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DEVELOPMENT OF A PNEUMATIC OLIVE HARVESTER

Mohamed Ghonimy[1,2], Mohamed Ibrahim[1], Abdelfatah Drees[3], Samy Marey[4*,5]

[4*]Corresponding author. Sciences, Technology and Innovation Unit, King Saud University, Riyadh, Saudi Arabia.
E-mail: samarey@ksu.edu.sa | ORCID ID: https://orcid.org/0000-0002-2061-2110

KEYWORDS

olive, pneumatic, hand-held, harvester, fruit removal, chemical abscission.

ABSTRACT

A pneumatic olive harvester was developed and evaluated in this study. The components of the developed machine were the limb clamp, vibrating unit, control elements, main tube, air-pressured hoses, control valve, and power source. The measurements that related to the development of the harvester were fruit and limb damage, and some physical and mechanical properties of the olives fruit-stem system. The results demonstrated that the effectiveness of the developed machine to harvest olive fruits. The appropriateness of the developed machine was evaluated by some criteria: machine productivity, fruit removal, fruit damage, limb damage depth at the contact point with the clamp of the machine, breakage of shaken limb, and consumed energy. The suitable values of these criteria were achieved at 27 Hz frequency and 60 mm stroke.

INTRODUCTION

Olives tree is an evergreen tree that has been known for more than 3000 years. Originally, it was found growing in the geographical areas surrounding the Mediterranean Sea. The number of olive trees in the world is currently estimated at more than 865 million distributed all over the world, of which 95% are located in the Mediterranean region (FAOSTAT, 2018). The Olive crop is considered one of the main crops all over the world, especially in the newly reclaimed areas. Most olive harvesting involves traditional methods, and the fruits are picked mostly by hand, picking the fruits individually, or beating the tree limbs with a pole, which causes them to fall. Canvases or nets are placed under the tree to collect the fallen fruits. However, this type of harvesting is time-consuming and involves intensive labor. Moreover, it results in a high level of fruit damage. Approximately 50%–60% of the total labor requirement is used for harvesting operations (Sessiz & Ozcan, 2006). The mechanical harvesting of olives is performed either by shaking or combing the tree (Nasini & Proietti, 2014). The producers prefer shaking over combing, as shaking causes less damage to the tree .Numerous sources can be used to power the harvesting equipment, including thermal engines (Diesel, Gasoline), electric motors, tractors, compressed air (pneumatic) and self-propelled equipment (Sibbett et al., 2005). Pneumatic machines avoid problems of excessive loads, unlike electrical machine (Nasini & Proietti, 2014). In addition, pneumatic systems are inexpensive, clean, safe, sensitive to vibrations, and easy to operate. The most factor that affect the olive mechanical harvesting is the ratio of fruit detaching force to the fruit mass (Almeidaa et al., 2015). To reduce the detachment force and facilitate the harvesting operation, chemical abscissions have been applied (Peterson et al., 2003). Hand-held harvesters are one of the important major methods employed in olive harvesting. These machines are characterized by fast performance compared to manual harvesting and reduced costs. Nevertheless, they do cause some damage by shaking branches and harvested fruits. Several researches were done to determine the optimum operating parameters of hand-held olive harvesters (Sola-Guirado et al., 2016; Alzoheiry et al. 2020; Ghonimy et al. 2020). Ibrahim (2018) found that the most suitable operating conditions of the hand-held olive harvesting machine were at a pitting head speed of 1100-1500 rpm with 17-cm head length. Under these conditions, the fruit removal, machine productivity, and fruit damage were 97.7%, 91. 5 kg/h, and 6.23 %

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[1] Department of Agricultural Engineering, Faculty of Agriculture, Cairo University, Giza, Egypt.
[2] Department of Plant Production and Protection, College of Agriculture and Veterinary Medicine, Qassim University, Buraydah, Saudi Arabia.
[3] Faculty of Agriculture Engineering, Al-Azher University, Assuit, Egypt.
[5]Agricultural Engineering Research Institute (AENRI), Agricultural Research Centre, Giza, Egypt.

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respectively. Younis et al. (2017) reported that the highest hand-held harvesting productivity was achieved at 1600 rpm and 3-min shaking period, whereas the least damage was reported at 900 rpm and 3 min, with the Kornaki variety. Zhou et al. (2014) found that the overall fruit removal efficiency of sweet cherry was 84% when the branches were shaken at the lowest excitation position, and the removal efficiencies dropped to 77% and 51%, and subsequently rose to 72% as the excitation position moved up the limbs. The fruit damage rates from low to high excitation positions were 20%, 28%, 20%, and 23%, which was approximately 10% higher than those of handpicked fruit. Khdair et al. (2018) found that the productivity of pneumatic comb and branch shaker machines increased by two and four times compared to the traditional method (manual harvesting), respectively. Further, the fruit detachment force (FDF) was reduced from 9.35 N to 5.65 N for the ‘Nabali Rosie’ olive variety at the Ethrel level of 3000 mg L^{-1}. Sessiz & Ozcan (2006) reported that the olives removal percentage using a pneumatic shaker for harvesting without chemical application was lower than 50%. The smallest fruit detachment force and the highest fruit removal (96%) were obtained by employing a frequency of 24 Hz and a 12.5 ml l^{-1} concentration of abscission chemical at a constant amplitude of 60 mm. In Egypt, the economic situation of the small-scale farms owners does not allow possession of olive fruits harvesting machines. Therefore, the aim of this study is to use the available low cost local materials in manufacturing a pneumatic olive fruits harvester and determine its optimum operation conditions.

MATERIAL AND METHODS

A pneumatic olive harvester was developed, manufactured, and evaluated to harvest the olive fruits. This study was realized through five stages: (i) determination of the physical and mechanical properties of the olive fruit-stem system, (ii) development of the pneumatic olive harvester, (iii) determination of the effective range of the operational parameters, (iv) evaluation of the developed harvester, and (v) evaluate-the effect of chemical abscission on the mechanical harvesting performance.

Plant parameters

Olive trees dimensions

This measurement was conducted on fifteen-year-old olive trees (*Shemlali* variety) at Siwa Oasis, Egypt. Trees were planted at 6 m intervals between rows and 6 m intervals within rows (278 trees ha^{-1}). The trees were trained to a modified central leader system. The olive trees were harvested at the appropriate harvesting stage (i.e., 21–25 weeks after full bloom). Fifteen olive trees were randomly selected. The dimensional characteristics of the selected olive trees were measured and reported in Table (1).

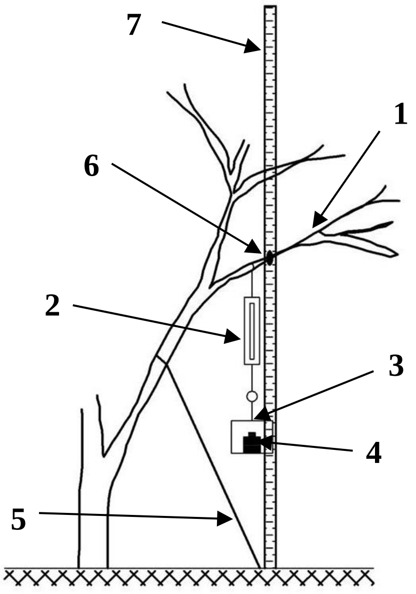
TABLE 1. Mean dimensions of *Shemlali* olive trees and branches.

Parameter	Length
Tree height, m	3.05 ± 0.32
Trunk height, m	0.8 ± 0.06
Limb diameter, mm:	
10% limb length	61.6 ± 4.0
20% limb length	56.0 ± 3.1
30% limb length	44.3 ± 3.2
40% limb length	34.1 ± 2.3
50% limb length	29.9 ± 4.1

Apparent stiffness of olive limbs (K)

Fifteen branches with a 36 mm mean diameter were randomly selected to measure the maximum branch deflection (δ) occurring at a load (N_l), the apparent branch stiffness (K) is determined using Equation 1. For this purpose, the tree trunk was supported, a leveling rod was fixed vertically, and the initial position of the branch was marked on the vertical leveling rod (Fig. 1). A spring balance scale was hanged in the branch at a distance of 40% of the branch length, as recommended by Erdoğan et al. (2003). The load was applied gradually at increment of 2 kg, and the corresponding deflection (≅ vertical displacement) of the branch was recorded on the leveling rod. The experimental results showed that the average K value was 3166 N m^{-1}.

$$K = N_l/\delta \tag{1}$$



1. Olive branch.
2. Spring balance scale.
3. Load cover.
4. Variable Load.
5. Support.
6. Pin.
7. Leveling rod.

FIGURE 1. Schematic diagram of loading procedure.

Physical and mechanical properties of olives fruit-stem system

Shemlali olive fruits were classified visually into three groups according to their maturity levels based on fruit skin and flesh color according to maturity index described by Guzmán et al. (2013). The selected maturity levels were as follows: a) Full mature stage (skin color of the fruit was yellow-green), b) Half-ripe fruits (more than half of the fruit skin color was turned red, purple or black), and c) Full-ripe fruits (all fruit skin color was purple or black with all the flesh purple to the pit). For each maturity level, a sample of 100 olive fruits was collected randomly to measure their physical and mechanical properties. These properties included fruit length, fruit diameter, fruit mass, bulk density, stem length, and effective firmness. Both of fruit length, fruit diameter, and stem length were measured using a digital vernier caliper with accuracy of ± 0. 1 mm. Olive fruit mass was determined using a digital balance with an accuracy of ±0. 1g. The bulk density of olive fruit was calculated by determining the mass of the fruit and its volume using volumetric calibration. The effective firmness was measured using FR-5120 digital fruit firmness tester (Accuracy of ± 0.5% + 2 digits). The ratio of the fruit detaching force to the fruit mass, R_{Fm} (N g^{-1}), is used to determine the suitability of the olive fruit for mechanical harvesting. The fruit detachment force was measured using a digital force gauge with 50 N capacity and accuracy of ± 0.01 N. The digital force gauge was attached to a selected fruit, and a pulling hand-force was applied and gradually enhanced until the fruit was separated. The maximum force was recorded as the static detachment force. Each detached fruit was subsequently weighed. The ratio (R_{Fm}) was calculated as follows:

$$R_{Fm} = \frac{F_d}{m_f} \tag{2}$$

Where:

F_d represents the fruit detaching force (N), and

m_f is the fruit mass (g).

Development considerations

The development of the pneumatic olive harvester has to be based on some important considerations such as: (i) being light weighted, (ii) being easy to operate and maintain, (iii) simple construction with low fabrication costs by utilizing simple components and locally available materials, and (iv) reduce the mechanical damage of branches during and after operations.

The components of the developed harvester

A pneumatic branch-shaker was manufactured, powered by a gasoline engine. The basic function of the branch-shaker is to convert the force of the pressurized air into a rotational motion, and subsequently to a reciprocating motion that is used to shake the olive tree branch. The main components of the shaker comprised the limb clamp, vibrating unit, main tube, air-pressured hoses, control elements, and the power source.

Limb clamp

The limb clamp (Fig. 2) consists of two parts of steel. One of them is fixed and links with the main tube by screw bolt. The second part shall be fixed to the first part so that the distance between the two parts ranged from 30 to 70 mm. The inside face of the clamp is covered with a layer of sponge which is covered with a layer of leather. The two interior parts of the clamp is called pad. The function of the pad system is to transmit shaking force from the shaker to the tree branch and to distribute the shaking and clamping force over a layer area to minimize stresses in the contact area.

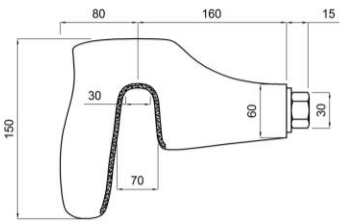
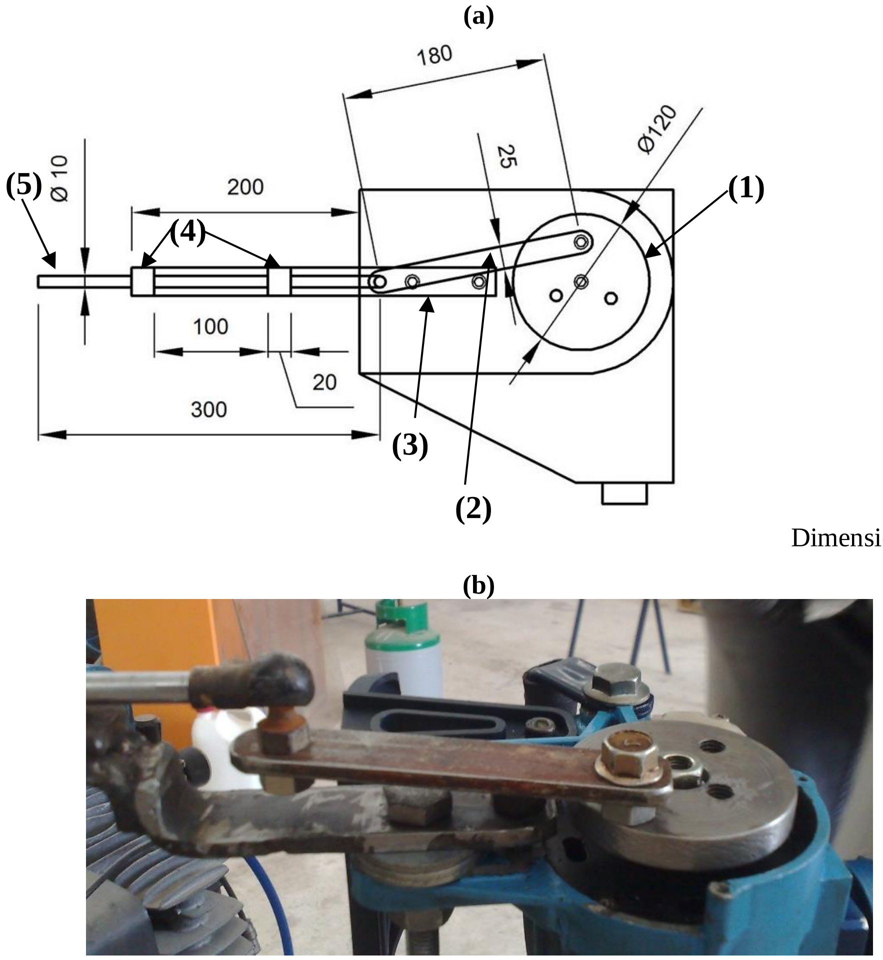


FIGURE 2. Sketch of limb clamp.

Vibrating unit

A slider-crank mechanism was constructed to provide the shaking motion. The vibrating unit (Fig. 3) consists of three main parts:



Dimensions in mm

FIGURE 3. (a) Diagram of vibrating unit: (1) circular disk, (2) transmission arm, (3) supporting rod, (4) sleeve, and (5) vibrating rod; dimensions are given in mm. (b) Photograph of vibrating unit.

The first part consists of a circular disk of 120 mm diameter, 20 mm thickness with three holes. The locations of these holes in the disk serve to select and adjust the proper stroke (50, 60, and 70 mm) as recommended by (Aiello et al., 2019). The second part consists of a connecting arm (200 mm length, 25 mm width, and 10 mm thick) to convert the rotational motion of the circular disk to a reciprocating motion of the limb clamp and subsequently to the tree branch. The third part is a vibrating rod (300 mm length, 10 mm diameter), which transmits the reciprocating motion from the connecting arm to the limb clamp.

Pneumatic motor

A pneumatic motor was used to convert pneumatic energy into mechanical energy (i.e., the reciprocating motion produced by the vibrating unit). A flow control valve was employed to adjust the shaking frequency.

Compressed air transmission tube

A steel tube (2000 mm length, 20 mm diameter, and 2.5 mm thickness) was used to convey the pressurized air from the air compressor tank to the pneumatic motor (Fig. 4). A control valve was connected to the tube to regulate the air flow rate.

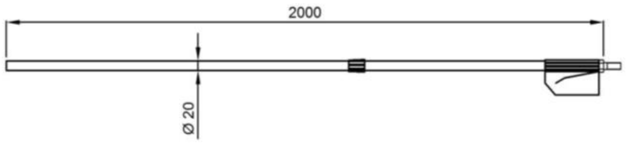


FIGURE 4. Compressed air conveyor tube; dimensions given in mm.

Hoses, valves, and pressure gauges

Air pressure hoses made from synthetic rubber of 8 mm inner diameter were used, with a maximum working pressure of 20 bar. An air pressure regulator was used to maintain the air pressure at 8 bar during the operation, and air pressure gauge was used to indicate the air pressure in the shaking system.

Power source

The motion of the olive branch is in fact extensively complex. It has a non-uniform biological structure, which has an infinite number of degrees of freedom. Therefore, the branch system was analyzed as a single degree of freedom, and the branch was considered as a stiffness member with internal damping. To estimate the required power to operate the harvester, the following parameters are required for the olive branches: (i) average value of branch apparent stiffness (K), (ii) average value of branch damping ratio (ε), (iii) olives branch natural frequency (ω_n), and (iv) the displacement lags impressed force (Phase angle, α). The apparent stiffness (K) of the olive branches was estimated using [eq. (1)], yielding an average value of 3.166 kN m^{-1}. The concept of free vibration decay was used to measure the internal damping ratio of the olive branch, which can be expressed as the logarithm of two successive oscillation amplitudes (X_1, X_2). The damping ratio (ε) was calculated according to Rao (2011) by:

$$\varepsilon = \frac{1}{2\pi(n-1)} ln \frac{X_1}{X_n} \tag{3}$$

Branches with fresh fruits were selected for this purpose; each branch was clamped to a massive steel support to eliminate any energy dissipation at the support, and the branch was subsequently manually displaced and released. This makes the branch vibrate at its natural frequency. By recording the change of oscillation amplitudes, and applying [eq. (3)], the average damping ratio (ε) was estimated to be 0.168. The natural frequency (ω_n), in Hz, of the olive branches was calculated from [eq. (4)] according to Rao (2011) as:

$$\omega_n^2 = \frac{K}{m}(1+\varepsilon^2) \tag{4}$$

Where:

K is the apparent stiffness (= 3166 N m^{-1});

m is the mass of unbalance (i.e., mass of the circular disk in Fig. 1, = 0.83 kg), and

ε is the damping ratio (0.168). Accordingly, the natural frequency (ω_n) of the olive branch was estimated to be 62.6 Hz.

The phase angle (α, rad), i.e., the displacement lags impressed force, was calculated according to Rao (2011) as:

$$\alpha = tan^{-1} \frac{2\varepsilon\left(\frac{\omega}{\omega_n}\right)}{\left[1-\varepsilon\left(\frac{\omega}{\omega_n}\right)^2\right]} \tag{5}$$

Where:

ε is the damping ratio (= 0.168);

ω is the maximum applied frequency (= 27 Hz), and

ω_n is the natural frequency of the olive branch (62.6 Hz). Accordingly, the phase angle (α) was estimated to be 0.1484 rad.

Regarding the determination of the mechanical properties of the wood using the resonance vibration method, Vobolis & Aleksiejunas (2002) described the wood as polymeric material and placed them into the category of visco-elastic materials. Hence, the wood's mechanical properties were defined in terms of elastic solids and viscous liquids (Fig. 5).

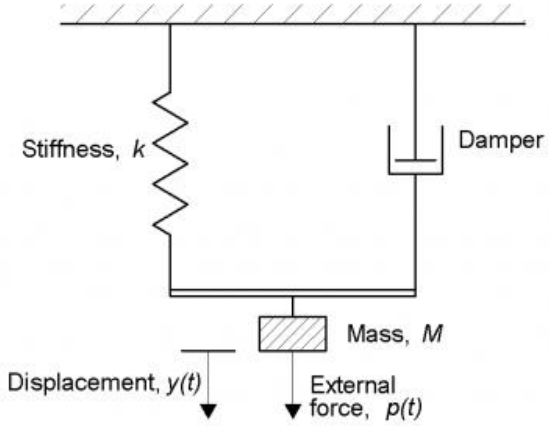


FIGURE 5. Olive branch, spring-mass-damper, model.

The olive branch was considered as a stiffness member with internal damping (Fig. 5). Thus, the externally applied force to the branch is equivalent to the summation of the spring force, movement force, and damping force (spring/mass/damper system). Thus, the force balance of the branch can be expressed by:

$$-Kx - C\frac{dx}{dt} + m\frac{d^2r}{dt^2}cos\omega t = M\frac{d^2x}{dt^2} \tag{6}$$

Where:

x is the instantaneous displacement of the branch from its equilibrium position (m);

C is the coefficient of viscous damping (N m s^{-1});

M is the branch mass (kg);

ω is the frequency, and

r is the radius of the circular disk.

Substituting (d^2r/dt^2) by ($r\omega^2$), [eq. (6)] can be expressed as:

$$mr\omega^2 cos\omega t = M\frac{d^2x}{dt^2} + Kx + C\frac{dx}{dt} \tag{7}$$

The instantaneous displacement of the branch (x) can be expressed by:

$$x = \frac{S}{2}\cos(\omega t - \alpha) \tag{8}$$

Where:

S is the maximum applied stroke. The first and second differentiation of the displacement, x, is given by:

$$\frac{dx}{dt} = -\frac{S}{2}\omega\sin(\omega t - \alpha) \tag{9}$$

$$\frac{d^2x}{dt^2} = -\frac{S}{2}\omega^2\cos(\omega t - \alpha) \tag{10}$$

Accordingly, the power (P = force × speed), required to vibrate the system can be expressed as:

$$P = (mr\omega^2 \cos \omega t)\left[-\frac{S}{2}\omega \sin(\omega t - \alpha)\right] \qquad (11)$$

The maximum required power ($P_{\max}$), in Watt, was obtained by differentiating [eq. (11)].

$$P_{max} = \frac{mr\omega^3 S}{4}(\pm 1 - sin\alpha) \qquad (12)$$

Substituting the values of m, r, ω, S, and α into [eq. (12)] gives the value of maximum required power (1024.58 W). A gasoline engine of 1100 W was selected. The different components of the manufactured harvester (air compressor, air tank, gasoline engine, power transmission system, pressure relief valve, and chassis) were assembled in a compacted size and illustrated in Fig. (6) and listed in Table (2).

Experimental measurements and evaluation criteria

Shemlali variety olive branches were shaken using the developed pneumatic harvester. The branches were chosen at a critical stage of maturity (containing full mature stage, half-ripe, and full-ripe olive fruits). Plastic nets were fixed on a stand to collect the removed fruits. The shaker was attached to each branch at a distance of 0.65 m from the trunk of the tree (i.e., ≈ 30–40 % of the limb length) as recommended by Erdoğan et al. (2003) .After shaking each branch, the fruits removed by the shaker were collected and counted.

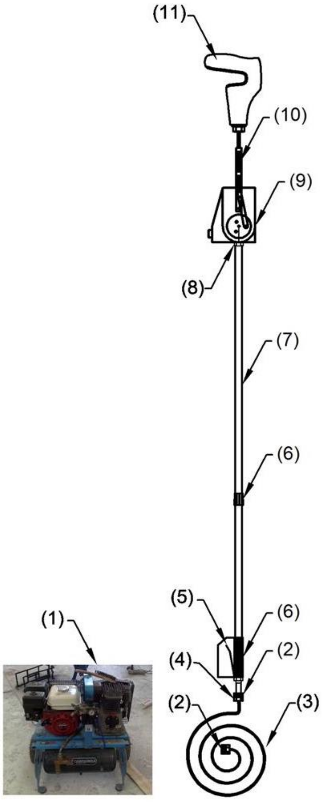


FIGURE 6. Pneumatic olive harvester components.

TABLE 2. The components of pneumatic olive harvester.

Item	Quantity	Title/Name	Item	Quantity	Title/Name
(1)	1	Air compressor and gasoline engine	(7)	1	Main tube
(2)	2	Coupler set with plug connection	(8)	1	Fitting connector
(3)	1	Air hose, 10-m length	(9)	1	Vibrating unit
(4)	1	Plug set with 1/4" connector	(10)	1	Shaking arm
(5)	1	Control valve	(11)	1	Lim clamp
(6)	2	Hand arm			

Experimental procedure

Frequency

Four frequencies were applied for testing the harvester (i.e., 21, 23, 25, and 27 Hz) according to (Leone et al., 2015). These frequencies were obtained by regulating the air pressure; they were measured using a hand-held digital photo/contact tachometer and listed in Table (3).

TABLE 3. Tested frequencies (Hz) corresponding to air pressure (bar).

Air pressure, (bar)	Frequency, (Hz)
5.1	21
5.5	23
5.9	25
6.3	27

Shaking stroke

Three strokes of 50, 60, and 70 mm were tested as recommended by Aiello et al. (2019).

Chemical abscission treatment

The abscission chemical (*Ethrel*) at a concentration of 12.5 ml l^{-1} (recommended by Sessiz & Ozcan 2006) was sprayed after harvest the olive trees by two weeks.

Evaluation criteria

Machine productivity

The productivity (Pm), in kg h^{-1}, of the developed harvester was calculated as follows:

$$Pm = \frac{W}{T} \tag{13}$$

Where:

W depicts the weight of the harvested fruits (kg), and

T is the total operating time (h).

Fruit removal

The fruit removal percentage (FR, %) was calculated according to Pu et al. (2018) as follows:

$$FR = \frac{M1}{M1 + M2} \times 100 \tag{14}$$

Where:

$M1$ is the weight of the harvested olive fruits (kg $tree^{-1}$), and

$M2$ is the weight of the olive fruits remained on the tree (kg $tree^{-1}$).

Fruit damage

Fruit damage percentage (FD, %) was calculated according to Khdair et al. (2018) as follows:

$$FD = \frac{Wd}{Wt} \times 100 \tag{15}$$

Where:

Wd is the weight of injured harvested fruits (kg), and

Wt is the total weight of harvested fruits (kg).

Limb damage depth (LD) at point of contact with machine clamp

The damage of the tree limb at the point of contact with the clamp of tree shaking machine was determined in terms of the bruise depth at the limb damage. This value of LD is measured by Vernier caliper.

Breakage of shaken limb

The breakage of shaken limb was measured in terms of the length of the breakage zone using a Vernier caliper.

Consumed energy (CE)

The CE depicts the specific power per unit capacity (W h kg^{-1}), calculated by:

$$CE = RP/Pm \tag{16}$$

Where:

RP is the required power to operate the harvesting system (1100 W), and

P_m is the machine productivity (kg h^{-1}).

Statistical analyses

Standard Error (SE) was applied to detect significant differences among treatment means. A multiple linear regression model was used for determining the relative contribution of related components to the dependent variable (Y).

RESULTS AND DISCUSSION

Physical and mechanical properties of *Shemlali* olives fruit-stem system

The average values of the olive fruit length, fruit diameter, bulk density, effective firmness, stem length, fruit mass, detachment force, and the ratio between detachment force and fruit mass (R_{Fm}) are listed in Table (4). It is clear that higher values of CV (more than 8%) were accompanied with the properties of fruit length, fruit diameter, fruit mass, and fruit detachment force, while lower values of CV (less than 6%) were accompanied with the bulk density, effective firmness, stem length, and fruit detachment force to mass ratio of olive fruit. All properties of fruit-stem system were significant among the three maturity stages except fruit length and stem length.

TABLE 4. Physical and mechanical properties of *Shemlali* olive fruit-stem system.

Property	Full mature stage		Half-ripe		Full-ripe	
	Mean value	CV[b]	Mean value	CV[b]	Mean value	CV[b]
Fruit length, mm	16.22±0.24[a]	14.66	16.32±0.18	11.17	16.45±0.22	15.32
Fruit diameter, mm	11.00±0.09	8.45	11.60±0.13	11.21	13.05±0.14	10.75
Bulk density, g cm^{-3}	1.73±0.00	2.02	1.00±0.00	3.87	0.99±0.00	3.33
Effective firmness, MPa	0.51±0.00	2.67	0.21±0.00	2.50	0.07±0.00	3.83
Stem length, mm	148.0±0.25	1.67	148.5±0.49	3.32	149.5±0.47	3.15
Fruit mass, g	1.40±0.02	11.46	1.48±0.03	14.65	1.62±0.02	13.54
Detachment force, N	3.14±0.04	12.67	3.00±0.03	11.59	2.44±0.04	14.66
R_{Fm}, N g^{-1}	2.26±0.01	5.21	2.12±0.00	3.95	1.52±0.00	4.22

[a] Standard Error (SE); difference between two means ≥SE indicates significant difference.

[b] CV Coefficient of variation (Standard deviation divided by mean value).

Machine productivity (*Pm*)

The effect of the frequency and stroke with and without chemical abscission on the machine productivity are shown in Fig. (7). The machine productivity (*Pm*) was observed to increase by increasing both the frequency and stroke. The *Pm* values were in the range of 79.5–90 kg h^{-1} and 46.5–72 kg h^{-1} with and without chemical abscission, respectively. This may be attributed to the increase in the inertia of the olive fruit, which overcomes the detachment force required to separate the fruit. The largest values of *Pm*, 72 kg h^{-1} and 90 kg h^{-1}, occurred at 27 Hz frequency and 70 mm stroke with and without chemical abscission, respectively. This observation could be attributed to the above-mentioned theory. Also, fig. (7) showed that the use of chemical abscission resulted in an increase of the machine productivity for all frequencies and stroke levels. This may be due to the formation of an abscission zone in the fruit stem as a result of the chemical treatment, which facilitates fruit separation and thus increases the machine productivity. These results were in agreement with the findings obtained by Sessiz & Ozcan (2006). Thus, the highest *Pm* occurred at 27 Hz frequency and 60 mm or 70 mm stroke.

The multiple regression analysis showed that there was a significant correlation between the frequency ($\boldsymbol{\omega}$), stroke (***S***), and machine productivity (***Pm***) for both cases with and without chemical abscission. Further, a multiple regression analysis yielded polynomial eqs (17) and (18) as follows:

For the use of chemical abscission:

$$Pm = 1.250\,\omega + 0.144\,S - 48.208 \tag{17}$$
$$R^2 = 0.773$$

For the absence of chemical abscission:

$$Pm = 3.740\,\omega + 0.178\,S - 39.033 \tag{18}$$
$$R^2 = 0.864$$

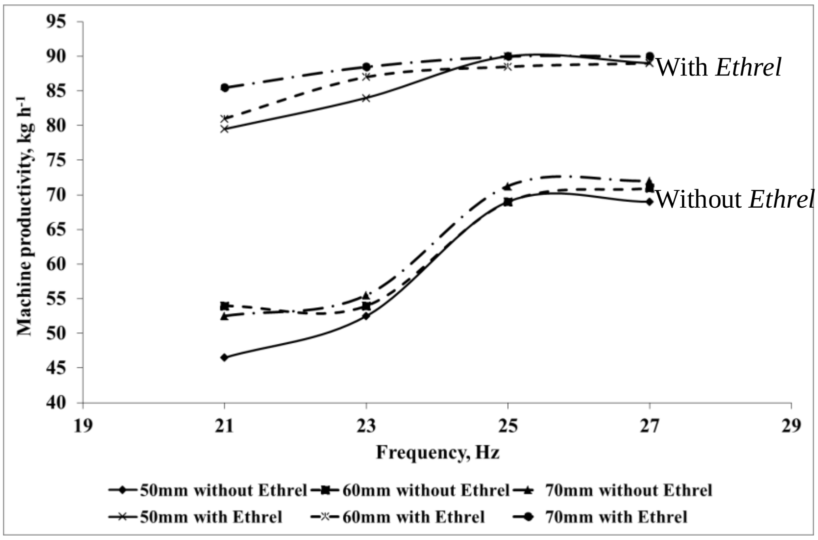


FIGURE 7. Effect of frequency and stroke on machine productivity with and without the use of chemical abscission.

Fruit removal (FR)

The average values of olive fruit removal (*FR*) are shown in Table (5). From Table (5), it is evident that the *FR* values (with and without chemical abscission) increased with increased frequency and stroke. The increase in the frequency from 21 Hz to 27 Hz caused an increase in the *FR* from 52.5% to 79% at 60 mm stroke for the treatment without chemical abscission. The same trend was observed for all other tested strokes. This may be attributed to increase in the centrifugal force due to the increase in the limb frequency, which enhances the fruit removal. For the treatment with chemical abscission, the percentage of fruit removal increased from 88.5% to 95.5% as the stroke increased from 50 mm to 70 mm at a frequency of 23 Hz. The same trend was found for all other tested frequencies. The highest values of *FR,* 81% and 99.6%, occurred at 27 Hz frequency and 60 mm or 70 mm stroke without chemical abscission. This may be attributed to the decrease in the detachment force in the case of chemical abscission. The results were in agreement with the findings obtained by Sessiz & Ozcan (2006) and Khdair et al. (2018). The multiple regression analysis showed that there was a significant correlation between the frequency ($\boldsymbol{\omega}$), stroke (***S***), and olive-fruit removal (*FR*) for both treatments with and without chemical abscission. Further, a multiple regression analysis yielded the following polynomial eqs (19) and (20):

With chemical abscission:

$$FR = 1.498\,\omega + 0.199\,S - 47.757 \tag{19}$$
$$R^2 = 0.746$$

Without chemical abscission:

$$FR = 4.705\,\omega + 0.280\,S - 62.712 \tag{20}$$
$$R^2 = 0.847$$

From Fig. (10) and Table (5), it is deduced that the highest ***Pm*** and ***FR*** were performed at 27 Hz frequency and 60 mm or 70 mm stroke.

TABLE 5. Effect of frequency and stroke on fruit removal with and without using chemical abscission.

Chemical abscission	Stroke, mm	Frequency, Hz			
		21	23	25	27
Without *Ethrel*	50	51.3±1.47[a]	53.7±1.34	77.1±1.15	77.0±1.87
	60	52.5±2.14	55.0±1.34	77.0±1.15	79.0±2.33
	70	60.1±2.76	61.4±1.89	79.0±1.37	81.0±1.67
With *Ethrel*	50	86.3±0.64	88.5±0.12	98.7±0.15	99.1±0.01
	60	92.0±0.17	96.0±0.22	99.0±0.19	99.6±0.00
	70	95.0±0.82	95.5±1.10	99.0±0.19	99.0±0.12

[a] Standard deviation (SD); difference between two means ≥SD indicates significant difference.

Fruit damage (*FD*)

The average values of olive fruit damage (*FD*) are presented in Table (6). The *FD* values were not affected by the frequency and stroke and ranged from 2.5% to 3.5% for all tested frequencies and stroke ranges. The low *FD* values may be attributed to the mechanism of the machine operation. The detachment occurs in the stem, and there is no direct contact with the fruit itself. Further, the fruits are collected in an above ground net, thus minimizing the damage caused by the fruit hitting the ground. Multiple regression analysis showed that there was no significant relation between the frequency (ω), stroke (S), and fruit damage (*FD*) for both the cases with and without chemical abscission.

TABLE 6. Effect of frequency and stroke on fruit damage (%) with and without chemical abscission.

	Stroke, mm					
	Without spraying *Ethrel*			With spraying *Ethrel*		
	50	60	70	50	60	70
21	2.8	2.5	3.2	2.6	2.8	3.0
23	2.5	2.5	3.0	3.0	2.9	3.0
25	2.6	3.0	3.1	3.5	3.0	3.0
27	3.0	3.0	3.4	3.1	3.0	3.5

Limb damage depth (*LD*) at point of contact with shaking machine clamp

The values of the limb damage (*LD*) at the point of contact with the clamp of the shaking machine (when the developed machine operates without chemical abscission) are shown in Fig. (8). The maximum value of limb damage depth, 2.7 mm, was found at a stroke of 70 mm and frequency of 27 Hz. Fig. (8) shows that the limb damage depth at point of contact with developed machine clamp decreased by increasing the shaking stroke above 60 mm. However, there were no effects of the tested frequencies (21 to 27 Hz) at the *LD* damage above one mm. Thus, the machine can be operated safely at frequencies from 21 Hz to 27 Hz and at the strokes from 50 mm to 60 mm. The stroke can also be increased from 60 mm to 70 mm, provided that the frequency does not exceed 23 Hz. A similar trend was found when the machine operated after spraying the olive trees with *Ethrel* (chemical abscission) at a concentration of 12.5 ml l^{-1}.

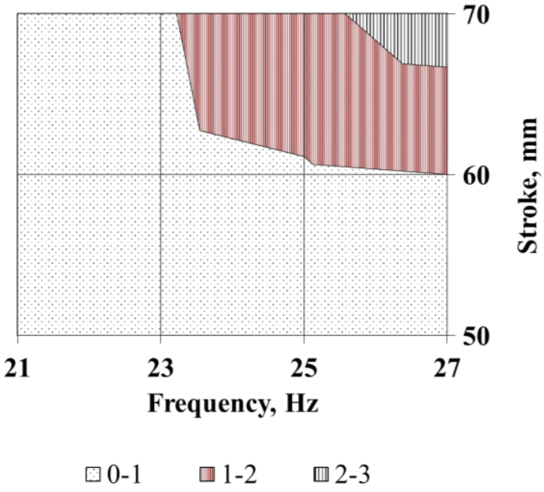


FIGURE 8. Effect of frequency and stroke on limb damage depth at point of contact with developed machine clamp.

The limb damage (*LD*) that resulting from operating the developed machine is like to girdling treatments that were applied by removing a narrow ring of the bark (maximum depth 1 mm) from base of branching zone. Girdling process regulates plant growth and photosynthesis for olive tree. Limb damage depth and griddling may positively affect ethylene which stimulates the induction of the floral buds and improve flowering in the following season. An increase in flower initiation following possible phloem blockage due to vibrating action, is usually evident in the season following treatment (Annabi, et al., 2019).

Breakage of shaken limb (*LB*)

The values of limb breakage (*LB*) in mm (when the developed machine operated without chemical abscission) are shown in Fig. (9). From Fig. (9) it's clear that the maximum value of limb breakage, 6.9 mm, occurred at stroke 70 mm and frequency 27 Hz. Also, Fig. (9) shows that, by increasing the stroke over 60 mm and frequency over about 23 Hz, the limb breakage was increased over one mm. But there were no effects of the tested frequencies on *LB* over one mm. Thus, the developed machine can be operated safely at frequencies from 21 to 27 Hz and the strokes from 50 to 60 mm. The same trend was found when the machine operated after spraying the olive trees with *Ethrel* (chemical abscission) at a concentration of 12.5 ml l^{-1}.

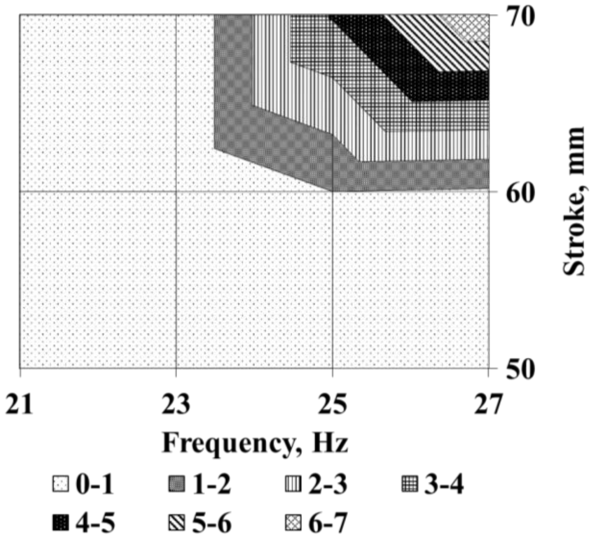


FIGURE 9. Effect of frequency and stroke on limb breakage.

Consumed energy (*CE*)

The average values of the consumed energy (***CE***) at different frequency and stroke levels (with and without application of abscission chemical) are presented in Fig. (10).

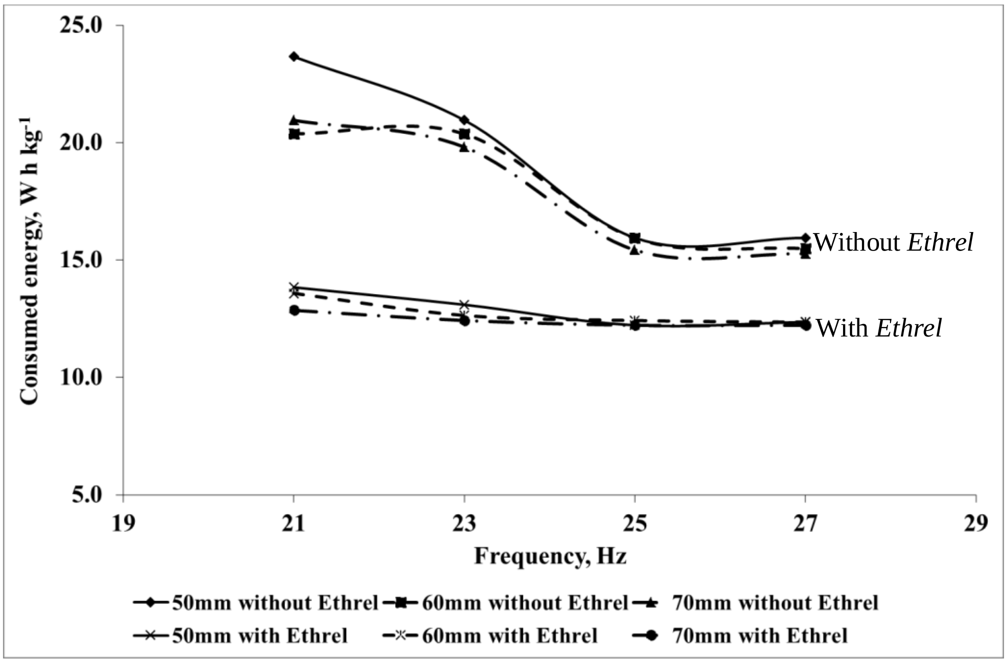


FIGURE 10. Effect of frequency and stroke on consumed energy with and without chemical abscission.

Increasing the frequency from 21 Hz to 27 Hz decreased the consumed energy by 51.69%, and a further 8.82% with chemical abscission at stroke of 60 mm. This may be attributed to an increase in productivity by augmentation of the frequency. Results show that applying the abscission chemical decreased the consumed energy by 37.37% at a frequency of 23 Hz and stroke length of 70 mm compared to without chemical abscission. This also may be attributed to the increase of machine productivity with the abscission chemical.

The results from this paper indicated that the maximum fruit removal & machine productivity with minimum fruits & limb damage was performed at 27 Hz frequency and 60 mm or 70 mm stroke. These results are similar to those found by Polat et al. (2017), who reported that the fruit removal was 93.27% at a frequency of 40 Hz and 20 mm amplitude.

Cost analysis

The olive harvesting cost involved for the developed machine was calculated as follows:

Fixed cost

The machine-related fixed costs included depreciation, interest, taxes, housing and insurance. Assuming a machine life expectancy of ten years, an interest rate of 10 % and a machine salvage rate of 10 % of the machine price (cost) of \$ 1500, the annual capital consumption (CC), which included the depreciation and the interest costs, was estimated at 25 % of the machine cost (Hunt, 1983). Therefore, the annual CC for the developed machine was estimated at \$ 375 With the assumption of 200 operating hours per year, the depreciation and interest costs were calculated at \$ 1.87 h^{-1}. The remaining three elements of the fixed costs (interest, taxes and housing) were, annually, assumed to be 2% of the machine cost (Hunt, 1983), which was calculated at \$ 30 y^{-1}, hence \$ 0.15 h^{-1}. The fixed cost was determined at \$ 2.02 h^{-1}.

Operation (variable) cost

The operational costs included the cost of labor, fuel cost, repair and maintenance. The labor cost was calculated based on three laborers were required to properly operate the machine and collect the harvested fruits. This cost was estimated at \$ 6.5 day^{-1} (8 h day^{-1}), hence the labor cost was calculated at \$ 0.81 h^{-1}. The fuel cost of the machine was determined to be \$ 0.39 h^{-1}. However, the cost of repair and maintenance was estimated at 2 % of the machine cost per 100 hours of operation (Hunt, 1983), which was calculated at \$ 0.3 h^{-1}. Therefore, the operation (variable) cost was determined at \$ 1.5 h^{-1}. Then the total machine cost was estimated at \$ 3.52 h^{-1}.

The olive harvesting cost (\$ kg^{-1}) is defined as the machine cost (\$ h^{-1}) divided by the machine productivity (kg h^{-1}). The average value of olive harvesting cost in case of applying the abscission chemical was \$ 0.041 kg^{-1} compared to \$ 0,12 kg^{-1} when the abscission chemical is not used.

CONCLUSIONS

The following conclusions are made from this investigation:

1. Spraying of olive trees before harvesting with *Ethrel* led to an increase both in machine productivity and fruit removal efficiency, as well as a decrease in consumed energy
2. Maximum machine productivities, 72 kg h^{-1} and 90 kg h^{-1}, were performed at 27 Hz frequency and 60 mm or 70 mm stroke with and without chemical abscission for olive fruits of the *Shemlali* variety.
3. Highest values of fruit removal, 81 and 99.6%, were performed at 27 Hz frequency and 60 mm or 70 mm stroke without and with chemical abscission respectively.
4. Olive fruit damage is not affected by the frequency and stroke range. The damage ranged between 2.5% and 3.5% for all tested frequencies and strokes.
5. The minimum value, ≤ one mm, of limb damage depth at the point of contact with the clamp of the shaking machine was found at frequencies from 23 to 27 Hz and strokes from 50 to 60 mm.
6. The minimum value of limbs breakage, ≤ one mm, was likewise found at frequencies from 23 to 27 Hz and strokes ranged from 50 mm to 60 mm.
7. The minimum values of consumed energy were achieved at 27 Hz frequency and 60 mm or 70 mm stroke with and without chemical abscission.

Therefore, the suitable parameters for the developed machine operation with regard to the machine productivity, fruit removal, fruit damage, limb damage at the point of contact with clamp of shaking machine, breakage of shaken limbs, and consumed energy were found to be at 27 Hz frequency and 60 mm stroke.

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