Performance evaluation of hand-held olive harvesters

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Abstract: The aim of this research is to evaluate three types (pulsed motion double head, hook type, and pneumatic comb) of commonly used hand-held olive harvesters for small scale olive orchards. The evaluation criteria were harvester productivity (*Pr*), fruit removal percentage (*FR*), fruit damage (*FD*), specific consumed energy (*SCE*), and olive harvesting cost (*HC*). Overall evaluation criterion (*OEC*) was developed depending upon the relative weight of each evaluation criterion. Relative weights were arranged according to the importance of each evaluation criterion. The results showed that the highest value of the overall evaluation criterion was 84.9% for the T3P1500 treatment (pulsed motion double head olive harvester at speed of 1500 rpm). Through this condition, the values of evaluating criteria were 88.4 kg h^{-1}, 98%, 6.6%, 17.0 W h kg^{-1}, and 0.041 \$ kg^{-1} for *Pr*, *FR*, *FD*, *SCE* and *HC* respectively. In addition, the values of *OEC* of the pulsed motion double head olive harvester for the other treatments (T1P1100 and T2P1300) outperformed the other harvesters at all treatments.

Keywords: olive, hand-held, harvester, overall criterion.

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1 Introduction

Olive cultivation is concentrated in the Mediterranean countries, where the production of olives in these countries is about 94% of the total world production (Fernández-Escobar et al., 2013). Olive harvesting is the most important operation among all operations of olive cultivation. However, manual harvesting is labor intensive and time-consuming (Bodria et al., 2013). According to Saracoglu (2006) manual harvesting alone costs about 30%- 60% of the total olive production cost. Deboli and Calvo (2009) also indicated that hand harvesting of olive is considered to be one of the major expenses of olive production. With an operator productivity level of 15 kg h^{-1}, the cost of manual harvesting may reach 50%-70% of the total revenue.

Mechanical harvesting of olives is a very important aspect in olive growing in order to reduce the production costs and assure higher oil quality (Testa et al., 2014). Almeidaa et al. (2015) mentioned that the factors affecting mechanical olive harvesting are orchard management, tree shape, canopy density, pruning methods, fruit removal force, fruit weight and the ratio between fruit removal force and fruit weight. Ferguson et al. (2010) stated that the factors affecting the mechanical harvesting of tree fruits by shaking are frequency, eccentricity, direction of shaking, fruit size, and detachment force to fruit weight ratio. Mansour et al. (2018) reported that the optimum harvesting of olive fruits was achieved when the fruit removal efficiency was more than 90% with minimal harvest time,

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minimum number of laborers, minimum fruit damage and minimum risk to workers.

Small farms use hand-held harvesters for separating the fruits from the olive trees by vibration or shaking. Alzoheiry et al. (2020) used a single degree of freedom and a two degrees of freedom mathematical models to estimate the natural frequency (F_N) of olive fruit-stem system. They found that the F_N values were 33.9, 31.9, and 28.0 Hz for the full mature stage, half-ripe olive, and full-ripe olive respectively. They also found that the maximum fruit removal percentage value, 90.6%, was achieved at a frequency of 35 Hz and amplitude of 25 mm while the maximum degree of full-ripe fruit selectivity value, 78.58%, was obtained at 25 Hz frequency and 25 mm amplitude. Famiani et al. (2014) studied different kinds of mechanical aid to harvest olive fruits with very large trees. Deboli et al. (2014a) mentioned that the different types of hand-held olive harvesters are beaters (pulse motion double head olive harvester), combs and hook types. Combs, detach the fruits by a beating action and by the vibration on the shoots and branches. In the case of shaking hooks, the fruit is detached only by the effects of vibration. The pulse motion harvesters are machines with an oscillating head equipped with thin carbon fiber sticks, and the fruit Harvesting is achieved by direct impact of sticks on the olive fruits or by vibration transmitted to the branches. Hand-held pneumatic combs had an improved harvester performance, but the hook type and pulse motion double head olive harvesters are the most popular tools used in olive tree orchards (Vieri et al., 2001).

Zhou et al. (2016) reported that the various methods of fruit detachment used in mechanical harvesting include twisting, pulling, cutting, bending and some combination of these methods. Nasini and Proietti (2014) stated that the most common methods of olive harvesting are shaking and combing. Catania et al. (2017) studied the level of exposure to vibration transmitted to the hand-arm system of the operators during the use of hand-held olive harvesters. Field and laboratory experiments were carried out using two types of harvesters (hook type and electric comb type). They found that the maximum vibration intensity was obtained on the right hand both laboratory (57.50 m s^{-2}) and in the field (51.57 m s^{-2}) tests for hook type harvester. Cerruto et al. (2012) evaluated the acceleration levels transmitted to the hand-arm system by electric portable olive harvesters. Eleven harvesters were used with four harvesting heads, different types of kinematics system, five bars, different diameters, different lengths and different materials (aluminum and carbon fiber). The classical flap-type harvester produced accelerations of around 20 m s^{-2}, while using a harvesting head with two parts in opposite movement lowered the accelerations to about 6 m s^{-2}. The use of carbon fibers for the bars, besides the reduction in weight, produced also a reduction in acceleration from 21 to 16 m s^{-2}. Ghonimy et al. (2020) developed and evaluated a hand-held olive harvester suitable for smallholdings. They found that the suitable machine productivity, fruit removal percentage and fruit damage percentage were achieved at 1600 rpm of head rotating speed. Sola-Guirado et al. (2018) developed a continuous lateral canopy shaker harvester and tested it on large olive trees in order to evaluate the vibration amplitude and frequency and their effects on the fruit removal efficiency. They found that the removal efficiency, shaking duration and amplitude were 77.3%, 28 s, and 0.17 m, respectively. El-Iraqi et al. (2011) found that the modified hand-held olive harvester increased labor productivity by about 5-7 times higher than the manual harvesting method. It also reduced the harvesting manpower requirements by about 90-130%. The reduction in the total harvesting cost (*HC*) ranged from 185% – 245% compared to manual harvesting. Ibrahim (2018) found that the most optimal operating conditions of the pulse motion double head olive harvester were speeds of 1100 rpm and 1500 rpm with 17 cm head length. At these conditions, the fruit removal percentage, machine productivity and fruit damage were 97.7%, 91.5 kg h^{-1} and 6.23%, respectively. Deboli et al. (2014b) evaluated the hand-arm vibration transmitted to the operator using an experimental electric labor saving machine with rotary combs having teeth of different dimensions covered by silicon to minimize the damage to the drupes. They found that the productivity of the handheld machines (pneumatic combs and electrical beater) were five and 4.5 times that of using hands.

The aim of this research was to evaluate three types (pulsed motion double head olive harvester, hook type olive harvester and pneumatic comb olive harvester) of commonly used hand-held olive harvesters used in small olive farms in the Kingdom of Saudi Arabia. The specific objectives were (a) to determine the values of some olive plant parameters including physical-mechanical properties of fruit-stem system, natural frequency of the olive fruit-stem system and suitable shaking stroke, (b) to establish and determine the values of the evaluation criteria which included machine productivity, fruit removal percentage, fruit damage, specific consumed energy and olive *HC*, (c) to perform field experiments to assess the performance of the three harvesters, and (d) to calculate the value of overall evaluation criterion.

2 Materials and methods

2.1 Tested harvesters

Field experiments were carried out at Buseita, Al Jawf Region, Saudi Arabia during 2017- 2018 seasons. Three types of hand-held olive harvesters were used: pulsed motion double head olive harvester, hook type olive harvester and pneumatic comb olive harvester. All the three machines were operated by 1500-watt portable electric generator (Firman 1500 Model Number PO1201, Firman Equipment, Peoria, Arizona, USA) which was operated by a gasoline engine.

2.1.1 Pulse motion double head olive harvester

The pulsed motion double head olive harvester is shown in Figure1. The technical specifications of this harvester are given in Table 1.

Figure 1 The pulse motion double head olive harvester.

Table 1 Technical specifications of pulse motion double head harvester

Part	Specification
Manufacture	Aggelis, Nikaia, Athens, Greece
Model	Asteras Model CF
Type of head	X.QUATTRO 4D with elastic thermoplastic spheres carrying 32 carbon fiber sticks
Type of movement	Roto-vibration
Maximum head speed	2500 rpm
Motor	High powered brushless motor (12 VDC) and 1500 Watt
Main rod	Aluminum, 25 mm diameter
Initial length	2.40 m (3.40 m with extension)
Weight	2.50 kg (without cable)

2.1.2 Hook type harvester

The hook type hand-held olive harvester is shown in Figure 2. The technical specifications of this harvester are given in Table 2. The harvester had small U shaped shaking hooks, that can be hooked to small olive branches (5 cm in diameter or less) the harvesting is achieved by transmitting the vibration to the branch. Shaking hooks rods must be equipped with antivibration systems on the handles in order to minimize vibrations transmitted to the operator. When the vibrator is operated, the vibration is transmitted through the tree branch to the fruits, causing the fruits to separate. Often the fruits are separated individually and few may be separated into groups (bunches).

Figure 2 The hook type hand-held olive harvester.

Table 2 Technical specifications of hook type hand-held olive harvester.

Part	Specification
Manufacture	Agricultural Machinery Manufacturer, Bursa, Turkey
Model	EmR400 Light
Vibration speed	3000 rpm
Stroke	70 mm
Main rod	High quality polish steel, 1060x260x260 mm
Engine power	1500 W
Weight	6.8 kg

2.1.3 Pneumatic comb olive harvester (flap type)

The pneumatic comb olive harvester (flap type) is shown in Figure 3. The technical specifications of this harvester are shown in Table 3. The oscillating combs are the most common category of olive harvesters. Oscillating combs mounted on pairs and swinging against one another comb the branches detaching the fruits. The teeth may vary in number and length. The combs with a large number of teeth are particularly useful in early harvesting of small olives with a high resistance to attachment. Combs with teeth of two sizes or a decreasing thickness from the base of the tip penetrate more easily into the vegetation.

Figure 3 The pneumatic comb olive harvester.

Table 3 Technical specifications of pneumatic comb olive harvester (flap type).

Part	Specification
Manufacture	Lisam SRL, Imola, Italy
Model	V8 Titanium Pneumatic Comb
Material	Titanium and magnesium
Effective tooth	Fabricated from technopolymer
Maximum frequency	2000 cpm
Working pressure	6 bar
Air consumption	160 lit min^{-1}
Net weight	2.7 kg
Electric motor	150 W

2.2 Determination of some olive plant parameters

In this part of study, the following determinations were carried out :(a) determination of the physical-mechanical properties of the fruit-stem system, (b) determination of the natural frequencies of the olive fruit-stem and (c) determination of the suitable shaking stroke.

2.2.1 Determination of the physical-mechanical properties of fruit-stem system

The physical and mechanical properties of the olive fruit-stem system (*Picual variety*) were determined at three maturity level (full mature stage, half-ripe and full-ripe). For each stage, fifty olive fruit-stem systems were randomly selected. The measurements include fruit mass (*m*), fruit radius (*r*), fruit detachment force (*F*) and stem length (*l*). The ratio of fruit detachment force to fruit mass (R_{fm}) was calculated from the following equation:

$$R_{fm} = \frac{F}{m} \quad (1)$$

Where:

R_{fm}=The ratio of the fruit detachment force to fruit mass (m s^{-2})

F=Fruit detachment force (N)

m=Fruit mass (kg)

2.2.2 Determination of the natural frequency of the olive fruit-stem system

To determine the natural frequency of the olive fruit-stem system, one-degree of freedom model was used. The olive fruit-stem system in the case of one-degree of freedom is a beam loaded with the mass at its end is shown in Figure 4. In this model, the stem is considered the beam and the mass represents the olive fruit. This model considers spring-mass behavior and viscoelastic effects. Through this model, the elasticity constant of the stem was determined using the beams general theory. The stem was considered as a cantilever beam loaded by fruit at its end. The stem was fixed horizontally on the vertical plate support and loaded with small weights ranged from 1 to 10 gram at its end. These weights caused a vertical displacement (deflection) of stem due to the viscoelastic effects. The distance between the initial and final position was equivalent to the stem deflection. The elasticity constant was calculated from the following equation (Ciro V., 2001).

$$K = L_b / D_v \quad (2)$$

Where:

Elasticity constant of stem (N m^{-1})

Load in bending test (N)

Vertical displacement of stem in bending test (m)

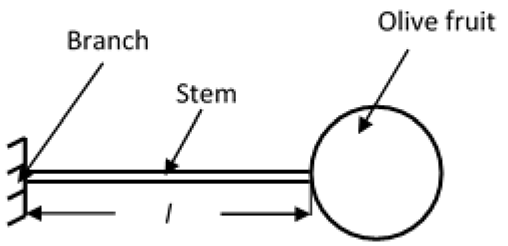

Figure 4 One-degree of freedom model of the olive fruit-stem system

The natural frequency was calculated using the following equation (Cai, 2016):

$$NF = \frac{1}{2\pi}\sqrt{\frac{K}{m}} \quad (3)$$

Where:

NF=Natural frequency of the fruit-stem system (Hz)

m=Fruit mass (kg)

2.2.3 Determination of the suitable shaking stroke

The suitable stroke of the olive branches was calculated from the following equation (Ghonimy, 2006):

$$S = 2 \times \left\{ \frac{\left\{ R_{Fm} \times l \times \left[\left(NF^2 - \frac{g}{l} \right)^2 + \left(2NF \times \sqrt{\frac{g}{l}} \zeta \right)^2 \right] \right\}^{1/2}}{NF^3} \right\} \quad (4)$$

Where:

S= Shaking stroke (m)

l= Stem length (m)

ζ = Damping ratio (-)

g = Gravitation acceleration = 9.81 (m s^{-2})

The Damping ratio (ζ) was calculated from the following equation (Ghonimy, 2006).

$$\zeta = \sqrt{1 - \frac{{\omega_d}^2 \times l}{g}} \quad (5)$$

Where:

ω_d = Damping frequency = $2\pi / t$ (rad s^{-1})

t = Time of one cycle (s)

A test was conducted to measure the time of one cycle (t). The olive fruit-stem system was fixed vertically on the plate support. The fruit was moved horizontally. The time of one cycle was determined using a stopwatch.

2.3 Field experiments

Olive branches were shaken using the hand-held olive harvesters. Olive branches were chosen at three critical stages of maturity (full-ripe, half-ripe and full mature). Nine nets were used for receiving the removed olive fruits. In the field experiment, 9 treatments were performed as shown in Table 4.

Table 4 Experimental treatments.

Treatment Description	Treatment Symbol
Pulse motion double head olive harvester at 1100 rpm	T1P1100
Pulse motion double head olive harvester at 1300 rpm	T2P1300

Pulse motion double head olive harvester at 1500 rpm	T3P1500
Hook type olive harvester at 24 Hz frequency and 70 mm stroke	T4H24
Hook type olive harvester at 28 Hz frequency and 70 mm stroke	T5H28
Hook type olive harvester at 30 Hz frequency and 70 mm stroke	T6H30
Pneumatic comb olive harvester at 24 Hz frequency	T7C24
Pneumatic comb olive harvester at 28 Hz frequency	T8C28
Pneumatic comb olive harvester at 30 Hz frequency	T9C30

2.4 Evaluation criteria

2.4.1 Machine productivity

The machine productivity (*Pr*) of the olive harvester was calculated from the following equation (Srivastava et al., 2006):

$$Pr = \frac{W_f}{T} \quad (6)$$

Where:

Pr=Machine productivity (kg h^{-1})

W_f=The total mass of harvested fruit (kg)

T=Total operating time (h)

2.4.2 Fruit removal percentage

The fruit removal percentage (*FR*) of hand-held olive harvester was calculated from the following equation (Polat et al., 2007):

$$FR = \frac{W_h}{W_h+W_r} \times 100 \quad (7)$$

Fruit removal percentage (%)

total mass of harvested olive fruit (kg tree^{-1})

total mass of olive fruit which are remaining stay on the tree (kg tree^{-1})

2.4.3 Fruit damage

The fruit damage (*FD*) was calculated from the following equation (Srivastava et al., 2006):

$$FD = \frac{W_d}{W_t} \times 100 \quad (8)$$

Where:

FD=Fruit damage (%)

W_d=The total mass of damage harvested olive fruit (kg)

W_t=The total mass of harvested olive fruit (kg)

2.4.4 Specific consumed energy

The specific consumed energy (*SCE*) was calculated for each olive harvester using the following equation (RNAM, 1995):

$$SCE = \frac{RP}{Pr} \quad (9)$$

Where:

SCE=Specific consumed energy (W h kg^{-1})

RP=The required power for operating the machine (W)

Pr=Machine productivity (kg h^{-1})

2.4.5 Olive harvesting cost

The olive harvesting cost (*HC*) is expressed in terms of cost per operating hour (\$ h^{-1}). The *HC* was determined using the fixed costs and variable costs according to the methods described by Oida (1997). The *HC* of olive fruits is expressed in terms of cost per kilogram of harvested olive as follows:

$$HC = \frac{Total\ cost\ (\$.h^{-1})}{Pr} \quad (10)$$

Where:

HC=Olive fruits harvesting cost (\$ kg^{-1})

Pr=Machine productivity (kg h^{-1})

2.5 Statistical analysis

The values of the evaluating criteria (*Pr*, *FR*, *FD*, *SCE*, *and HC*) were statistically analyzed using the computer program CoStat ver. 6.400. An analysis of variance was performed using randomized complete block design- one factor model. The means of the evaluating criteria were compared at a probability level of 0.05.

2.6 Overall evaluation criterion

Due to the multiple evaluation criteria of machinery, it is possible that the value of one criterion is higher for one of the machines while the values of the other evaluation criterion decrease, making it difficult to compare between the machines. Therefore, the use of an overall criterion that includes all the evaluation criteria results in a single value that leads to an easier more reliable comparison. The overall evaluation criterion (*OEC*) was calculated according to Roy (2014) in the following three steps: The evaluating criteria were arranged according to their relative weights, determining the quality characteristic for each criterion, and calculating the value of the overall evaluation criterion.

2.6.1 Arranging the evaluating criteria according to their relative weights

The overall evaluation criterion (*OEC*) depends upon the relative weight for each evaluation criterion. The relative weights were selected after a precise analysis of the relative importance of each evaluation criterion. The evaluation criteria used in this research were *HC*, fruit removal percentage (*FR*), machine productivity (*Pr*), fruit damage (*FD*), and specific consumed energy (*SCE*). The evaluation criteria were arranged according to their relative weights as sown in Table 5.

Table 5 Assigned weights of the evaluation criteria.

Evaluation criteria	Relative weight (%)
Harvesting costs	30
Fruit removal percentage	30
Machine productivity	25
Fruit damage	10
Specific consumed energy	5

The relative weights of the evaluating criteria were decided based on the nature of the harvesting process and the interests of small farmers (hand-held olive harvester is used mainly in very small farms). The *HC* had the highest relative weight (30%) because the *HC* represent the main problem of the olives production process in small farms. The Specific consumed energy (*SCE*) was given a lower value of relative weight (5%) because its values were included in the calculation of the machine productivity and *HC*.

2.6.2 Determining the quality characteristic for each criterion

The quality characteristic (*QC*) indicates the direction of desirability of the evaluation numbers. Depending on the criteria and how it is measured, the value of *QC* (higher or lower) will determine its usefulness (better).

2.6.3 Calculating the value of overall evaluation criterion

The overall evaluation criterion (*OEC*) was calculated from the sum of the contributions of all evaluating criteria. Any contribution criteria was calculated using the following equations:

(a) For higher *QC* value

$$Cn = \left[\frac{(C_v - W_v)}{(T_v - W_v)}\right] \times Rw \qquad (11)$$

(b) For lower *QC value*

$$Cn = \left[1 - \frac{(T_v - C_v)}{(T_v - W_v)}\right] \times Rw \qquad (12)$$

Where:

Cn=Criterion contribution (%)

Cv=Criterion value (-)

Wv=Worst value (-)

Tv=Target value (-)

Rw=Relative weight (%)

Then, the overall evaluation criterion (*OEC*) was calculated using the following equation:

$$OEC\ (\%) = HC \text{ contribution} + FD \text{ contribution} + FR \text{ contribution} + Pr \text{ contribution} + SEC \text{ contribution} \qquad (13)$$

3 Results and discussions

3.1 Olive plant parameters

The average values of some properties of the olive fruit-stem system at different ripening stages are shown in Table 6. The average values of elasticity constants (*K*) of stem, and the values of natural frequency (*NF*) are shown in Table 7. The values of shaking stroke (*S*) are also shown in Table 7. The average values of natural frequency were 30.1, 28.1 and 24.0 Hz for full mature stage, half-ripe and full-ripe fruits, respectively. The estimated values of damping ratio (ζ) were 0.103, 0.103 and 0.106 for full mature stage, half-ripe and full-ripe fruits respectively. The estimated shaking stroke was about 70 mm.

Table 6 Some properties of the olive fruit-stem system at different maturity levels.

Property	Olive maturity level		
	Full Mature	Half-Ripe	Full-Ripe
Fruit mass, *m* (g)	4.38	5.00	5.09
Fruit radius, *r* (mm)	9.65	10.07	10.07
Fruit detachment force, *F* (N)	7.10	6.40	6.40
Fruit detachment force: Mass ratio, *R:m* (m s^{-2})	1685.15	1284.00	1252.37
Stem Length, *l* (mm)	21.86	24.99	25.18

Table 7 The elasticity constants of stem, natural frequency of fruit-stem system, and shaking stroke.

Property	Olive maturity level		
	Full Mature	Half-Ripe	Full-Ripe
Elasticity Constants, *K* (N m^{-1})	155.5±1.52 [a]	154.6±2.60	115.6±1.93
Natural Frequency, *NF* (Hz)	30.1±0.67	28.1±0.94	24.0±0.35
Shaking Stroke, *S* (mm)	64±0.86	64±0.19	74±0.66

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

3.2 Evaluation criteria

3.2.1 Machine productivity

The average values of machine productivity (*Pr*) are shown in Table 8. The results showed that the highest value of machine productivity (88.4 kg h^{-1}) was found with the T3P1500 treatment (pulsed motion double head olive harvester at the speed of 1500 rpm) while the lowest value (55.6 kg h^{-1}) was found with the T4H24 treatment (hook type olive harvester at the 24 Hz frequency and 70 mm stroke).

In pulsed motion double head olive harvester, the *Pr* increased by 3.8% and 14.1% when the head rotating speed increased from 1100 to 1300 and 1500 rpm respectively. These *Pr* results of the pulsed motion double head olive harvester were in agreement with the findings obtained by Younis et al. (2017).

Table 8 The average values of evaluating criteria for the varies treatments

Treatment	*Pr* (kg h^{-1})	*FR* (%)	*FD* (%)	*SCE* (W h kg^{-1})	*HC* ($ kg^{-1})
Pulse double motion T1P1100	77.1bc*	95.3a	5.5a	19.5cd	0.047cd
Pulse double motion T2P1300	80.0abc	97.1a	6.0ab	18.8cd	0.045cd
Pulse double motion T3P1500	88.4a	98.0a	6.6a	17.0d	0.041d
Hook type T4H24	55.6e	62.4f	2.0d	27.0a	0.067a
Hook type T5H28	64.7d	75.0e	2.5d	23.2b	0.057b
Hook type T6H30	70.0cd	80.1d	2.1d	21.4bc	0.052bc
Pneumatic comb T7C24	65.1d	82.7cd	4.5c	23.0b	0.057b
Pneumatic comb T8C28	78.5abc	86.6bc	5.3b	19.1cd	0.047cd
Pneumatic comb T9C30	83.4ab	88.3b	6.2ab	18.0cd	0.044cd

Note: *Means within same column with similar letters are not significantly different at the 0.05 level.

FR = Fruit removal percentage, *FD* = Fruit damage, *SCE* = Specific consumed energy, *HC* = Harvesting cost

3.2.2 Fruit removal percentage

The average values of fruit removal percentage (*FR*) are shown in Table 8. The maximum value of *FR* (98.0%) was found with the T3P1500 treatment (pulse motion double head olive harvester at the speed of 1500 rpm) while the minimum value of *FR* (62.4%) was found with the T4H24 treatment (hook type olive harvester at the 24 Hz frequency and 70 mm stroke). Fruit removal happens when the summation of the forces acting on the fruit are greater than the failure stress of the fruit-stem.

3.2.3 Fruit damage

The maximum values of fruit damage (*FD*) were found with the pulse motion double head olive harvester as shown in Table 8. The *FD* increased from 5.5% to 6.6% with increasing the harvester head rotating speed from 1100 to 1500 rpm. This increase in *FD* was the result of the increase in the number of shocks to the fruits during the work of the machine due to increasing the harvester head rotating speed which causes more damage to olive fruits. These results are similar to the results reported by Younis et al. (2017) and Ibrahim (2018). The results, also, showed that the minimum values of *FD* were observed with the hook type olive harvester. The *FD* values for the hook type olive harvester ranged from 2.0% to 2.5%. The low *FD* values of the hook-type harvester are due to the nature of the machine operation mechanism where there is no direct contact between the effective part of the machine and the harvested fruits. In addition, fruits are collected in an above ground net, thus minimizing the damage that can be caused by the fruit hitting the ground.

3.2.4 Specific consumed energy

The values of specific consumed energy (*SCE*) for all treatments are shown in Table 8. The *SCE* values ranged from 17.0 to 27.0 W h kg^{-1}. The results showed that the values for both the pulse motion double head olive harvester and the pneumatic comb olive harvester are almost equal. The increase in *SCE* values for hook type olive harvester was due to its lower machine productivity compared with the other two types of harvester.

3.2.5 Harvesting costs

The calculation of the harvesting costs *(HC)* was based on 2019 prices and they included fixed and variable costs. The total *HC* were 3.62, 3.65 and 3.69 $ h^{-1} for the pulse motion double head olive harvester, the hook type olive harvester and the pneumatic comb olive harvester, respectively. Table 8 shows the *HC* of olive is expressed in terms of cost per Kg of harvested olive. The results showed that the minimum value of *HC* of 0.041 $ $kg^{-1}$was achieved with the pulsed motion double head olive harvester at the speed of 1500 rpm. The maximum value of *HC* of 0.067 $ kg^{-1} was observed with the hook type olive harvester at the 24 Hz frequency. The statistical analysis (ANOVA) showed in Table 8 indicted significant differences among the treatments for every evaluating criterion.

3.3 Overall evaluation criterion

The quality characteristic (*QC*), worst value (*Wv*), target value (*Tv*), and relative weight (*Rw*) of the evaluating criteria are shown in Table 9. These values were used to calculate the contribution of the evaluating criteria into the overall evaluating criterion (*OEC*). The maximum and minimum values for each evaluating criterion were considered to represent the values of *Wv* and *Tv*, respectively.

Substituting the values in Table 9 into Equation 13 gives the values of overall evaluation criterion (*OEC*) as shown in Table 10. The results showed that the highest value of overall criterion was 84.9% for pulse motion double head olive harvester at the speed of 1500 rpm). Also, the values of *OEC* of the pulse motion double head olive harvester for the other treatments (1100 and 1300 rpm) outperformed the other harvesters at all treatments. The higher *OEC* of the pulse motion double head olive harvester was due to the low operating costs and increased fruit removal percentage.

Table 9 Values of evaluating criteria related to the overall evaluation criterion.

Evaluating criteria	Worst Value	Target Value	Quality characteristics	Relative Weight (%)
HC, \$ kg^{-1}	0.067	0.041	Lower	30
FR, %	62.4	98.0	Higher	30
Pr, kg h^{-1}	55.6	88.4	Higher	25
FD, %	6.6	2.0	Lower	10
SCE, W h kg^{-1}	27.0	17.0	Lower	5

Note: *HC* = Harvesting cost, *FD* = Fruit damage, *FR* = Fruit removal percentage, *Pr* = Machine productivity, *SCE* = Specific consumed energy.

Table 10 Values of the overall evaluation criterion.

Treatment and Symbol	*OEC* (%)
Pulse motion double head harvester at 1100 rpm (T1P1100)	70.2
Pulse motion double head harvester at 1300 rpm (T2P1300)	74.8
Pulse motion double head harvester at 1500 rpm(T3P1500)	84.9
Hook type harvester at 24 Hz (T4H24)	13.9
Hook type harvester at 28 Hz (T5H28)	40.6
Hook type harvester at 30 Hz (T6H30)	54.3
Pneumatic comb at 24 Hz (T7C24)	42.8
Pneumatic comb at 28 Hz (T8C28)	64.3
Pneumatic comb at 30 Hz (T9C30)	70.2

Based on *OEC*, the pulsed motion double head olive harvester came first (*OEC* in the range of 70.2% to 84.9%), followed by the pneumatic comb olive harvester (*OEC* in the range of 42.8% to 70.2%) and the hook type olive harvester olive harvesters (*OEC* in the range of 13.9% to 54.3%).

3.4 Discussion

In this paper, three types of hand-held olive harvesters (pulsed motion double head olive harvester, hook type hand-held olive harvester and pneumatic comb olive harvester) that designed for small olive farms were evaluated. The results indicated that the average values of natural frequency for olive fruit-stem system were 30.1, 28.1 and 24.0 Hz for full mature stage, half-ripe and full-ripe fruits, respectively. These results are similar to those found by Alzoheiry et al. (2020), who reported that the natural frequency were 34.84, 32.33 and 26.92 Hz for full mature stage, half-ripe and full-ripe fruits, respectively. The estimated values of damping ratio were 0.103, 0.103 and 0.106 for full mature stage, half-ripe and full-ripe fruits respectively. In addition, the estimated shaking stroke was about 70 mm. Then, the importance of each criterion was determined and the evaluating criteria were assigned their relative weights. Finally, field experiments were performed to test the performance of the three harvesters and calculate the value of overall evaluation criterion.

The highest values of machine productivity (88.4 kg h^{-1}) and fruit removal percentage (98.0%) were achieved using the pulsed motion double head olive harvester at a speed of 1500 rpm, while the lowest value of machine productivity (55.6 kg h^{-1}) and fruit removal percentage (62.4%) were found with the hook type olive harvester at 24 Hz frequency and 70 mm stroke. The higher machine productivity values of pulsed motion double head olive harvester were due to the higher fruit detachment obtained by direct impact of sticks on olive fruits and the by vibration transmitted to the branches. In addition, the increased values of fruit removal percentage with the pulsed motion double head olive harvester may be due to the impact force transmitted to the olive fruit during its direct contact with the elastic sticks (the effective part of the harvester). The highest fruit damage (5.5-6.6) was observed with the pulse motion double head harvester while the lowest fruit damage (2.0%-2.5%) was observed with the hook type harvester. The low fruit damage values of the hook-type harvester are due to the nature of the machine operation mechanism where there is no direct contact between the effective part of the machine and the harvested fruits. These results are similar to those found by Deboli et al. (2014b), Younis et al. (2017), and Alzoheiry et al. (2020). The specific consumed energy values ranged from 17.0 to 27.0 W h kg^{-1} for all tested machine types. The total harvesting costs were 3.62, 3.65 and 3.69 \$ h^{-1} for the pulse motion double head harvester, the hook type harvester and the pneumatic comb harvester, respectively.

The results showed that the highest value of overall criterion (*OEC*) was 84.9% for the T3P1500 treatment (pulsed motion double head olive harvester at speed of 1500 rpm). The values of *OEC* of the pulsed motion double head olive harvester for the other treatments (T1P1100 and T2P1300) outperformed the other harvesters at all treatments. The higher *OEC* value of the pulse motion double head olive harvester was due to the lower in operating costs and highest fruit removal percentage.

4 Conclusions

The performance of different hand-held olive harvesters for small holdings were evaluated based on machine productivity (*Pr*), fruit damage (*FD*), fruit removal percentage (*FR*), specific consumed energy (*SCE*), and olive *HC*. The pulse motion double head olive harvester outperformed all the other harvesters in the machine productivity, and the fruit removal percentage. Among all the harvesters, the hook type olive harvester had the smallest fruit damage percentage. Because no single machine outperformed all the other in all the evaluation criteria an overall evaluation criterion was required to standardize the evaluation of the machines. The relative weights of the evaluating criteria were decided considering the nature of the harvesting process and the interests of small farmers. The maximum value, overall evaluating criterion (*OEC*) was 84.9% for the pulse motion double head olive harvester at 1500 rpm of head rotating speed. Through this condition, the values of evaluating criteria were 88.4 kg h^{-1}, 98%, 6.6%, 17.0 W h kg^{-1}, and 0.041 \$ kg^{-1} for *Pr*, *FR*, *FD*, *SCE* and *HC* respectively.

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