaping pruning improves the dynamic response of centuries-old olive trees to branch-shaker vibrations application. Front. Plant Sci. 14:1155120.

Carbó, J.L.E., Connell, J.H. 2017. Almond harvesting. In: R. Socias i Company, T.M. Gradziel (Eds.), Almonds: botany, production and uses. Cabi Publishing, pp. 406-27.

Castillo-Ruiz, F.J., Sola-Guirado, R.R., Castro-Garcia, S., Gonzalez-Sanchez, E.J., Colmenero-Martinez, J.T., Blanco-Roldán, G.L. 2017. Pruning systems to adapt traditional olive orchards to new integral harvesters. Sci. Horticult. 220:122-129.

Castro-Garcia, S., Aragon-Rodriguez, F., Arias-Calderón, R., Sola-Guirado, R.R., Gil-Ribes, J.A. 2020. The contribution of fruit and leaves to the dynamic response of secondary branches of orange trees. Biosyst. Eng. 193:149-156.

Castro-García, S., Blanco-Roldán, G.L., Gil-Ribes, J.A., Agüera-Vega, J. 2008. Dynamic analysis of olive trees in intensive orchards under forced vibration. Trees 22:795-802.

Castro-García, S., Blanco-Roldán, G.L., Gil-Ribes, J.A. 2012. Vibrational and operational parameters in mechanical cone harvesting of stone pine (Pinus pinea L.). Biosyst. Eng. 112:352–358.

Chau, W.Y., Loong, C.N., Wang, Y.H., Chiu, S.W., Tan, T.J., Wu, J., et al. 2022. Understanding the dynamic properties of trees using the motions constructed from multi-beam flash light detection and ranging measurements. J. R. Soc. Interface 19:20220319.

Chen, Y., Zhao, J., Chen, Q., Chen, J. 2021. Simulation for fitting the bending shape of fruit branches of lycium barbarum based on the finite element method. Horticulturae 7:434.

Connor, D.J., Gómez-del-Campo, M., Rousseaux, M.C., Searles, P.S. 2014. Structure, management and productivity of hedgerow olive orchards: A review. Sci. Hortic. 169:71-93.

Dias, A.B., Falcão, J.M., Pinheiro, A., Peça, J.O. 2020. Evaluation of olive pruning effect on the performance of the row-side continuous canopy shaking harvester in a high density olive orchard. Front. Plant Sci. 10:1631.

Dias, A., Falcão, J., Pinheiro, A., Peça, J. 2022. Effect of mechanical pruning on olive yield in a high-density olive orchard: an account of 14 years. Agronomy (Basel) 12:1105.

Du, X., Chen, D., Zhang, Q., Scharf, P.A., Whiting, M.D. 2012. Dynamic responses of sweet cherry trees under vibratory excitations. Biosyst. Eng. 111:305-314.

Ferguson, L., Rosa, U.A., Castro-Garcia, S., Lee, S.M., Guinard, J.X., Burns, J., et al. 2010. Mechanical harvesting of California table and oil olives. Adv. Horticultural Sci. 24:53–63.

Ghonimy, M., Alharbi, A., Ibrahim, M.M. 202). Damping behavior of olive trees under trunk shaking. Sci. Rep. 15:11615.

Homayouni, T., Gholami, A., Toudeshki, A., Afsah-Hejri, L., Ehsani, R. 2022. Estimation of proper shaking parameters for pistachio trees based on their trunk size. Biosyst. Eng. 216:121-131.

Hoshyarmanesh, H., Dastgerdi, H.R., Ghodsi, M., Khandan, R., Zareinia, K. 2017. Numerical and experimental vibration analysis of olive tree for optimal mechanized harvesting efficiency and productivity. Comp. Electron. Agr. 132:34-48.

James, K.R. 2014. A study of branch dynamics on an open-grown tree. Arboricult. Urban Forest. 40:25-134.

Kovacic, I., Zukovic, M., Radomirovic, D. 2018. Sympodial tree-like structures: from small to large-amplitude vibrations. Bioinspir. Biomimetics 13:026002.

Lavee, S. 2010. Integrated mechanical, chemical and horticultural methodologies for harvesting of oil olives and the potential interaction with different growing systems. A general review. Adv. Horticult.Sci. 24:5–15.

Leone, A., Romaniello, R., Tamborrino, A., Catalano, P., Peri, G. 2015. Identification of vibration frequency, acceleration, and duration for efficient olive harvesting using a trunk shaker. T. ASABE 58:19–26.

Lodolini, E.M., Polverigiani, S., Sirugo, M., Neri, D. 2018. Damage to several olive cultivars by two over-the-row harvesters in high-density orchards. Acta Hortic. 1199:415-419.

Lodolini, E.M., Polverigiani, S., Giorgi, V., Famiani, F., Neri, D. 2023. Time and type of pruning affect tree growth and yield in high-density olive orchards. Sci. Horticult. 311:111831.

Ma, R., Homayouni, T., Toudeshki, A., Ehsani, R., Zhang, X. 2022. An experimental study and mathematical modeling of vibration transfer in pistachio trees using an inertia-type trunk shaker and field-adapted wireless sensors. Shock Vib. 9966848.

Messina, G., Sbaglia, M., Bernardi, B. 2025. Mechanical harvesting of olive orchards: an overview on trunk shakers. AgriEngineering 7:52.

Murphy, K.D. Rudnicki, M. 2012. A physics-based link model for tree vibrations. Am. J. Bot. 99:1918-1929.

Nasini, L., Proietti, P. 2014. Olive harvesting. In: C. Peri (Ed.), The extra-virgin olive oil handbook. Wiley, pp. 87-105.

Niu, Z., Xu, Z., Deng, J., Zhang, J., Pan, S., Mu, H. 2022. Optimal vibration parameters for olive harvesting from finite element analysis and vibration tests. Biosyst. Eng. 215:228-238.

Pérez-Ruiz, M., Rallo, P., Jiménez, M.R., Garrido-Izard, M., Suárez, M.P., Casanova, L., et al. 2018. Evaluation of over-the-row harvester damage in a super-high-density olive orchard using on-board sensing techniques. Sensors (Basel) 18:1242.

Sanchez-Cachinero, P., Luque-Mohedano, R., Sola-Guirado, R.R. 2022. Computational model for the dynamic characterisation of a trunk shaker. Agriculture (Basel) 12:2158.

Sola-Guirado, R.R., Aragon-Rodriguez, F., Castro-Garcia, S., Gil-Ribes, J. 2019. The vibration behaviour of hedgerow olive trees in response to mechanical harvesting with straddle harvester. Biosyst. Eng. 184:81-89.

Sola-Guirado, R.R., Luque-Mohedano, R., Tombesi, S., Blanco-Roldan, G. 2022. Effect of leaves in the dynamic response of olive tree branches and their computational model. Comp. Electron. Agr. 203:107490.

Sola-Guirado, R.R., Sánchez-Cachinero, P., Blanco-Roldán, G. 2023. Simultaneous trunk and branch shaking in an over-the-row olive harvester. Biosyst. Eng. 231:92-103.

Sola-Guirado, R.R., Sanchez-Cachinero, P., Tombesi, S. 2024. Configurable trunk shaker for the mechanical harvesting of different fruit branches. J. Vib. Control 30:2050-2058.

Théckès, B., Boutillon, X., De Langre, E. 2015. On the efficiency and robustness of damping by branching. J. Sound Vib. 357:35-50.

Tombesi, S., Farinelli, D. 2014. Evaluation of canopy elasticity, light penetration and reciprocal shading for optimal canopy management in high density hedgerow olive orchards. Acta Hortic. 1057:315-320.

Tombesi, S., Poni, S., Palliotti, A., Farinelli, D. 2017. Mechanical vibration transmission and harvesting effectiveness is affected by the presence of branch suckers in olive trees. Biosyst. Eng. 158:1-9.

Torregrosa, A., Porras, I., Martín, B. 2010. Mechanical harvesting of lemons (cv. Fino) in Spain using abscission agents. T. ASABE 53:703-708.

Tous, J. 2011. Olive production systems and mechanization. Acta Hortic. 924:169–184.

Xiaoqiang, D., Chuanyu, W., Leiying, H., Junhua, T. 2015. Dynamic characteristics of dwarf chinese hickory trees under impact excitations for mechanical fruit harvesting. Int. J. Agr. Biol. Eng. 8:17-25.

Xue, T., Wu, J., Zhang, Z., Zhang, C., Tenenbaum, J.B., Freeman, W.T. 2018. Seeing tree structure from vibration. arXiv:1809.05067v1.

Zhang, X., Niu, Z., Deng, J., Mu, H., Cui, Y. 2022. Vibration simulation and experiment of three open-center shape olive trees. Vibroengineering Proc.41:60-65.

Zhou, J., He, L., Zhang, Q., Karkee, M. 2014. Effect of excitation position of a handheld shaker on fruit removal efficiency and damage in mechanical harvesting of sweet cherry. Biosyst. Eng. 125:36-44.

Zhuo, P., Li, Y., Wang, B., Jiao, H., Wang, P., Li, C., et al. 2022. Analysis and experimental study on vibration response characteristics of mechanical harvesting of jujube. Comp. Electron. Agr. 203:107446