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Original article

Design and implementation of a new pneumatic harvester for olive fruits harvesting

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Summary

The objective of this study was to measure and evaluate the performance of a New Pneumatic Harvester (NPH) for harvesting the olives fruit and compare the results with those of similar cases. The study involves two sections, namely, the NPH and the collector system. Two oily types of olive (*Mari* and *Yellow*) were selected to evaluate the NPH and the collector system. The randomized complete block design and Duncan's multi-scope test were used for variance analysis and means comparison purposes, respectively. The dependent parameters used to evaluate the NPH were harvesting productivity, harvesting efficiency, and leave downfall percent. Also, the fruit damage was selected for the collector system. Results showed that the NPH can harvest 92% of olive fruits. The highest amount of harvesting productivity belongs to NPH of 29.47 kg h^{-1}. The percent of leaves downfall in the harvesting process was found to be 2.55%. Using the collector system can reduce the level of damaged fruit from 60.8% to 25.12% and from 60.54% to 24.54% in the *Mari* and *Yellow* variety.

Keywords
harvesting damage, manual harvest, olive tree

Nomenclature

F: force (N)
P: pressure (bar)
D: pneumatic cylinder diameters (m)
A: piston area (m^2)
Q: air flow (cm^3 min^{-1})
M: fruit mass (kg)
V: velocity (m s^{-1})
E: energy (j)
H: efficiency (%)
K_1: mass of detached fruits (kg)
K_2: mass of undetached fruits (kg)

Significance of this study

What is already known on this subject?

- Harvesting is one of the major problems with the olive plant.

What are the new findings?

- Criteria for designing the New Pneumatic Harvester (NPH) were: easy design, simple to use, low weight, high productivity, less fruit damage, and low operating costs. The main novelty of this type of harvester is low operating costs and use in gardens far from the energy networks.

What is the expected impact on horticulture?

- NPH can detach 92% of olives on the tree in a short time. This machine is very practical because it can work effectively in traditional and small gardens in different situations. The collector system saves time, prevents olive fruit from damage, and can be used for all harvesting methods.

Introduction

The olive tree is one of the Mediterranean plants that its fruits used as a cannery and oil extraction (Barbera et al., 2013). Olive has traditionally been known among people, which is also important for health and used as a strategic food in some countries (Fiorino et al., 2010).

One of the major problems with the olive plant is harvesting, which is mostly done in four ways: 1. picking up the fruit on the ground; 2. harvesting manually; 3. harvesting via branch shaker; and 4. harvesting mechanically (Lupi et al., 2012). Harvesting is the final step in field production of olive fruits, but if done at the wrong time or in the wrong way it can markedly affect the grower's net return. The economic success of super-intensive olive plantations is mainly achieved due to the full mechanization of harvesting (Ottanelli et al., 2019). The olive harvest is expensive in terms of wages and adequate labor supply has brought about many problems (Zipori et al., 2014). Fruit damage, damages related to the olive tree, quality reduction, human injuries, time consumption, and costly process in the traditional ways are problems existing in the harvesting process. Mechanized harvesting is done in many different types, such as the trunk and limb shakers. Because of device feature like power supplement implementation of this shakers are difficult (Çakmak et al., 2011). Although, the mechanized harvesting methods are efficient but they have usage costs problems. Therefore, the best harvest should be inexpensive and highly efficient.

Many researchers have investigated shaker design, analyzing harvesting efficiency and tree damage. Researchers studied the effect of shaking force and the amplitude of the shaking on the mechanized harvesting of olive. They showed that an increase in olive tree diameters trunks led to an increase in shaking force and a decrease in amplitude of the shaking. So, for mechanized harvesting in the big olive trees with big trunk diameters more power must be applied (Babanatsas et al., 2019). A comparative study was done to investigate the various ways of olive harvesting. Results show that harvesting through shaking the stem is the best way to remove the olive fruit from a tree (Yousefi et al., 2010). Five different olive harvesters were investi-

gated. The flat type olive harvester has more vibration value index (Çakmak et al., 2011). The effect of two types of olive tree harvesting (Trunk Shaker and Mechanical Harvest Aid) on harvesting time were studied. Results show that harvesting the olive trees with mechanical harvest aid can save more time (Nayeri and Torkashvand, 2016). Results concerning the examination of harvesting type on harvesting efficiency show that with increasing the fruit removal force the harvesting efficiency was decreased (Zipori et al., 2014). A study on four types of olive harvester: plastic combs, small shakers, rotating combs, and vibrating combs were done. Researchers indicated that all types of harvesters except the small shaker improve the worker's productivity (Bentaher and Ben Rouina, 2002). Results of the study on a pneumatic harvester showed that manual harvesting and mechanical harvesting methods had a significant effect. The pneumatic comb machine had higher bruised fruit than the manual harvesting (Ahmad, 2018). With an increase in the operating velocity, the productivity harvesting and damage percentage increased and the 1,250 rpm operating velocity value could be a good alternative for harvesting (Mansour et al., 2018). Two methods of harvesting olive fruit, namely, mechanized harvesting with pneumatic harvester and manual harvesting were investigated, which indicated that due to the presence of the collector system, using mechanized harvesting can reduce the fruit damages (Plasquy et al., 2019). Mechanical canopy and trunk shaking were investigated in line with the harvesting mechanization of table olive orchards. Accumulating the trunk shaker and shaker combs can increase the bruise index of olive fruits. The lowest bruise index of olive fruits belongs to the manually-type harvest with a 0.5% value (Sola-Guirado et al., 2020).

The designing and fabrication of olive fruit harvester have long since been the subject of many types of research. Applying some of these systems may exert large costs on farmers, and the efficiency of these machines requires significant economic costs that many producers cannot afford. For this large group of farmers, new models have recently been presented. Nevertheless, the use and utility of some of these machines still entail difficulties, such as the large weight, difficult access to the trunks, or handling the fruit boxes. In this study, results concerning the evaluation of a new design of portable pneumatic olive harvester with a fruit collector system are presented to fix some of the harvesting problems. The parameters of the evaluation of the harvesting machine, such as the harvesting efficiency, harvesting productivity, and olive tree damage were compared with those of the manual method and similar harvesting methods. Finally, the effect of fruit collector on fruit damage was investigated in the current work.

Materials and methods

Harvester machine design

The main criteria for designing the New Pneumatic Harvester (NPH) were as follows: easy design, simple to use, low weight, high productivity, less fruit damage, and low operating costs. The main novelty of this type of harvester is low operating costs and use in gardens far from the energy networks. A double-sided jack was used to provide jaw movement, so the required airflow rate, pressure drop, airflow control valve, and jack size must be defined.

To show the advantages and disadvantages of the present device with existing devices, the results of the evolution of the NPH compared with a Pneumatic Harvester (PH) that the features of the PH are shown in Table 1.

Fruit detachment force

The first step of harvesters' design is to understand the characteristics of the olive fruit. For measuring fruit detachment force from tree branches, three trees of each verity were selected and ten olive fruits of each tree accidentally were selected. The force required to detach them was measured by a mechanical force gauge. The mechanical gauge of FG-5020 model was used and calibrated in the Precision Process Calibration Laboratory with the approval of No. 681 of the Standard Institute of Iran.

The fruit detachment force employed to determine the applied force on the pneumatic jack. So to determine this amount assuming that all of the jaw surface covered by the olive fruit and the detachment force in this situation was calculated.

1. **Amount of airflow.** The amount of airflow was expressed in liter per second of free air (f.a.d).
2. **Directional control valve.** This valve can work through making changes in the airflow direction which are classified as follows:
   1. Number of ways;
   2. Number of pulley positions;
   3. Valve operation method;
   4. Diameter of the valves.
3. **Machine pipes.** The pipe diameter is a very important factor for designing pneumatic systems. When the low pipe diameter was applied, the pressure dropped and the airflow velocity increased accordingly. In the case of water penetration into the pipe, the clogged pipes situation was expected to happen. Two conditions, namely, 5–8 m s^{-1} and 0.5 bar were found to be appropriate for the airflow velocity and the pressure dropped.

Jack design

The first step for jack design is to define the required pressure and velocity of air to detach the olives from the tree. Equation (1) shows the jack piston, which was used to calculate the air force.

$$F_m = P \times a \tag{1}$$

After selecting jaws frequency and active volume of the piston, the cam length and Air Mass Flow (AMF) were calculated. The amount of AMF for jaw movement to open the jaw was calculated by Equation (2), and in the closed cycle, Equation (3) was used for the AMF. Finally, the total AMF to open and close the jaws was calculated by Equation (4).

$$Q_{ext} = \pi \times \left(\frac{D^2}{4}\right) \times x \times n \times \left(\frac{P_1 - P_0}{P_0}\right) \tag{2}$$

$$Q_{ret} = \pi \times \left(\frac{D^2 - d^2}{4}\right) \times x \times n \times \left(\frac{P_1 - P_0}{P_0}\right) \tag{3}$$

$$Q_{tot} = \pi \times \left(\frac{2D^2 - d^2}{4}\right) \times x \times n \times \left(\frac{P_1 - P_0}{P_0}\right) \tag{4}$$

Assuming that the total pneumatic energy was converted to the kinematic energy, the maximum velocity could be determined using Equation (5).

$$E = \frac{1}{2} m (v_{max})^2 \tag{5}$$

The total energy required was calculated by Equation (6):

$$E = \frac{\frac{1}{2}P \times \pi D^2 \times (0.5)^2}{2g \times 4} \quad (6)$$

The total energy for opening the jaw was calculated by Equation (7):

$$E = 5 \times 10^{-4} \times P(D^2 - d^2) \quad (7)$$

The determinations show that the detachment force of olive fruit from the tree and the pressure required for the pneumatic jack were 10 N and 7 bar, respectively. The machine had one handle and it was gripped by one operator's hand and a telescoping rod up to a maximum length of 3 m. The harvesting mechanism had two jaws and each jaw contained 7 fingers that allowed for easy and deep access to all types of foliage without getting caught in the branches. 90 degrees was selected for the angle between two jaws based on the previous researches. The jaws had 18 cm length and the distance between them must be equal to the olive fruit width, so 1 cm distance was considered. We assume that in every impact of jaws, 23 olive fruits were detached from tree branches. So, the total force required for each impact was determined. The force related to the pneumatic cylinder was determined by Equation (8).

$$2f_d Cos\left(\frac{\theta}{2}\right) = F \quad (8)$$

The amount of force of each jaw for the olive fruit detached from the tree was 325.3 N, and for calculating the piston diameters Equation (9) was used.

$$F = A \times P \quad (9)$$

After determining the piston diameters, the length of the cam was calculated and the standard jack with these characters was selected.

Table 1. PH technical features.

Number	Feature	Amount
1	Model	Campagnola srl
2	Weight	1 kg
3	Length	1.8–3 m
4	Max. pressure	7 bar

1. Cylinder design. The cylinder provides a closed system which assists the movement of the piston. For moving the piston across the cylinder in high frequency, valves must be used or the manual control applied. Because of the operation conditions, the pneumatic valve was selected to change the airflow direction. When the pneumatic valve was in position A, high air pressure pushed the piston to the right side (Figure 1). By moving the piston to right, the airflow was transferred to the C input of the pneumatic valve which changed the direction of airflow, resulting in the activation of the B position of the pneumatic valve. When high-pressure air moves to the B output of the pneumatic valve, the piston moves to the left side, and air moves toward the D input of the pneumatic valve, and such a cycle is replicated. After assembling the parts, the frequencies of these cycles were measured by an electronic eyes sensor. The frequency of the piston movement is 5.21 Hz in 7 bar air pressure. So, after defining design parameters, the mechanical value of No. G1/8'' was selected. Other parts of the harvester such as the chain, cam, and pneumatic value along with the parts were designed.

Figure 2 shows the details of NPH, including harvester jaws, cylinder and pneumatic valve, power transmission, and telescoping rod.

2. Collector system. The common properties of the collector system for olive fruit are shown in Table 2. By applying this system, the olive fruits falling from the tree were collected into a box. The driving power of the collector system is provided by labor.

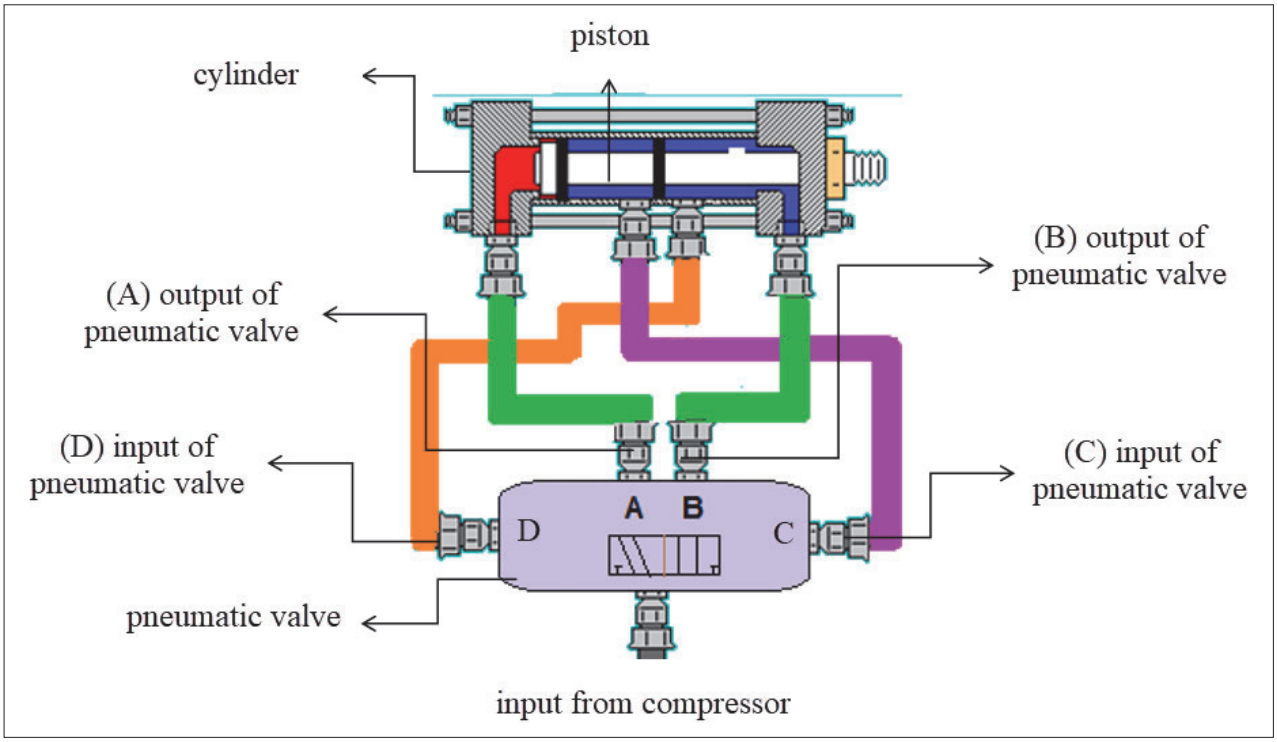


Figure 1. Schematic of the piston, cylinder, valve, and connector pipes.

Table 2. Collector system properties.

Parameters	Value
Chasses length	140 cm
Chasses width	95 cm
Trunk holder height	60 cm
Trunk diameter	Up to 40 cm
Cover diameter	300 cm

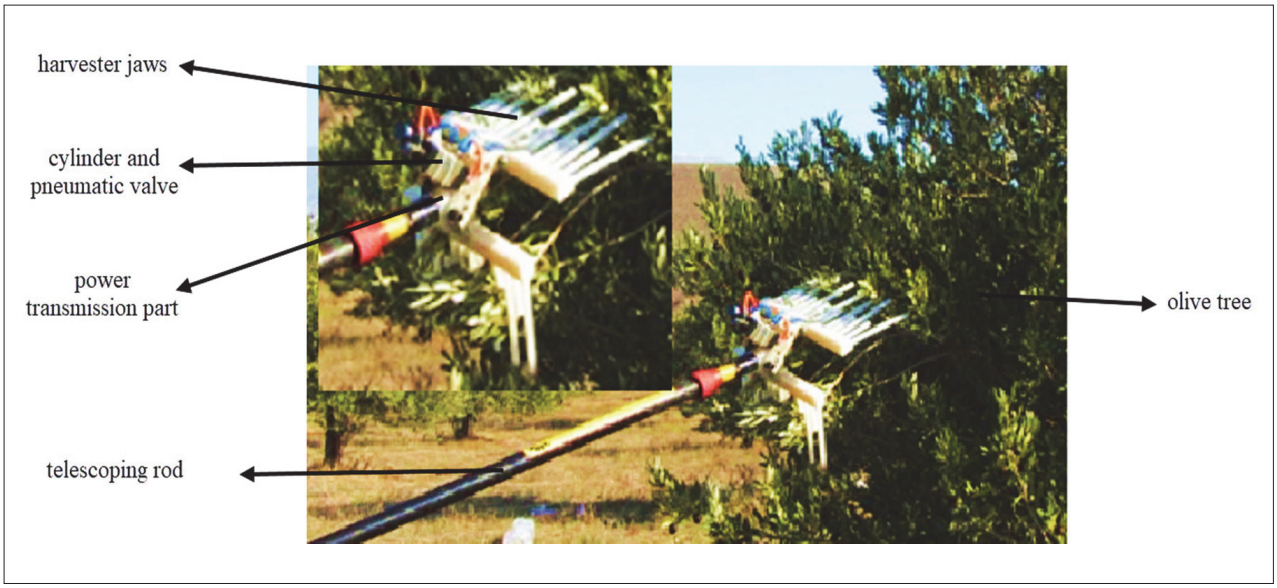


Figure 2. The parts of the New Pneumatic Harvester (NPH).

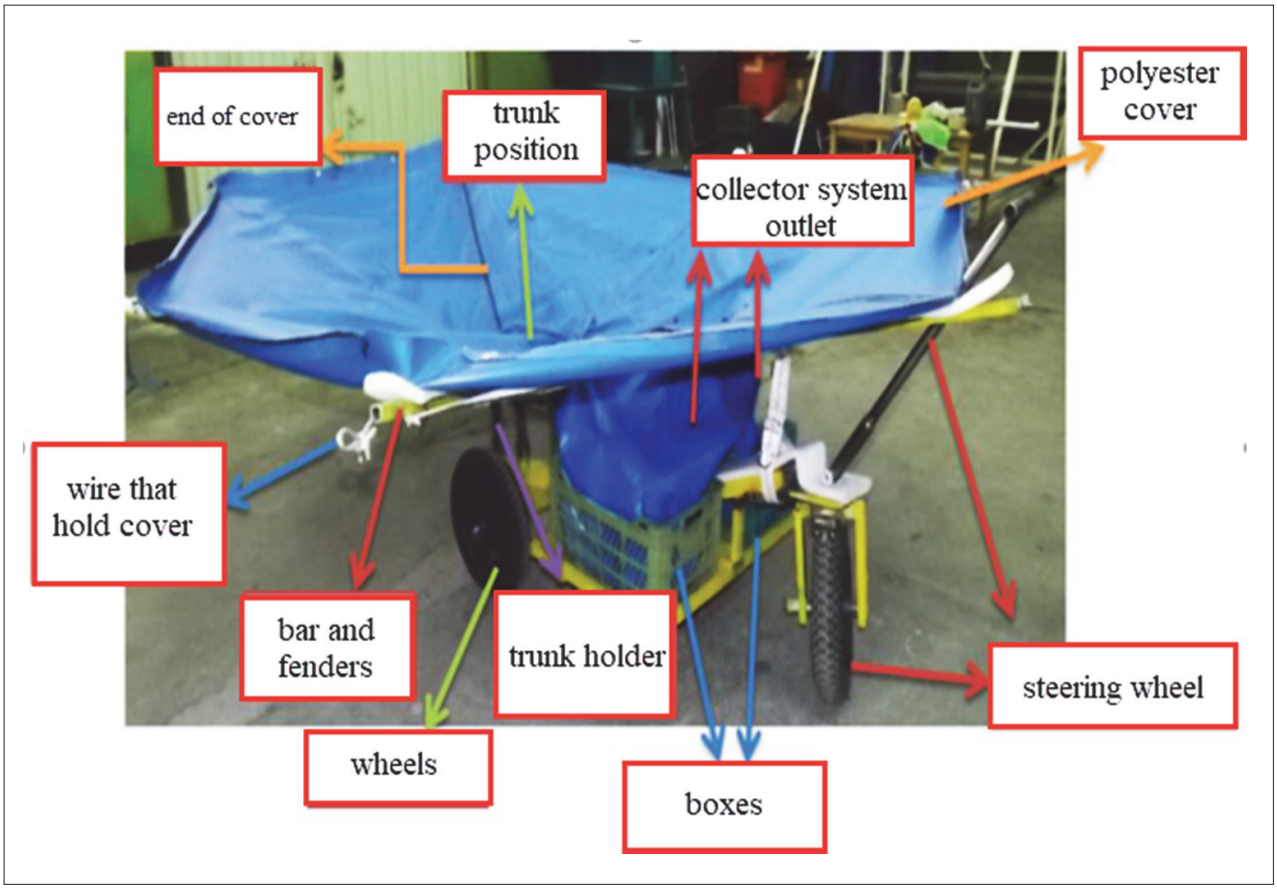


Figure 3. Collector system parts.

Table 3. Result of variance analysis for HP.

Parameters	df	SST	MST	F
Block	2	34.925	17.462	1.6126
Harvest method	2	283.554	141.777	13.093
Total	4	43.314	10.828	
CV	25%			

It is possible to conclude from Figure 3 that the collector system is ready to collect the fruits in the box. The collector system includes the wheels, steering wheel, bendable bars, wire for hold cover, polyester cover, trunk holder, position for boxes, and outlet, all of which are assembled on chassis.

Evaluation criteria

The oily type of olive was used for evaluation. Tests were conducted in the Ashrafieh garden in Qazvin province in Iran and the fruit ripening index was 4.52%. The age of olive trees was 20 years and the height of trees was up to 3.5 m. The variance analysis was done in randomized complete block design and the statistical computations as well as analyzing the data were performed by the MSTAT-C software. Duncan's multi-scope test was used for comparison of the means.

The performance of the developed harvest machine was measured by the harvesting productivity (HP), harvesting efficiency (HE), and leaves downfall percent (LD). The performance of the developed collector system was measured by the olive fruit damage (FD). For measuring the harvesting productivity of olive fruit harvester, the total mass of detachment fruits was recorded using the machine. The total harvesting time includes selecting, detaching fruit, and the time required for moving machine between olive trees inside the field. The productivity of the operated harvester was calculated using Equation (10) (Polat et al., 2007):

$$HP = \frac{k_1}{T} \quad (10)$$

Harvesting efficiency was calculated by Equation (11) (Srivastava et al., 2006):

$$HE = \frac{k_1}{k_2 + k_1} \times 100 \quad (11)$$

The percent of olive leaves downfall is defined as the percent of branches and leaves fall down by the harvester and was calculated by Equation (12):

$$TD = \frac{M_{bl}}{M_{tbl}} \times 100 \quad (12)$$

The total weight of branches and leaves of the olive trees were previously measured. Some trees that had to be removed were collected and weighed separately, finally the mean weight of the branches and leaves of three trees were used in the Equation (12).

Fruit damage includes the visual inspection and the fruit appearing broken to the naked eye. Fruit damage was calculated by Equation (13):

$$FD = \frac{M_d}{M_t} \times 100 \quad (13)$$

Results and discussion

Harvesting machine

1. Harvesting productivity. Harvesting productivity was calculated using Equation (10) and the results of variance analysis for harvesting productivity among three types of harvesters, including manual harvest (MH), pneumatic harvester (PH), and new pneumatic harvester (NPH) (machine of this study) are shown in the Table 3. Results showed that the three harvesters have a significant difference at 5% levels of probability. Due to different treatments, the means were compared and the NPH was found to have more HP placed in a group (a) with an amount of 29.47 kg h^{-1}. The PH was placed in a group (b) with an amount of 21.33 kg h^{-1} and the MH was placed in a group (c) with an amount of 9.37 kg h^{-1}.

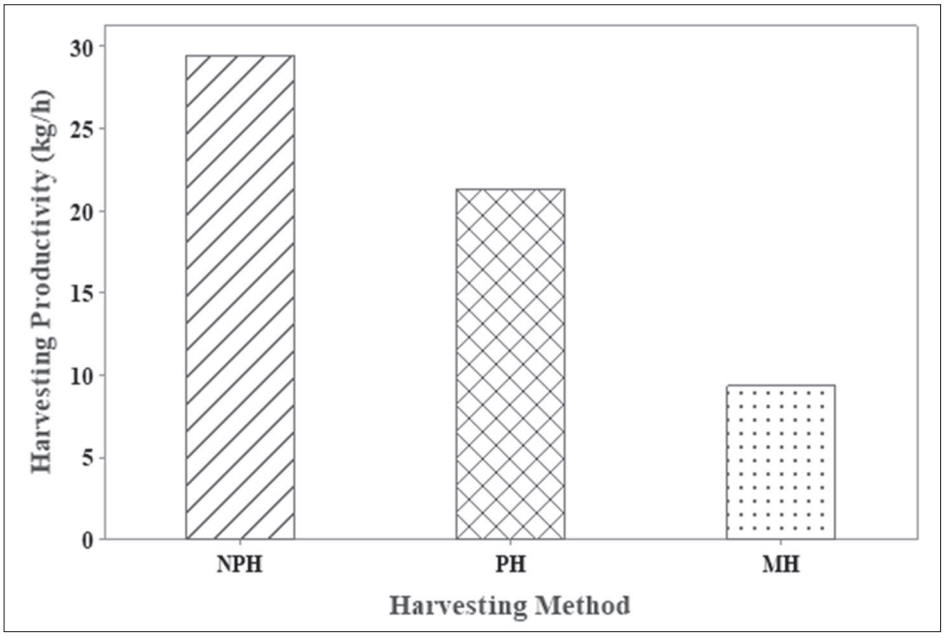


Figure 4. HP means for three harvesting methods.

Table 4. Result of variance analysis for HE.

Parameters	df	SST	MST	F
Between data	1	717.883	717.838	118.644**
Inside data	4	24.203	6.05	
CV	3.25%			

Figure 4 shows the HP means for three harvest methods. Due to the special properties of NPH such as the power of vibration, frequency, and shape of a bar, the HP of this machine was more when compared to two other methods of harvesting. Kermani (2016) indicated that the mounted branches shaker machine has 130.72 kg h^{-1} of HP, but it fails to be used in traditional gardens. This type of harvester needs a tractor to perform, which is not feasible for small gardens (Kermani, 2016).

2. Harvesting efficiency. Table 4 shows the results of variance analysis related to the difference between two types of harvesting machine concerning the Harvesting Efficiency (HE). The analysis shows that the effect of machine type on HE is significant at 1% probability. The pneumatic harvester can detach 86% of olives from the tree, but NPH shares 92% of HE. Because of the availability of all olives on the tree, the HE of this method is considered as 100% for labor in the case of manual harvest (Figure 5). It is very important to understand how to place the harvesting head on the telescoping rod. The angle between the harvester head and telescoping rod in the NPH is fixed and the jaws move between 123 to 213 degrees, and such a property differs from the PH. The other important difference resulting in increased HE is the jaws speed, where they move quicker in NPH compared to the PH. Some places of olive fruits on the tree are not available for NPH and PH. The harvester rod plays the important role in the HE. Whatever the harvesters rod has high maneuverability the more olive fruits can be detected and the HE increased.

Kermani (2016) showed that the olive tree branches shaker machine has 84.51% HE, but compared to other machines, the leaves downfall percent in this harvesting method is high.

3. Leaves downfall percent. Equation (12) was used to determine Leaves downfall percent (LD). After harvesting, all the branches and leaves were collected and weighted. By increasing in branches and leaves that fall from the tree the LD was increased. Table 5 shows the variance analysis among the three harvesting methods and olives types. The effect of variety (type) on LD was not significant, but harvesting methods have a significant effect on LD. Figure 6 shows the LD for three harvesting methods; the new pneumatic harvester has more LD than the two other harvesting methods. The speed of jaws in the PH is 1,080–1,150 rpm, while in the NPH the minimum speed of jaws is 1,290 rpm. This difference in jaws speed led to an increase in the leaves' downfall percent.

Comparison of the means of harvesting method shows that the NPH with an amount of 2.52% LD has the highest detachment of leaves from the tree. The PH and MH were not significantly different, and they were placed in a group (b). The electrical rotation bar in Kermani's (2016) research has the highest LD with a 2.20% damage (Kermani, 2016). Due to the problems with the head location on the handle in the NPH, the amount of LD was increased, however, such a problem can be surmounted.

Collector system

Olive fruits fall on the ground after harvesting and get damaged as a result of this matter. To prevent the olive fruits from damage, a collector system gathering the fruits into the box was designed and manufactured. For evaluating the collector system, two types of olive trees were harvested with the new pneumatic harvester, and the percent of damaged and undamaged olive fruits were investigated. Table 6 shows the damaged and undamaged olive fruit in the NPH with the collector systems and manual harvest without the collector system.

Results show that the use of a collector system can de-

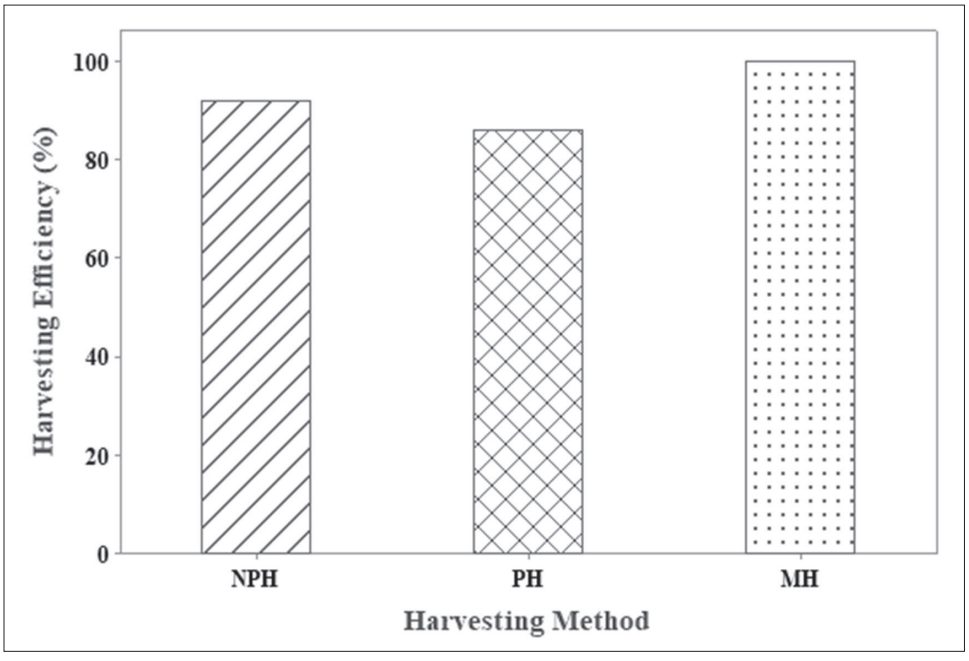


Figure 5. HE means for three harvesting methods.

Table 5. Result of variance analysis for LD.

Parameters	df	SST	MST	F
Block	2	0.286	0.143	4.2503
Harvest method	2	1.006	0.503	14.934*
Total	4	0.135	0.034	
CV	8.93%			

Table 6. Damaged and undamaged fruits in two types of harvesting method in *Mari* and *Yellow* variety.

	MH		NPH	
	Undamaged fruit (%)	Damaged fruit (%)	Undamaged fruit (%)	Damaged fruit (%)
Mari	39.2	60.8	74.88	25.12
Yellow	39.45	60.54	75.45	24.54

Table 7. Results of measuring the injured parameters for the olive fruits in the manual harvest.

	Number of injured olives	Weight of injured olives	Number of bruised olives	Weight of bruised olives	Number of not-injured olives	Weight of not-injured olives
Means	14.87	15.51	45.42	45.29	39.71	39.20
Standard deviation	1.70	1.71	2.04	1.98	1.95	1.87
Average deviation	6.35	6.39	7.65	7.39	7.30	6.99
Variance	40.37	40.89	58.52	54.67	53.29	48.93
Minimum	2.52	2.31	32.28	33.84	27.07	27.26
Maximum	28.97	28.18	59.40	57.87	52.46	52.60

Table 8. Result of measuring the injured parameters for the olive fruits in the case of harvesting with NPH.

	Number of injured olives	Weight of injured olives	Number of bruised olives	Weight of bruised olives	Number of not-injured olives	Weight of not-injured olives
Means	7.98	8.33	15.98	16.79	76.02	74.88
Standard deviation	1.14	1.36	2.75	2.79	2.96	2.98
Average deviation	3.22	3.84	7.77	7.89	8.37	8.42
Variance	10.34	14.78	60.34	62.29	70.14	70.99
Minimum	3.88	3.80	6.03	7.41	59.70	60.02
Maximum	13.75	15.61	31.34	31.44	85.34	83.34

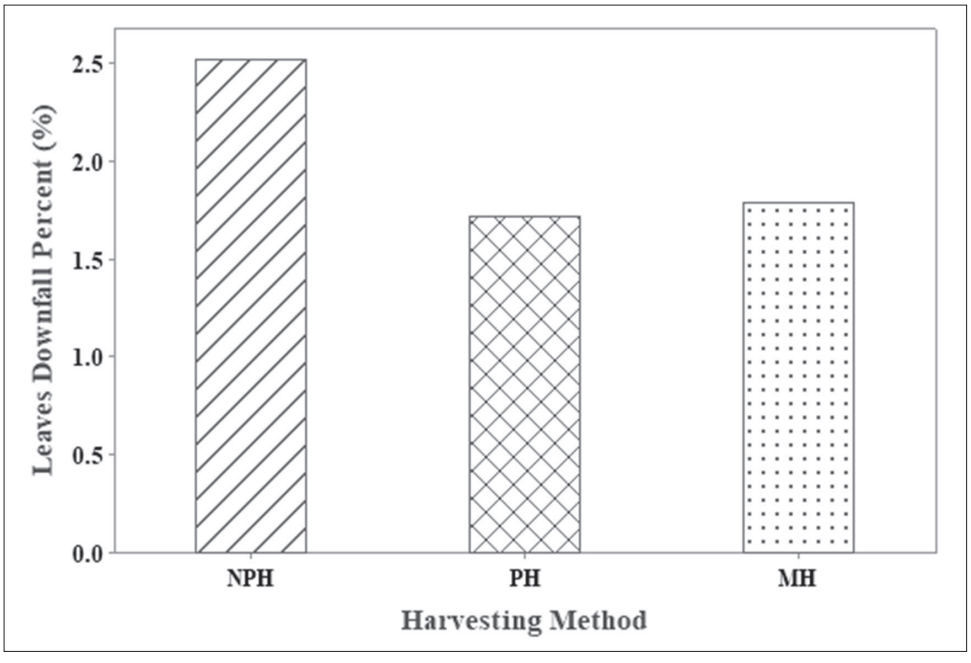


Figure 6. LD means for three harvesting methods.

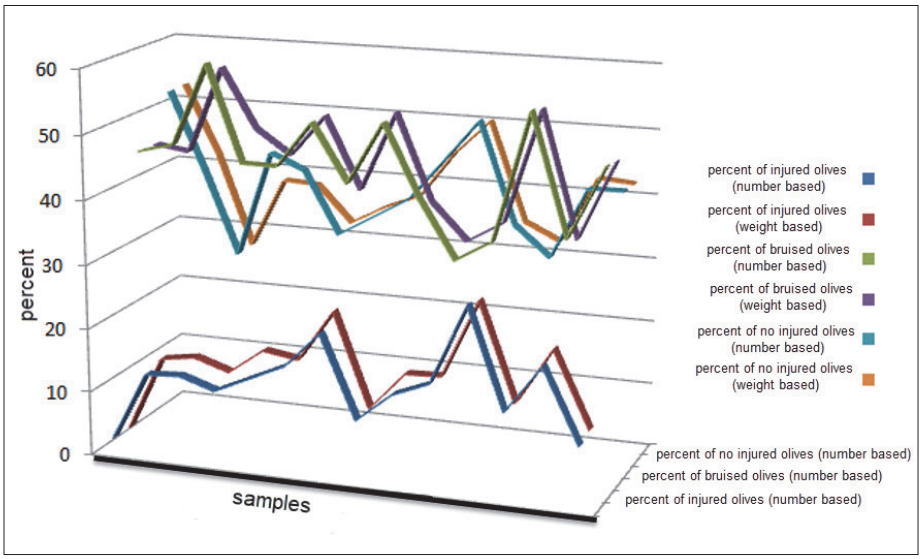


Figure 7. Illustration of the injured, bruised, and not-injured olive fruit in the manual harvest.

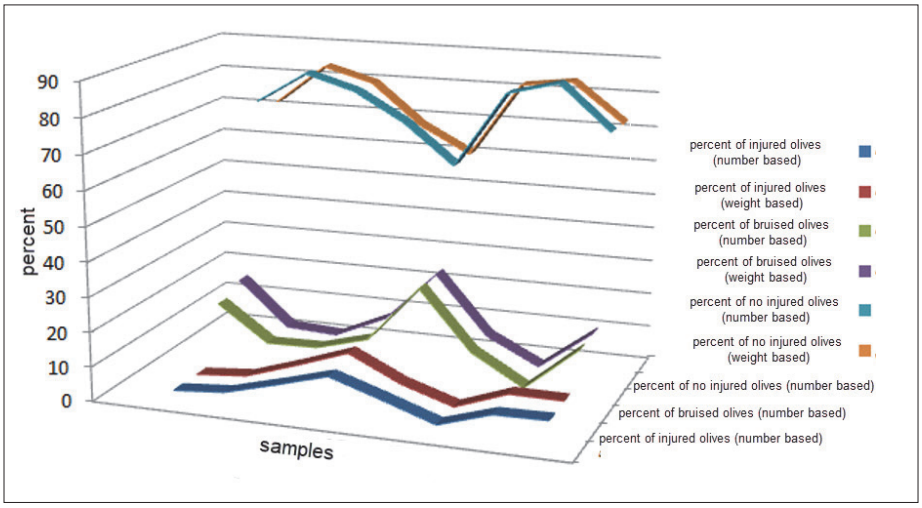


Figure 8. Scheme of the injured, bruised, and not-injured olive fruit in harvesting with NPH.

crease the fruit damage (FD) from 60.80% to 25.12% in the *Mari* variety. Similar results were achieved for the *Yellow* variety. Table 6 shows the damaged and undamaged olive fruit for the harvesting of *Yellow* olive fruit variety in the two harvesting methods. Figure 7 shows the injured, bruised, and uninjured olive fruit percent in fourteen measured samples for the manual harvest. Due to the difference in the weight of olive fruits, the percent of each group shown was based on the number and weight of olive fruits. In the manual harvest, a large portion of the fruits of the olive falls on the ground, then is picked up and collected into the box. This process led to the bruising of more than half of the olive fruits. Table 7 shows the means, standard deviation, average deviation, variance, minimum and maximum of weight along with the number of injured, bruised, and uninjured olive fruits in the manual harvest. Results show that after harvesting the fruits of the olive in the manually harvest method, 45.29% of olives fruits were bruised. Bruising occurred on the skin of the olive fruits as a result of fruit hitting on the soil. Also, the injuring situation occurred when fruits were hit by sharp branches or stones.

The percent of injured, bruised, and uninjured olive fruits for NPH based on the number and weight is shown in Figure 8. The results improved significantly. Most parts of the olives fruit had no injury in the harvesting process. Olive fruits that were detached from the tree fall in the collector systems and avoid contact with the stones or the soil/ground. Table 8 shows the results of measuring related to the injured olive fruit parameters. The means of uninjured olive fruits in the NPH increased from 39.71% to 76.02%. This means that the NPH was able to save almost half of the olive fruits. The jaws hitting olive fruits and detached fruits from brunches after that fruits falling from the tree and collide with the branch and trunk of the tree. This process caused almost 24% damage to the olive fruits. 16% of the olive fruits in the harvesting process were bruised and the rest of the damaged fruits got the ruptured skin, which was then classified as the injured fruits.

Conclusions

Harvesting is one of the important steps in the olive farming and the device used also strongly effected on the quality of the harvesting. In this study, we tried to investigate the New Pneumatic Harvester performance to show its advantage compared with other pneumatic harvesters that exist in the market. When considering the fruit ripening index of 4.52%, one can say only 8% of olive fruits remained on the trees. On the other hand, the amount of HP was 29.47 kg h^{-1}. This result shows that NPH can detach 92% of olives on the tree in a short time. In the case of the traditional and small gardens, this machine is very practical because it can work effectively in the garden in different situations. The collector system saves more time and prevents olive fruit from damage and can be easily used for every harvesting method.

Acknowledgments

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