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Table Olives Mechanical Harvesting with Trunk Shakers: Orchard Adaption and Machine Improvements

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Currently, hand harvesting is the most widely used method to harvest table olives. However, table olives profitability is in a delicate situation due to low prices and steady rising costs. Economical feasible mechanical harvesting methods are in development in some producer countries such as USA, Spain and Israel, in order to improve this sector competitiveness. This research aims to improve mechanical harvesting performance in existing orchards. Results show that the mean value of harvester efficiency with trunk shakers is 72 %, without additional rod beating or abscission agents are not applied. In orchards where the trees have been trained into shapes that facilitate the vibration transmission, fruit properties have had a limited effect on harvester efficiency. In order to achieve harvester efficiency greater than 85 %, the tree trunk vibration parameters were set above acceleration value of 183 m s^{-2}, and at a frequency of 28.1 Hz. Adjusting the vibration parameters, giving an adequate power of the machine, training the canopy to reduce volume thus facilitating the vibration transmission to the fruit, together with effective reduction of fruit bruising and mitigation of bark damage are all required to ensure the success of vibration harvesting systems for green olive processing.

1. Introduction

The most table olive production is located in the Mediterranean basin, although it is expanding to new producer countries. This crop harvesting remains primarily manual. Workers use ladders to reach the fruit located in the upper branches and pick down the olive fruits letting them fall into panniers suspended in front of them at waist level (Rejano et al., 2010). The panniers are then dumped it on bins spread on the olive tree rows and these are then taken away for processing. This crop currently finds itself in a delicate situation due to the lower prices paid for the production of table olives and the costs rising of hand harvesting. Competiveness is decreasing and net returns on table olive production are falling dramatically (EC, 2012). Table olive mechanical harvesting, is underway in some producing countries such as USA, Spain and Israel, where they are developing an economically feasible mechanical harvesting methods (Zipori et al., 2014).
Mechanical harvesting of table olives is not a common practice due to low harvesting efficiency and high fruit damage limitations (Ferguson, 2006). Unripe table olives have a high fruit removal force (FRF) and are bruised easily (Segovia-Bravo et al., 2011). However, low harvesting efficiency values are not only owing to high FRF, but other variables such as tree training and tree structure also play an important role in harvesting efficiency (Castro-Garcia et al., 2014). In Spain, trunk shakers are employed in untrained and poorly layout orchards to mechanical harvesting, therefore adequate tree training and orchard layout, could improve harvesting efficiency and machine performance (Castillo-Ruiz et al., 2013)
The aim of this study is to determine which parameters have more influence on mechanical harvesting in order to give orchard adaption highlights and machine adjustment recommendations.

2. Materials and methods

A total of 22 orchards were mechanical harvested during five harvesting seasons (2008 to 2012). Three types of table olive orchards were tested: traditional, traditional trained to mechanical harvesting and intensive

(Figure 1). The trees from the traditional orchards were formed by more than one not right trunks with expanded canopies. The traditional orchards trained to mechanical harvesting had a single trunk per tree, in an attempt to increase the harvester productivity (ha h^{-1}), removing lower branches to make easier the trunk shaker access. The intensive orchards comprised open vase-shaped trees with an upright trunk and 2-3 scaffold branches. 19,600 kg of fruit were collected from 400 olive trees of the Manzanilla cultivar (*Olea europaea pomiformis*).



Figure 1: Orchard types: traditional orchards (left), traditional orchards trained to mechanical harvesting (middle) and intensive orchards (right)

Orchard features influence mechanical harvesting performance, tree and trunk size were measured to determine how difficult is to stimulate the tree through trunk shaking. Fruit bruising was evaluated to determine mechanical harvesting feasibility for table olives. Bark damage was also evaluated in a 0 to 4 scale, where 0 is undamaged trunk, 1 level is slightly damaged trunk that have cracking areas, 2 level is when the trunk has reduced peeled off areas, 3 level is when the trunk has large peeled off areas and 4 level is when the trunk has completely girded (Figure 2).


Figure 2. Bruised fruits (left) and completely girded trunk caused by trunk shaker (right)

The FRF (fruit removal force) and FW (fruit weight) of each tree were determined, measuring 30 fruits taken around the tree. Measurements were taken using a dynamometer (Correx, 1 to 10 N measuring range, Haag-Streit AG, Koeniz, Switzertland). Tests were carried out with 15 orbital trunk shakers from different manufacturers. The machines were operated according to manufacturer instructions, with no complementary rod beating. In all cases shaking was applied during 15 s, enough time to knock off fruit predisposed to harvesting using a trunk shaker (Blanco-Roldán et al., 2009). The removed fruit was weighed and the fruit that remained in the tree was hand harvested by professional pickers to determine harvesting efficiency.
The trunk shakers were described by their working parameters. The vibration signals were measured and stored using a dynamic signal analyser (OROS, 25 PC-pack II, OROS SA, Meylan, France) for the recording and analysis of the signals, together with two triaxial piezoelectric accelerometers (PCB, 356A02, PCB Piezotronics Inc., Depew, NY, USA), placed on the tree trunk and the vibration head, to determine the root mean square value of the resultant acceleration and the frequency value of the vibration. For three harvesting seasons, between 2008 and 2010, the oleo-hydraulic power was measured using an oil flow sensor (Flo-tech, FSC-1000, Flotech Solutions Limited, Stockport, UK) and pressure sensor (Parker, SCP-600, Parker Hannifin Corp., Cleveland, OH, USA) before the hydraulic motor that moves the eccentric mass. Multiple linear regression (MLR) models ($P<0.001$) were carried out with three factors of influence as independent variables and harvesting efficiency as the dependent variable. Independent variables were selected as important factors of tree, fruit and machinery.

3. Results and discussion

Table 1 shows the characteristics of the table olive orchard sample tested. Traditional orchards showed high mean values for the canopy volume (23.1 m^3), high yield levels (57.0 kg/tree) and lower tree heights (3.3 m). When they are planted, these orchards were designed for manual harvesting of the fruit and are preferred to other tree shapes due to their high yields and ease of manage (Lavee et al., 2012). The traditional orchards trained to mechanical harvesting show less mean canopy volume (18.9 m^{-3}) and a slight consequent reduction in fruit production (51.3 kg $tree^{-1}$), although yield efficiency, as reported by Farinelli et al., (2012), was increased from 2.6 kg fruit m^{-3} for traditional orchards to 3.1 kg fruit m^{-3} for trained traditional orchards. Adapting trees from traditional orchards means that their characteristics are more similar to trees in intensive plantations. Accordingly, the average characteristics of the table olive tree tested were a height of 3.4 m, a canopy volume of 20 m^3 and a fruit production of 48.1 kg per tree.

Table 1. Description of the table olive orchards mechanical harvested with a trunk shaker from 2008 to 2012 harvesting seasons. Showed values are mean and standard deviation in brackets ( ). Values in the same row followed by the same letters are not significant differences (ρ<0.05 HSD Duncan test)

Type of table olive plantings	Traditional	Traditional trained to mechanical harvesting	Intensive
Tested orchards	6	4	12
Tested trees	78	110	212
Tree height (m)	3.3 (0.6) b	3.4 (0.3) ab	3.5 (0.6) a
Canopy volume (m^3/tree)	23.1 (9.4) b	18.9 (6.6) a	20.2 (9.1) a
Trunk height (m)	1.3 (0.6) b	1.1 (0.3) a	1.0 (0.3) a
Trunk diameter (cm)	20.7 (5.1) b	19.1 (5.2) a	17.9 (5.0) a
Production (kg/tree)	57.0 (24.8) b	51.3 (12.6) b	44.0(23.8) a

The harvesting efficiency results were obtained without complementary rod beating, using trunk shakers. In terms of harvesting efficiency, there were no significant differences between the three types of plantations (Table 2), with mean values of between 71.2 and 73.8% for traditional trained to mechanical harvesting and intensive orchards, respectively. This result could be partly due to a high variability among different trunk shakers tested where harvesting efficiency is more shaker-influenced rather than orchard-influenced. These values are lower than that shown by Zipori et al. (2014), where the ‘Manzanilla’ table olive was harvested in Israel, but spraying the trees with an abscission agent, achieving a harvesting efficiency of 76.0 % for the 2011 harvesting season and of 99.5 % for the 2012 harvesting season. Those authors highlighted that it is not necessary to use an abscission agent to get high harvesting efficiency results, although they nevertheless advise complementary rod beating to achieve high levels, if post-harvest treatment enables the quality of the harvested fruit to be kept. In similar testing using trunk shakers on table olives in California, Ferguson and Castro-Garcia (2014) found harvesting efficiency levels with a mean value of 77.5 %. They underline, however, that the major challenge with trunk shakers was trunk damage in terms of peeled off bark. In their trials, fruit bruising is not a limiting factor due to the change of fruit colouring during California-style black ripe olive processing.

Table 2. Characteristics of the trunk shakers tested during mechanical harvesting of each type of table olive orchards. Showed values are mean and standard deviation in brackets ( ). Values in the same row followed by the same letters are not significant differences (ρ<0.05 HSD Duncan test).

Harvesting parameters	type of table olive orchards		
	Traditional	Traditional trained to mechanical harvesting	Intensive
Frequency (Hz)	28.4(3.9) b	28.8 (4.2) b	26.2 (3.2) a
Trunk acceleration (m s-2)	182 (71) a	210 (85) b	161 (57) a
Tractor power (kW)	77.5 (3.5) a	85.1 (11.0) b	79.6 (11.8) a
Vibration power (kW)	28.31 (9.67) b	32.11 (16.11) b	22.60 (7.25) a
Harvester efficiency (%)	72.1 (8.7) a	71.2 (10.3) a	73.8 (10.1) a

Tested orchard provided a broken bark percentage that varied from 0 to 10 % of the harvested trees. Bark damage occurrence and intensity, depended on the grabbing system configuration (geometry, material, material hardness and grabbing pressure). Other authors point out the importance of bark damage to consider a mechanical harvesting method suitable to use. The clamp system is an important component of the shaker and it has been given an especial design consideration to eliminate damage to the tree (Erdogan et al., 2003).

For citrus crop, other authors reported that bark damage could be affected by the period in which the tree is harvested (Torregrosa et al., 2009).
Despite the differences in the machine design and its working parameters, there was a significant linear relationship between the tree trunk acceleration and the vibration frequency. Also, canopy volume was significantly related to tree production (Figure 3). The resulting vibration transmission from the machine to the tree is determined by a combination of machine design and the characteristics of the tree itself (Abdel-Fattah et al., 2003). In cases where levels of harvester efficiency were over 85 %, they were achieved with mean frequency measures of 28.1 Hz and 183 m s^{-2} for tree trunk acceleration.

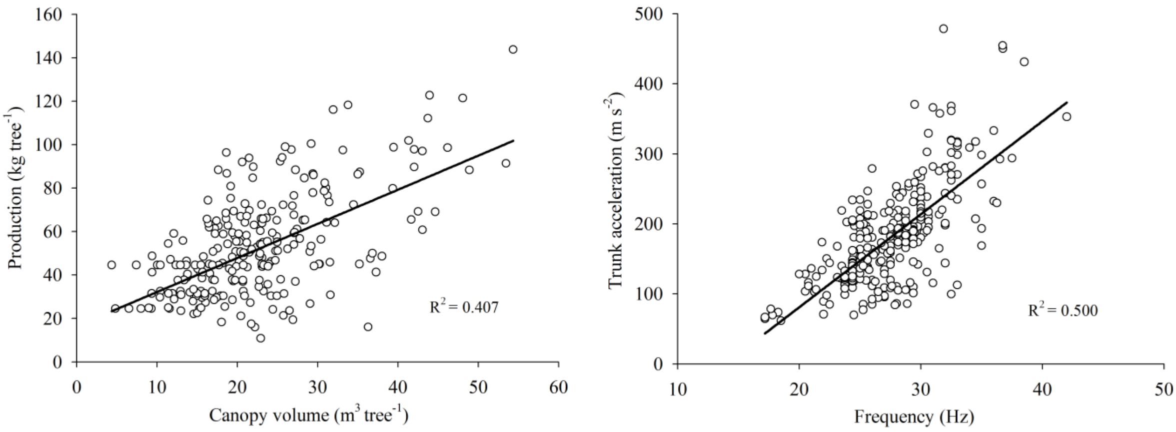

Figure 3: Linear trend between canopy volume and production per tree (left) and linear trend between frequency and trunk acceleration (right)

There is a significant linear relationship between the power used for the shaking and the frequency applied to the tree (Pearson correlation =0.544, sig=0.000). At times, the observed limitations of the machine in reaching high levels of harvesting efficiency was due to limited power of the tractor resulting in a fall in oil supply and then, in frequency and acceleration of the vibration. This factor is especially limiting in orchards with large canopy volumes where high power is required for the tree shaking (Horvath and Sitkei, 2001), and cause dramatic reductions in harvesting efficiency when at the same time tractor power is low.
Although FRF is an important variable, other harvesting parameters could be determining factors for harvesting efficiency. During the vibration of the tree, the fruit is also subject to inertial phenomena, bending forces and fatigue, which provokes the fruit detachment, reducing importance attributed to the FRF (Tsatsarelis, 1987). In addition, fruit beating with neighbouring objects (fruit and branches) also helps the fruit removal (Rosa et al., 2008).
The MLR model applied could explain 33.3 % of the total variance of measured harvester efficiency for three factors. Nevertheless, the MLR models for each type of table olive orchard gave interesting results with high levels of fit in each one (Table 3). For all types of plantation, the increase in production per tree results in a reduction in harvester efficiency. In terms of mechanical harvesting, it is useful to have smaller trees to shake, in other words, a greater number of trees per surface area. Nevertheless, harvester productivity (ha h^{-1}) can be negatively affected (Connor, 2006). Studies on mechanical pruning for adapting traditional table olive plantations noted that a reduction in the canopy volume of 58% resulted in only a 21% fall in production (Ferguson and Castro-Garcia, 2014).
High values of vibration power applied to tree harvesting in traditional orchards trained to mechanical harvesting and intensive orchards lead to better results for harvesting efficiency. Therefore, an increment of vibration power was related to the increase in the vibration parameters: frequency (Pearson correlation=0.544; sig=0.000) and tree trunk acceleration (Pearson correlation=0.562; sig=0.000). However, vibration power in traditional orchards did not result in increased harvester efficiency, and fruits that were applied higher vibration power, showed higher bruising levels.
High FRF/FW values had significant influence on harvester efficiency for intensive orchards. It was due to this orchard type was characterized by better training for mechanical harvesting, and tree structure did not damp vibration transmission. However, FRF/FW played an inverse role for trained to mechanical harvesting and traditional olive orchards. In these cases, the relationships are less important in terms of the MLR model fit. This could be explained by the fact that in the case of traditional and trained to mechanical harvesting orchards, the fruit is concentrated on pendulum branches far from the shaking point, and the shaking is

applied through long and inclined trunks and branches. Thus, others factors such as vibration damping could become prevalent and limit the fruit detachment process.

Table 3. Multiple linear regression models of harvester efficiency of table olives with trunk shakers according to the table olive orchard type

Table olive orchard type		Constant	Production (kg tree-1)	Vibration power (kW)	FRF/FW
Traditional	beta	98.254	-0.543	-0.237	9.799
	t	22.788	-13.575	-2.604	2.928
	sig	0.000	0.000	0.014	0.006
	R2	0.870			
	gl	35			
Traditional trained to mechanical harvesting	beta	58.319	-0.200	0.375	6.390
	t	12.473	-2.371	6.200	2.491
	sig	0.000	0.020	0.000	0.015
	R2	0.401			
	gl	79			
Intensive	beta	125.614	-0.821	0.253	-25.029
	t	27.862	-11.007	3.326	8.893
	sig	0.000	0.000	0.002	0.000
	R2	0.804			
	gl	42			
All types	beta	78.563	-0.410	0.306	3.950
	t	27.404	-8.341	5.558	1.809
	sig	0.000	0.000	0.000	0.072
	R2	0.333			
	gl	158			

4. Conclusions

In conclusion, trunk shaker mechanical harvesting of table olives without complementary rod beating or the use of abscission agents required the implementation of initiatives to improve harvesting efficiency. The intensification of olive orchards, with more trees per hectare and lower production per tree has played an important role in improving harvesting efficiency. Furthermore, vibration parameters were an important factor to get high levels of harvesting efficiency. Also an important part of a successful mechanical harvesting method was to reduce fruit bruising, and bark damage. Improvements to the machinery as well as the plantation design or adaptation, and/or a complementary effective post-harvest field treatment are necessary to achieve a satisfactory result with trunk shakers in table olive harvesting.

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