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Mechanical Harvesting of Wild Almond (*Amygdales Scoparia*) by a Pneumatic Branch Shaker

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Abstract

Amygdales Scoparia, a species of wild almond native to the Middle East and South Asia is grown in calcic–rocky mountains of Iran. The conventional method of harvesting this fruit is by hand. For mechanized harvesting, a portable and light weight pneumatic branch-shaker system was designed and fabricated. For determining the effect of amplitude and frequency of vibration on fruit detachment rate an experiment was conducted in Kherameh region which is located in Fars province. The flow of pressurized air and electrical current necessary for operating the system are provided by a set of electric generator and an air compressor on a portable palette. For controlling the frequency of vibration and changing the amplitude of oscillation, the shaker was equipped with a programmable logic controller (PLC) and a pantograph system, respectively. The experiment was conducted by using a factorial design based on a completely randomized design with four replications. The effect of three levels of oscillation amplitude (2, 5 and 8 cm) and three levels of oscillation frequency (8, 12 and 16 Hz) on percent and rate of fruit detachment was investigated during 5 second intervals. The results showed significant effect of frequency and amplitude of oscillation on the percentage of fruit detachment, while their interaction effect was not significant. The cumulative graphs of fruit detachment rates showed that the maximum fruit detachment is obtained at all amplitudes and frequencies of oscillation during the first 5 seconds from the beginning of harvesting. Finally, the 5 cm amplitude and frequency of 16 Hz was suggested as the most suitable amplitude and frequency of oscillation with 90% fruit detachment during 5 seconds oscillation. Comparing hand and mechanical harvesting showed the harvesting rates of 4.91 and 14.7 (tree/minute), respectively.

Key words: Tree harvesting, Oscillation frequency, Oscillation amplitude, Fruit detachment rate

1. Introduction

One of the wild species of almond (*Amygdalus scorpia*) which is native of Iran is locally known as Alook or Mojak and occupies large areas in many parts of Iran and its neighboring countries. Wild almond which belongs to *Rosaceae* family is a nice looking green and thorny tree having abundant branches, stable stems with the canopy diameter of 2 to 2.5 meters. The plant roots have rapid deep growth and sometimes penetrate up to 6 meters in the soil. The plant is resistant to the adverse conditions of mountains and in high foothills between 800 to 2700 meters elevation from sea level; with annual rainfall between 150 mm to 250 mm. Its leaves are twisted, lanceolated or spoon- shaped and serrated–arched edged with average length of 40 mm and width of 7 mm. This plant has smooth and shiny branches with white petal blooms which appear on the branch before green leaves grow. Its fruits are hard and oval shaped with average length of 20 mm and width of 12 mm covered with small soft woolly hairs having smooth kernels with shallow grooved lines. Its kernel contains Amygdalin, Diastase and Benzoic aldehyde. Its kernel paste mixed with starch and mint is used as a cough depressant and congestion relief medicine. It is also used as an ointment for relieving skin sunburn and prevention of dark skin patches as well as an anti-aging cream (Tavakoli & Frahnoosh, 2008). Since *Amygdalus scorpia* trees are not possessed by private ownership, the trees are harvested by native people of Kharameh region in Fars province. Certainly, each person who harvests more fruits during the harvesting season will benefit much more. Common method of harvesting this fruit is through applying oscillatory motion of branches by hitting the top fruit bearing branches with hand or wood sticks. Therefore, the pattern of hand harvesting can be changed to mechanical harvesting, if the mechanical system has the capability of maneuvering and working in the regions of growing this tree.

The researches show that four methods are used for mechanical harvesting: air shaker, trunk shaker, branch shaker and canopy shaker. In air shaker type, the trees canopy is shaken by high speed air flow generated by a powerful fan. In the trunk shaker method, the shaker is firmly clamped to the trunk at a height from ground level and the whole tree is shaken all together. In the branch shaker technique, the shaking system is connected to each branch and is shaken, separately. In canopy shaker method, a number of arms enter the tree canopy and the canopy is oscillated by shaking the arms (Whitney, 1973).

Most of the modern mechanical harvesting machines are designed and constructed in order to separate all of the ripe fruits with the first time harvesting in any harvesting season. One time harvesting of the produce has the shortcoming that a large part of the harvested product doesn't have the desirable quality. This is because, the unripe fruits haven't reached to the required quality and the over ripped fruits are subjected to damage and spoilage. Therefore, the amount of the economic benefit depends on the fruits quality on the harvesting day. The important point in this kind of harvesting is that the maximum amount of the ripe fruits should be harvested during the first harvesting, because the amount of the remained fruits becomes so low which makes the second harvesting operation expensive and uneconomical (Sanders, 2005).

Theoretically, it was shown by Stafford and Diener (1971) that the frequency of the oscillation given to the branch should be equal to its natural frequency of oscillation in order to have most effective fruit detachment; in this condition, the amplitude of the oscillation increases extensively and fruits are detached from the branch with less throwing motion. On the other hand, the extensive increase of oscillation amplitude at tree natural frequency should be avoided due to its potential damaging of shaken branches (Srivastava *et al.*, 2006).

Many experiments which have been conducted on various kinds of trees show that if an oscillation of 20 - 40 Hz with oscillatory amplitude of 20 - 25 mm is performed on trees with hard and low-flexible branches, the harvesting performance has higher efficiency. While, oscillation frequencies of 1.5 - 6 Hz with oscillation amplitude of 100 - 125 mm are more suitable for soft and long branches, resulting to higher fruit detachment. Accordingly, the most recommended limit for citrus fruits is 1.5 - 6 Hz for frequency of oscillation and 100 - 125 mm for the amplitude of oscillation (O'Brien *et al.*, 1983).

One of the most important decisions that can have an important impact on percentage of harvested fruit is the selection of suitable harvesting time. Even though, mechanical harvesting time is usually the same as the common local harvesting time, but researchers indicate the suitable harvesting time as when the number of over-ripped fruits is equal to the unripe ones (O'Brien *et al.*, 1983). The other important decision that fruit growers should make each year is when to start harvesting which is usually determined by properties such as detachment force, weight and ripeness. While, other important factors which harvesting operation is dependent on, are hardly adjusted; among which the main structure of the tree, empty spaces between trees and variation of the harvesting machines can be pointed out (Blanco-Roldan *et al.*, 2009).

Extensive experiments have been carried out in the field of mechanical harvesting by applying different levels of amplitude and frequency and valuable experimental information about harvesting fruit and the damages sustained by tree have been obtained. Fridley & Adrian (1966) presented an experimental relation (1) expressing the percentage of the harvested fruit as a function of influencing parameters "amplitude and frequency of oscillation".

$$\mathrm{Re}\,moval\% = 100\left(1 - e^{-ks^{a}\omega^{b}}\right) \tag{1}$$

Where in:

S: Oscillation amplitude (m); ω : Oscillation frequency $(\frac{Rad}{s})$; and k, b, a: experimental coefficients.

Abounajmi and Loghavi (2001) Studying Shahani date palm harvesting showed that the highest percentage of ripe fruit and the lowest amount of the unripe fruit detachment are obtained at 60 mm amplitude and 5 Hz frequency, and more ripe fruit is harvested when applying vertical oscillation than the horizontal oscillation.

In a research, an inertia type branch shaker was used to harvest olive fruits and the results showed that the tree should be shaken at the frequency range of 20 - 28 Hz and the amplitude of 20 - 30 mm for 10 seconds to obtain efficient fruit separation (Kececioglu, 1975).

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An inertial shaker was used by Parameswarakumar and Gupta in 1991 in order to harvest mango fruits. The results showed that the shaker should be used at the amplitude of 76 to 102 mm and the frequency of 11 to 13 Hz for 4 seconds in order to harvest the highest percentage of the fruit with the lowest rate of damage. In a shaking mechanism system, a pneumatic pump and jack was used, in which the jack was connected to the end of the shaker boom and the reciprocating motion of the jack piston at low stroke caused shaking motion (Coppoc, 1974). Sessiz and Özcan (2006) constructed a tractor mounted pneumatic branch shaker system and conducted some experiments in order to harvest olives by using this branch shaker and abscission chemical. They achieved 96% fruit removal at shaking frequency of 24 Hz and using 6.25 mLL^{-1} abscission chemical.

The main objective of this study is to investigate the feasibility of mechanical harvesting of wild almond in Kherameh region of Fars province using a pneumatic branch shaker with adjustable shaking frequency and amplitude.

2. Materials and Methods

In this research, to determine the effect of the vibration amplitude and frequency on the detachment rate of wild almond (*Amygdalus sccopria*) a pneumatic branch shaker system with the possibility of adjusting amplitude and frequency was used. The shaker system was composed of the following two main parts:

1. The package of air tank and electric generator.
2. The portable vibrating arm.

The package of air tank and electric generator, as shown in figure 1, includes the following components: 1- Battery (12 Volt); 2- Alternative type dynamo; 3- Gasoline engine (4 kW); 4- The compressor driving belt tightening system with the possibility of removing compressor load on the engine during engine start-up; 5- Piston-type compressor; 6- Pressure relief valve; 7- Air tank; 8- Chassis.

The portable vibration arm equipped with a pantograph system to change oscillation amplitude is shown in figure 2. For generation of oscillating motion, a double action pneumatic cylinder equipped with a solenoid-activated directional control valve was employed. For periodic activation of the solenoid, a square pulse generator system was needed. In this research, a Mini PLC type programmable logic controller made by Siemens Company of Germany with an abbreviated name of LOGO, model 12/24 RC was used.

For investigating the effect of three oscillation frequencies (8, 12, 16 Hz) and three amplitudes (2.0, 5.0, 8.0 cm) during 5 seconds vibration duration on detachment percentage of wild almond fruits, a 3×3 factorial experiment was conducted with four replications using a completely randomized design employing SPSS software. Field tests were conducted at the end of spring 2014 in a hilly area around district of Kharameh located at 80 km east of Shiraz, Iran. The selected test area had a low slope and the shaker system was easily transferred and assembled. Since the vibrational package was connected to the air tank and electric generator package with a 30 meters long high pressure hosing, frequent relocation of pneumatic power unit was not needed.

In order to collect the detached fruits, a tablecloth was spread under the test branch and after every shaking treatment, the detached fruits were collected to be counted and weighted for further analysis. Then, the rest of the fruits remained on the test branch were handpicked to be counted and weighted for calculation of the fruit detachment percentage (P) by using relation (3) (Polat *et al*., 2007).

$$P = \frac{m_r}{m_r + m_u} \times 100 \quad (3)$$

Where: m_r: the number or mass of the removed fruit, m_u: the number or mass of the un-removed fruits from each test branch. In order to measure the separation rate of fruits during shake harvesting, a digital camera (Canon model Powershot G16) was used to take continuously one image, each half second during each shaking treatment. The camera was installed on a pillar in such a way that it can take complete photographs of the tablecloth and the falling almonds. The camera was triggered to take pictures simultaneously with starting each shaking action and 10 images were taken and recorded during each 5 seconds shaking test.

The static separation force of wild almond fruits with stem or without stem from the branch was measured by using a tensile dynamometer (Model FG-5100 made by Lotron Company) and the fruit masses were obtained by using a precision scale.

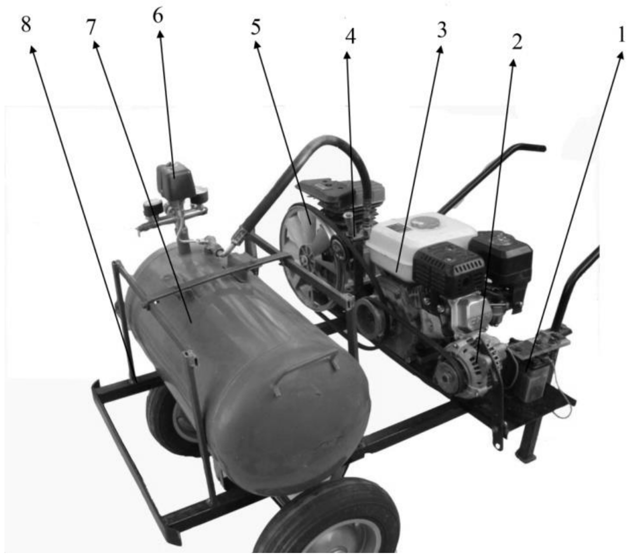

Figure 1. The package of air tank and electric generator

1. Battery, 2. Electric generator, 3. Fuel tank, 4. Air compressor, 5. Cooling fan, 6. Pressure gauge, 7. Air tank, 8. Package frame

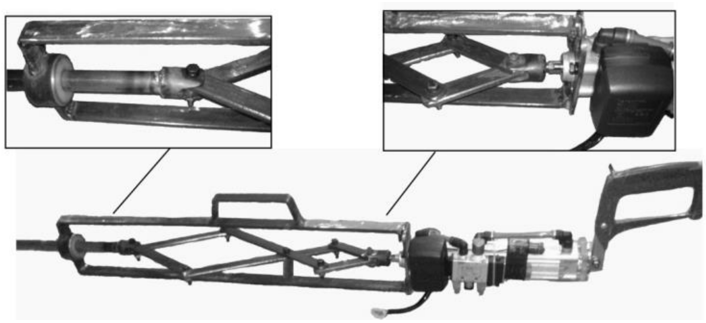

Figure 2. The portable vibration arm with the Pantograph system to change oscillation amplitude

For comparing the capacity of mechanical harvesting and hand harvesting, an experiment was designed and performed with three repetitions. In each repetition, 10 trees were randomly selected and were divided into two groups. The first group was harvested by hand and the second group was harvested by the branch shaker. The effective elapsed time for harvesting each tree was measured and the average harvesting capacity was obtained based on tree per hour ($\frac{Tree}{hr}$). Also, by knowing the oscillation time – duration and the weight of the harvested fruit, the time – duration of harvesting one kilogram of wild almond ($\frac{min}{kg}$) was calculated.

3. Results

3.1. Amplitude and frequency of oscillation

In table 1, the effect of vibration frequency and shaking amplitude on the harvested fruits is presented. The results of the variance analysis shows that vibration frequency and shaking amplitude both have significant effect on the performance of the branch shaker at 5% probability level; while their interactive effects were not significant, which implies the independency of the investigated variables.

Table 1. Analysis of variance of the effect of investigated variables on fruit removal

Source of Variation	Sum of Squares (SS)	Degree of Freedom (df)	Mean square (MS)	F
Frequency	10555.95	2	5277.97	201.45**
Amplitude	3374.36	2	1687.18	64.40**
Frequency× Amplitude	231.61	4	57.90	$2.21^{n.s}$
Error	707.40	27	26.20	
Total	14869.32	35		

$n.s$: Non Significant, **: Significant at P<0.05

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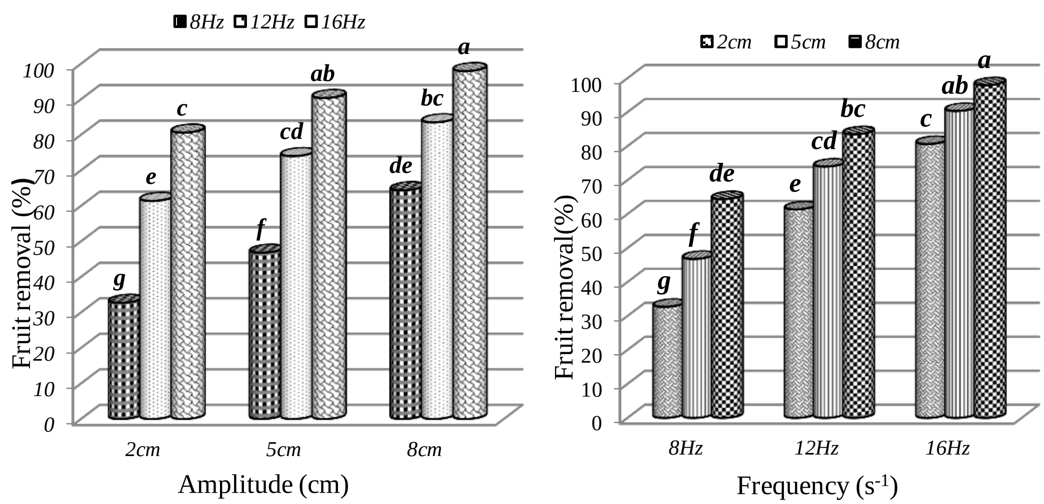
Comparing the means, by using Duncan test at 5 percent level for features of oscillation frequency and amplitude showed (Fig. 3- a and b) that at all amplitude levels, the fruit detachment percentage increased by the increase of oscillation frequency. Also, it shows that at 8 Hz frequency the fruit removal percent increases significantly with the increase of oscillation amplitude. But, at constant frequencies of 12 Hz and 16 Hz, the detachment percentage of the fruits increases significantly with the increase of oscillation amplitude from 2 cm to 5 cm, while the increase of oscillation amplitude from 5 to 8 cm doesn't show any significant increase of the detachment percentage. Therefore, despite 98% fruit removal at frequency of 16 Hz and amplitude of 8 cm, the selection of 5 cm oscillation amplitude and frequency 16 Hz, which causes 90% fruit removal, seems more logical due to lower energy consumption with no significant reduction in fruit removal.

Comparing the F values in table 1 and the slopes and intervals between graphs of fitting lines in figure (4-a and b) show the stronger effect of oscillation frequency than the oscillation amplitude on fruit detachment.



a b

Figure 3. Effect of (a) Amplitude and (b) Frequency of vibration on fruit removal percentage
(Similar letters indicate no significant difference at p=0.05 [DMRT])

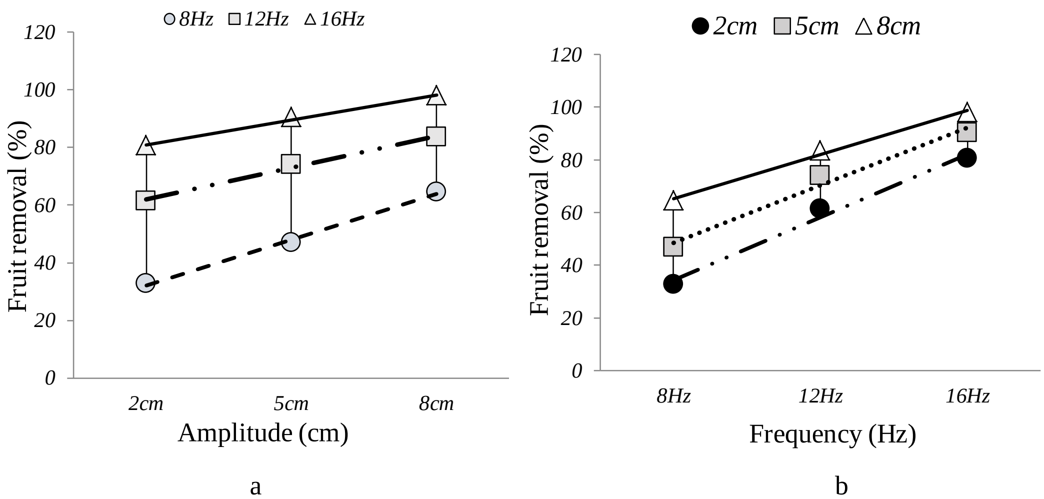


Figure 4. (a) Effect of shaking amplitude on fruit removal at three different levels of frequency; (b) Effect of shaking frequency on fruit removal at three different levels of amplitude

3. 2. The separation rate of the fruit

Among the taken images in order to investigate the separation rate of the fruits, those related to the most suitable amplitude and frequency of oscillation (5 cm and 16 Hz, respectively) are shown in figure 5.

The study of the separation rate of the fruits at 5 cm oscillation amplitude and at different levels of oscillation frequency shows that the harvesting rate is increased by increasing the frequency of oscillation and the highest separation rate at any frequency, occurs at 2.5 seconds after starting the shaking tests (Fig. 6).

In figure 7 comparing the separation rates of three levels of amplitude at 16 Hz frequency, shows that the maximum rate of fruit separation at the lowest amplitude of oscillation (2 cm) occurred 3 seconds after the beginning of harvesting. While, at 5 cm and 8 cm amplitudes, the maximum rate of fruit separation is obtained 2.5 seconds after the beginning of shaking.

The cumulative fruit detachment percentage at 5cm amplitude and three frequencies (8, 12 and 16 Hz) showing the total percentage of the harvested fruit in each half second is presented in figure 8. The considerable point in this figure is the necessary time duration for harvesting the maximum product. As it is observed at 5 cm amplitude and 16 Hz frequency, the maximum yield of the system (90%), was obtained 3.5 seconds after the beginning of harvesting operation. At 12 Hz frequency, the maximum yield (74%) is harvested 4 seconds after the beginning of harvesting operation. While, at frequency of 8 Hz, the maximum fruit harvesting is only 47% which occurs after 5 seconds.

3. 3. Comparing mechanical and hand harvesting

The results of this comparison as given in table 2, shows that the average time – duration necessary for hand harvesting is significantly greater than mechanical harvesting (14.7 and 4.92 trees/h, respectively). Consequently, the performance of mechanical harvesting based on the number of trees per hour is about three times greater than harvesting by hand.

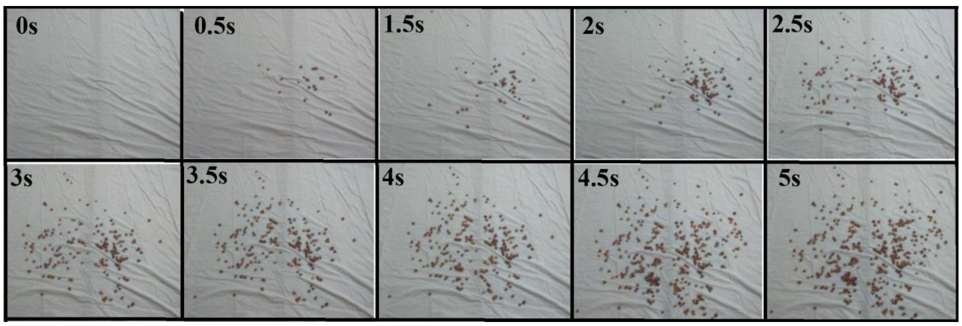


Figure 5. Images taken at 0.5 second intervals

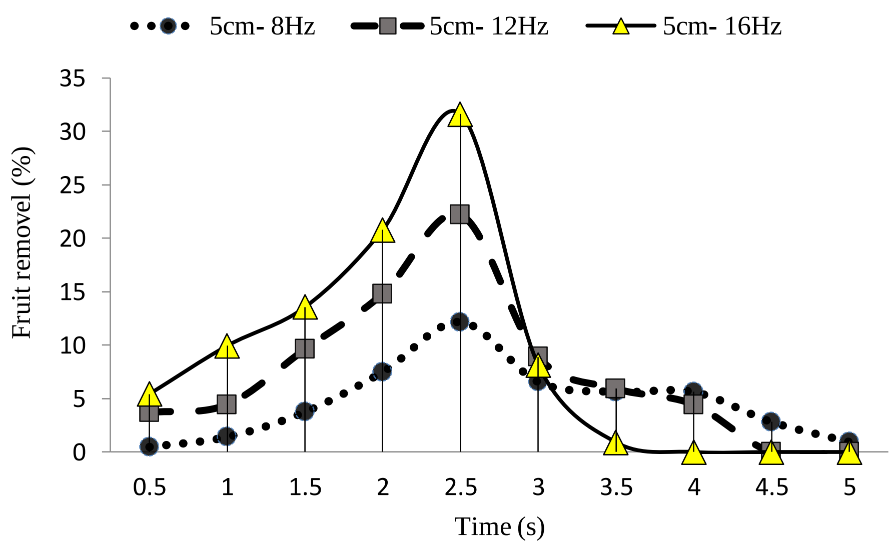


Figure 6. Fruit removal rate at the amplitude of 5 cm and three levels of frequency (8, 12 and 16 Hz) within 5 seconds

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Table 2. Comparison of mechanical and hand harvesting of wild almond fruits

Harvesting method	Average time required to harvest one tree (min/tree)	Time for harvesting one kilogram of fruit (min/kg)	Tree harvesting rate (trees/h)
Hand harvesting	12.2	0.45	4.91
Mechanical harvesting	4.15	0.15	14.7

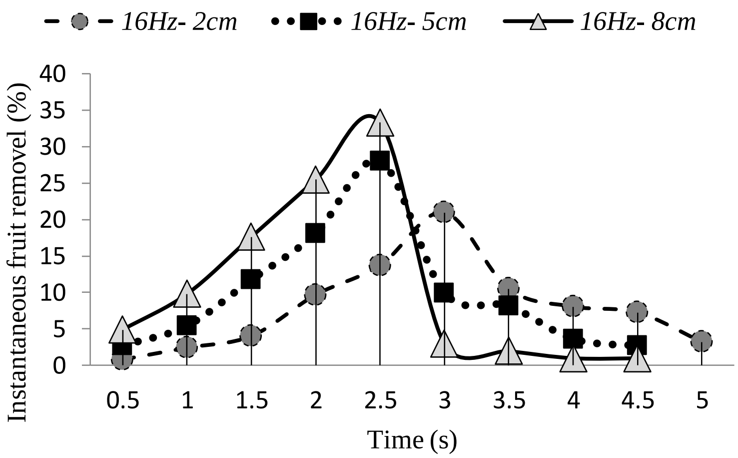

Figure 7. Fruit removal rate at the frequency of 16 Hz and three amplitude levels (2, 5 and 8 cm) within 5 seconds

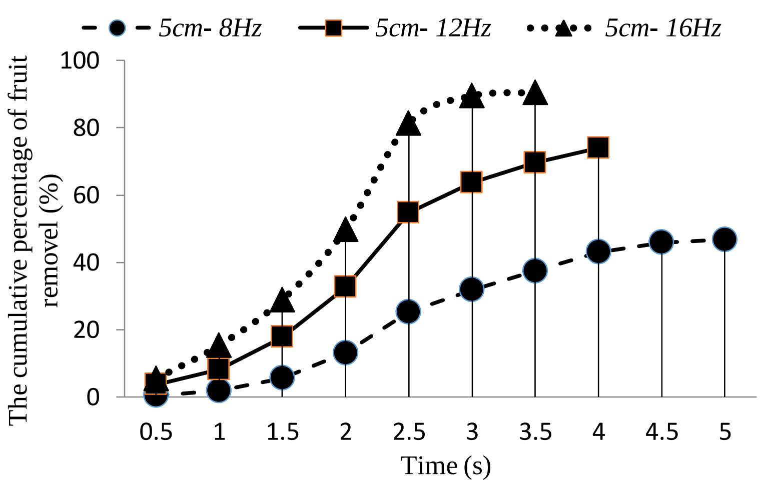

Figure 8. The cumulative percentage of fruit removal at the amplitude of 5 cm and three oscillation frequencies (8, 12 and 16 Hz) during a 5 second shaking test.

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3. 3. The static and dynamic fruit detachment force

The mean values of static fruit detachment force and fruit mass were obtained as 0.51 N and 0.0028 kg, respectively. The dynamic force (F) caused by vibration was obtained according to relation (4) and was compared with the static separation force (Murphy, 1950).

$$F = \frac{S}{2} m\omega^2 \qquad (4)$$

In this relation: *m*: fruit mass (kg), S: oscillation amplitude (m) and ω : frequency of vibration (Rad/s).

The mean values of dynamic force imparted on fruits at different combinations of amplitude and frequency of oscillation, as given in table 3, shows that in most cases that caused large amount of fruit detachment (≥ 80%), the average dynamic force was larger than the static detachment force. In other words, these treatments have been able to create the necessary force for separating the fruit.

Finally, a logarithmic relation was derived as $P_r = 23.26 \ln\left(F_d\right) + 96.93$ with $R^2 = 0.91$ between the calculated dynamic force (F_d) by relation (4) and fruit removal percentage (P_r) (Fig. 9).

Table 3: Mean dynamic force calculated at different frequency and amplitude combinations

Frequency of oscillation (1/s)	Frequency of oscillation (Rad/s)	Average fruit mass in kilograms	Amplitude (meter)	Dynamic force fruit removal (N)	Fruit removal Percent
8	50.24	0.0028	0.02	0.07	32.7
			0.05	0.18	46.8
			0.08	0.28	64.4
12	75.36	0.0028	0.02	0.16	61.38
			0.05	0.40	73.98
			0.08	0.64*	83.5
16	100.48	0.0028	0.02	0.28	80.62
			0.05	0.71*	90.35
			0.08	1.13*	97.93

*Treatment that impart dynamic forces greater than the average static fruit retention force

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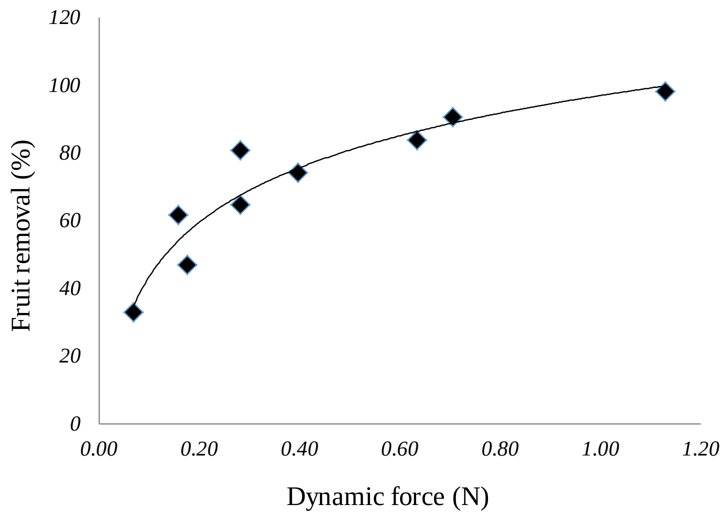

Figure 9. Relationship between dynamic force and fruit removal percentage

4. Discussion

Vibrational frequency and shaking amplitude both showed significant effect on the performance of the branch shaker, while according to analysis of variance (Table 1), their interactive effects were not significant implying the independency of the investigated variables. Similarity of the slopes of fruit removal curves versus vibration amplitude at different levels of frequency as shown in Figure 4 is another proof of this independency. This kind of independency has already been shown by Golpira (1988) studying the effects of shaking frequency and amplitude on olive harvesting and Loghavi and Mohsenin (2006) studying the effects of shaking frequency and amplitude on detachment of lime fruit. Erdoğan *et al.* (2003) and Safdari *et al*. (2010) reported the significant increase of almond fruit detachment percentage with increasing the frequency and amplitude of oscillation during 10 seconds shaking tests. Khirieh (2006) in harvesting apple, Polat *et al.* (2007) in harvesting pistachio and Khorsandi *et al.* (2012) in harvesting figs reached similar results. The main reason of increase in fruit detachment percentage can be attributed to the increase in dynamic forces and cyclic stresses suffered by the attachment point of fruits to the branch.

The stronger effect of oscillation frequency than the oscillation amplitude on fruit detachment as detected by larger F value of frequency than amplitude in table 1 and steeper slope of fruit detachment percent versus frequency curve (Figure 4), can be explained by the fact that the dynamic force imparted to the fruits on a shaken branch is related to the first power of amplitude and second power of frequency (Eq. 4). This phenomenon has been reported by many researchers studying the effects of shaking parameters on fruit detachment including Loghavi & Mohsenin (2005), Loghavi & Rahimi (2007) and Khorsandi *et al.* (2012). But, in the study conducted by Rezaei (2015) on olive harvesting by pneumatic branch shaker, no remarkable difference was observed between the fitting lines of oscillation amplitude and frequency. In other words, the increase of oscillations amplitude and frequency both had the same rate of effect on the percentage of olive detachment. Regarding the differences in damping properties and vibrational models of olive and wild almond branches, the existence of this difference is explainable. O`Brien *et al.* (1983) reported in different investigations that trees with hard and low- flexible branches need larger frequency of oscillation and smaller amplitude of oscillation than the trees with soft and long branches in order to harvest the product by shaking methods.

Studying the effect of oscillation frequency on harvesting rate that showed increasing rate of fruit detachment by increasing the frequency of oscillation can be attributed to the larger inertia force and larger number of oscillation cycles imparted to the fruits at higher frequencies, which consequently causes higher fatigue stresses leading to larger fruit removal. Also, the effect of oscillation amplitude on fruit separation rate can be attributed to greater inertial force at higher oscillation amplitudes and shorter time duration needed to impart the required stress cycles for fruit detachment. Considering cumulative fruit detachment rate versus shaking duration as depicted by figure 8 shows that at 16 Hz frequency and 5 cm amplitude, fruit detachment of over 90% is obtained after only 3.5 second shaking, Therefore, the maximum shaking time duration is suggested to be limited to 5 seconds in order to decrease the potential damage suffered by the tree and to prevent the time and consuming energy to be wasted. Khorsandi *et al*. (2012) conducted an experiment for harvesting figs using the same hand held branch shaker used in this study. By studying the instantaneous and cumulative fruit removal rates, they concluded that almost 100% of fruits are harvested during the first 4 seconds after the beginning of harvesting. So, 5 seconds was suggested as the maximum necessary time for harvesting operation.

The comparative performance of mechanical harvesting versus hand harvesting based on the number of trees per hour is comparable to work of Polat *et al.* (2007) on pistachio who reported hand and mechanical harvesting rate of pistachio as 4.07 and 12.3 trees per hour, respectively. Wingate–Hill and Brown (1981) found that mechanical harvesting is not always cheaper than hand harvesting. In comparing the cost of harvesting by hand with air shaker and trunk shaker methods, they found that the cost of harvesting by hand was equal to the lowest range of mechanical harvesting expenses of these two methods. The cost of mechanical harvesting for every ton of the harvested fruit depends on the amount of the product, the kind of the harvesting machine, the cost of the abscission chemical (the highest cost of mechanical harvesting is spent for using the abscission chemical for intensifying the abscission layer) and the rate of damage suffered by the fruits during the harvesting process.

Regarding the dynamic forces imparted to the fruits during shaking tests, as it is observed in table 3, at frequency of 16 Hz and amplitudes of 5 cm and 8 cm, the calculated dynamic forces are larger than the average static force needed for separating the fruit (0.51 N), so, 100 percent fruit separation is expected; but it is worth mentioning that this force is calculated with the assumption that the whole branch clamped to the branch shaker has been oscillating with the frequency and amplitude of the branch shakers hook. While, it is known that depending on the vibrational form and damping properties of the branch, different points of branch may have smaller or larger oscillatory amplitude than that of shaker clamping point. Consequently, the dynamic force will be variable along the branch; therefore, at 16 Hz frequency, on the average only about 90 percent of the fruits are separated from the branch.

5. Conclusion

In this study, the effects of shaking frequency and amplitude on wild almond fruit detachment was investigated by using a pneumatic hand held limb shaker with adjustable shaking frequency and amplitude. Analysis of variance and mean comparison of fruit detachment data showed that the effects of shaking amplitude and shaking frequency on fruit detachment were significant. The maximum fruit detachment was obtained at all amplitudes and frequencies of oscillation during the first 5 seconds from the beginning of harvesting. The most suitable combination of shaking frequency and amplitude with 90% fruit removal was determined at 5 cm amplitude and 16 Hz frequency.

The harvesting capacity of the branch shaker was about three times larger than hand harvesting; so using this system can have higher relative advantages for harvesters. The system has low weight and is equipped with long air transfer hose; therefore, it can be used in hillside regions with no need for frequent relocation of pneumatic power unit.

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