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The Effects of Shaking Frequency and Amplitude on the Detachment of Estahban Dried Fig (*Ficus carica* cv. Sabz)

F. Khorsandi[1*], M. Loghavi[1] and S. Kamgar[1*]**

1. Department of Mechanics of Agricultural Machinery, College of Agriculture, Shiraz University, I.R. Iran

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ABSTRACT-The aim of this study was to determine the most suitable shaking frequency and amplitude for shake harvesting Esfahan's edible fig (*Ficus carica* cv. Sabz). A hand held limb shaker with adjustable shaking frequency and amplitude was used for this study. A 3x3 factorial experiment with three levels of oscillating frequency (10, 12 and 14 Hz) and three levels of shaking amplitude (20, 32.5 and 45 mm) was conducted to investigate the effects of shaking frequency and amplitude on fruit detachment. 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 percentage of unripe fruit detachment significantly increased at higher levels of shaking amplitude and frequency. Complete ripe fruit detachment (100%) and relatively high unripe fruit detachment (16.9%) was obtained at a shaking amplitude of 45 mm and frequency of 14 Hz, but a shaking amplitude of 45 mm and shaking frequency of 10 Hz with high ripe fruit detachment (93.3%) and acceptable unripe fruit detachment (9.4%) is recommended. Harvesting rate during 5s of shaking was measured which showed that the optimum time needed to harvest a limb is only 4s. Comparison of mean values of cumulative fruit removal of 60% (T60) and 90% (T90) at frequency amplitude combinations indicated that the shaking duration necessary for 60% and 90% fruit removal both followed a decreasing trend by increasing the shaking amplitude and frequency. This study suggests the feasibility of utilizing limb shakers as a practical approach for selective harvesting of ripe fruits.

Keywords: Fig harvesting, Removal rate, Shaking frequency, Shaking amplitude

INTRODUCTION

Fig Production and Conventional Harvesting

Iran is one of the largest fig producers in the world. It is estimated by FAO that in 2008, fig trees were cultivated on an area of about 462800 hectares across the world. In Iran, fig trees cover 52000 hectares of land and produce 88000 tons of figs. Iran is the third largest fig producer after Egypt (304000 tones) and Turkey (205000 tones) (FAO 2008).

* Former Graduate Students, Professor and Assistant Professor, respectively
** Corresponding Author

This study was conducted in Estahban, which is the main rain fed fig producing region in Fars province, Iran with an acreage of more than 20,000 ha propagated by stock. There are more than 2 million home bred fig trees in 22000 hectares of plain land and mountains of the region producing about 22000 tons of dried figs. This distinguishes Estahban as the largest producer of dried figs in Iran and the world (Anonymous 2009). Dried figs are the fruit of the tree ″*Ficus Carica*. L cv. Sabz ″, from which, the greater portion of moisture has been removed. Figs are dried quite naturally through exposure to the sun. Dried figs are processed to bring their moisture content to 14 - 20% to as high as 30%. Most of the fruit is dried before marketing. From the last days of July, figs start to ripen. Harvesting season starts from the first days of August and continues to the middle of October. The amount of fruit yield depends on various factors such as age of the tree, tree spacing, orchard management, weather conditions, amount of precipitation, type of soil and existence or non existence of blights and diseases. The trees usually begin to fructify at the age of 4 to 5 years, but in water independent conditions, fig trees bear a significantly economic yield when they are 10 to 15 years old. In Estahban, each tree yields almost 10 to 15 kg of dried figs (11). There are two traditional methods for fruit harvesting; in the first method, farmers wait for figs to be sun-dried on the trees and fall down spontaneously on the ground or catching surfaces, then orchard men gather them once a week. Another method is hand shaking the fruit bearing limbs with a pole. In each method, figs fall down on the ground or are caught on a catching surface. Then the collected fruits are spread on a concrete surface, exposed to straight sun light for further drying. In the first method, the produce is exposed to rain fall, bacteria and mold spores and pests. The second method is labour intensive and causes tree damages. In order to eliminate these difficulties and disadvantages, mechanical harvesting of figs is necessary and inevitable in the future.

Vibratory Harvesting

Adrian and Fridley (1) stated that harvesting by shaking the limbs and trunks is the most promising. The basic principle is to accelerate each fruit so that the inertia force developed will be greater than the bonding force between the fruit and the tree (10). The excitation force is typically derived from cyclic oscillation of either a slider-crank mechanism or two opposite rotating eccentric masses connected to the tree to be harvested (17). It was observed that the most important disadvantage of harvesting by mechanical shakers is the damage imparted to the fruit (5). The catching units used in shake harvesting are collecting surfaces that extend under the tree, covering the drop area of the detached fruits (4). Mechanical shakers are large scale harvesting equipment with potential applications for a wide range of fruits, berries and nuts. In general, harvesting equipment based on principles of a mechanical shaker consist of a shaker, collecting frame (catching units) and conveying units, mounted on a self-propelled carrier, usually a tractor (13).

Effects of Shaking Amplitude and Frequency on Fruit Removal

An inertia type shaker for olive harvest was developed and it was suggested that for optimum fruit removal, the olive tree should be shaken in the range of 20-28 Hz and an amplitude of 20-30 mm for 10s (9). Parameswarakumar and Gupta (14) developed a slider-crank type limb shaker for harvesting mango fruits. Their studies showed that to obtain maximum fruit removal with minimum tree damage, the shaker should be operated in the range of 76–102 mm amplitude and frequencies of 11–13 Hz for 4

s. An inertia type limb shaker, hydraulically powered and driven by the tractor power take-off was tested for harvesting apricots (6). The limbs were shaken at 20, 30, 40, 50 and 60 mm amplitudes and frequencies of 10, 15 and 20 Hz. The optimum shaking time, frequency and amplitude for maximum fruit removal, were found to be 5 s, 15 Hz, and 40 mm, respectively. The effects of three levels of oscillating frequency (5, 7.5 and 10 Hz) and three levels of shaking amplitude (20, 40 and 80 mm) on fruit removal were investigated using a tractor mounted limb shaker for shake harvesting of lime trees (12). An 80 mm amplitude and 10 Hz frequency were reported as the appropriate combination with about 95% fruit detachment and negligible leaf shattering. Sessiz and Ozcan (16) harvested olives by a pneumatic branch shaker and abscission chemicals. Maximum harvesting efficiency (96%) was achieved at 24 Hz and 6.25 mLL^{-1} of abscission chemical concentration. An inertia type limb shaker, hydraulically powered and driven by the tractor power take-off was tested for harvesting pistachio nuts (15). In the field tests, the tree limbs were shaken at amplitudes of 40, 50, 60 mm and frequencies of 10, 15, 20 Hz. The machine was able to remove 100 % of the pistachio nuts at 60 mm amplitude and 20 Hz frequency, but 50 mm amplitude and 20 Hz frequency with 95% fruit removal was suggested because the shaker caused excessive vibration of the frame when it was operated at greater amplitudes.

The Effect of Shaking Duration on Removal Rate and Efficiency

Blanco-Roldan et al. (3) studied the effects of shaking duration and repetitions on the removal efficiency of harvesting oil olives. By analysis of the images of the removal process they showed the importance of shaking time and the number of vibration repetitions on fruit removal. During the initial and middle periods of the harvesting season, the use of two consecutive vibrations (10+10 s) removed more fruit than one continuous vibration (20 s). They also showed that the detachment process of the olives accumulated throughout the shaking time exhibited a sigmoid growth curve with an initial moderate slope, corresponding to the start of the shaking and the arrival of the first fruits to the ground, while the majority of the fruits were removed in an exponential phase. Finally, the remaining fruits were detached in a gradual and constant manner until the end of the shaking.

No attempt has been reported regarding the investigation of the possibility of vibratory harvesting of fig trees. Thus, the objectives of the present research were: (a) to investigate the effects of shaking frequency and amplitude on fig fruit detachment, (b) to determine the optimum shaking frequency and amplitude for effective fruit detachment and (c) to determine fruit removal rate.

MATERIALS AND METHODS

Shaking Tests

Field experiments were conducted during the 2009 harvesting season in Estahban Fig Research Station, located in Estahban valley, Fars province, 54 02'30" E, 29 07'45" N and +1760 m high. The trees (*Ficus carica*. cv. Sabz) that were selected for shake harvesting tests had the same age and were in similar growing conditions. The experimental design was a 3x3 factorial experiment arranged in a completely randomized design in three replications. The effects of three levels of shaking frequency (10, 12 and 14 Hz) and three levels of shaking amplitude (20, 32.5 and 54 mm) on fruit detachment were investigated.

Fig trees in the Estahban valley are mostly located on hillsides, therefore, tractor-mounted or self-propelled shakers cannot be used for harvesting the fruit. A hand-held shaker (SCUOTIMAS, Italy), powered by a 2.1 kW gasoline engine was used for shake harvesting trials (Figure 1). The shaker total mass including a 1.8 m boom and 40mm wide hook was 14 kg. The shaking amplitude was fixed at 32.5 mm and the maximum shaking frequency at full engine throttle was 22.5 Hz. During the shaking tests, the desired shaking frequencies could be selected by proper throttle setting of the shaker engine. For selecting the desired shaking amplitudes, as described in the following section, a novel amplitude changing mechanism was designed, fabricated and mounted on the shaker.

Fig. 1. The hand-held shaker and the the amplitude changing mechanism used for shake harvesting trials. (Shaker boom and hook not shown)

Amplitude Changing Mechanism

A novel mechanism was designed, fabricated and mounted on the shaker (Figure 2). The primary amplitude of the shaker was 32.5 mm. By changing the position of the fixed pivot point of the new mechanism, the other two desirable amplitudes (20 and 45 mm) were also selectable.

Fig 2.

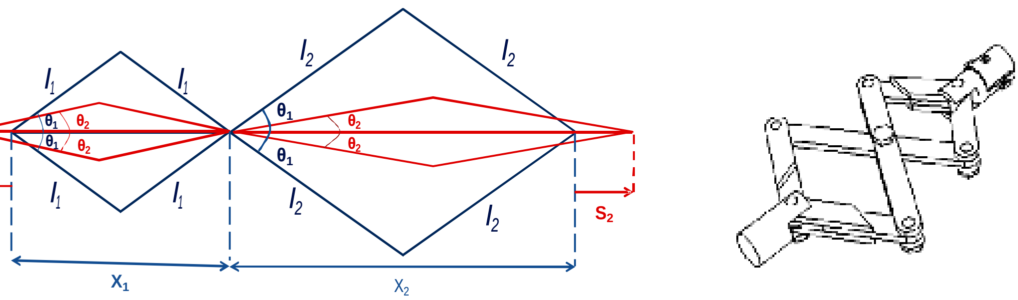


Fig. 1. Schematic diagram of the amplitude changing mechanism

The governing equations relating the output amplitude (S_2) to the input amplitude (S_1) are given as:

$$s_1 = 2l_1 \cos q_2 - 2l_1 \cos q_1 = 2l_1(\cos q_2 - \cos q_1) \quad (1)$$

$$s_2 = 2l_2 \cos q_2 - 2l_2 \cos q_1 = 2l_2(\cos q_2 - \cos q_1) \quad (2)$$

By replacing $\cos\theta_1$ and $\cos\theta_2$ as:

$$\cos q_1 = \frac{x_1}{2l_1} \qquad \cos q_2 = \frac{x_1 + s_1}{2l_1} \quad (3)$$

$$S_2 = 2l_2\left(\frac{x_1 + s_1}{2l_1} - \frac{x_1}{2l_1}\right) = \frac{l_2}{l_1}(s_1) \quad (4)$$

Before conducting any limb shaking test, limb total length and its diameter at the point of shaker boom attachment (1/3 of the limb length from the base), were measured with a graduated tape and a calliper, respectively. Diameters of the chosen branches varied between 30 to 40 mm at the shaker attachment point. The number of ripe and unripe figs on the selected limb and other neighbouring branches were counted because it was possible that fruits of other branches fall on the catching surface during the shaking test. After completion of any shaking test, according to the corresponding shaking amplitude and frequency combination, which lasted for only 5 seconds, detached ripe and unripe fruits on the catching frame and those remaining on the shaken branches were removed and then separately counted and weighed. The fruit removal percentage was determined by the following equations:

$$P_r = 100\frac{M_{rr}}{M_{rr} + M_{ur}} \quad \text{and} \quad P_u = 100\frac{M_{uu}}{M_{ru} + M_{uu}} \quad (5)$$

Where Pr is the ripe fruit removal percentage, is M_{rr} the mass of ripe fruits removed in g, and M_{ur} is the mass of unremoved ripe fruits in g. P_u is the unripe fruit removal percentage, M_{uu} is the mass of unremoved unripe fruits in g and M_{ru} is the mass of removed unripe fruits in g. The limb shaking frequency was measured by a Vibration meter Model TV300 made in China by the Time Group Company.

Fruit Catching Frame

One of the most important disadvantages of mechanical harvesting is fruit damage. In order to resolve this problem, the most common approach has been to remove the fruit by shaking the trees and collecting them on a catching surface placed beneath the tree (8). For this purpose, a circular catching surface, as show in Figure 3, was designed and fabricated. Preliminary experiments showed that a 2 m diameter circular frame is suitable for collecting at least 95% of the detached fruits resulting from shaking each individual limb. The circular frame was made of stainless spring wire with four legs attached to the frame in order to keep the catching surface off the ground and rough and irregular surfaces. The catching surface was made of light weight washable canvas. The total weight of the catching frame was about 250 g and it was easily foldable to a 70 cm circle.

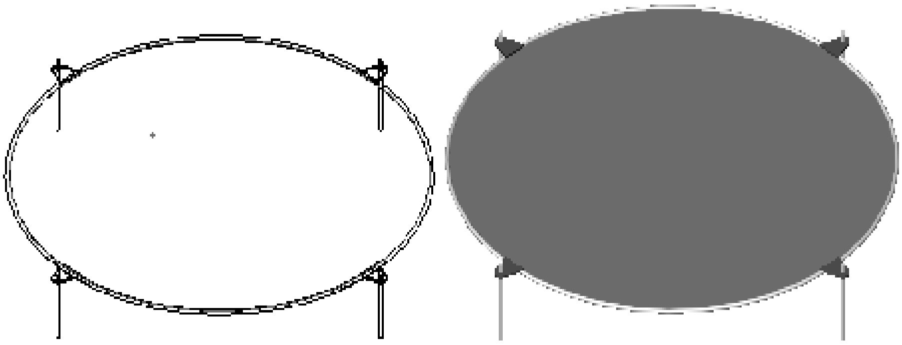


Fig. 3. Light weight catching frames for collection of detached figs during shake harvesting trials

Fruit Removal Rate

In order to determine the rate of fruit detachment during any shaking treatment, a digital camera (Sony, model DSC-H10, Japan) capable of taking consecutive pictures every 0.5 second was used. The camera, fixed on a tripod, was positioned in a proper place and aimed at the fruit catching frame such that the picture of the whole catching surface be captured in consecutive shots under natural and uniform light intensity. The camera was triggered to start taking pictures at the same moment the shaker started to shake a branch. Therefore, for every shake harvesting test that lasted for 5s, ten consecutive pictures of detached fruits were grabbed which could be used for determining fruit removal rate.

The shaking times corresponding to the cumulative fruit removal of 60% (T60) and 90% (T90) were determined for each treatment. In other words, T60 and T90 are the shaking times necessary to obtain 60% and 90%, fruit detachment, respectively. In the experiments conducted by Blanco-Roldan et al. (3), the T60 parameter represented the time corresponding to the greatest detachment rate phase of the fruits, while T90 marked the beginning of a reduced and gradual fruit detachment.

RESULTS AND DISCUSSION

The Effects of Shaking Frequency and Amplitude on Fruit Removal

As shown in Table1, the results of the analysis of variance of ripe fruit data indicate highly significant effects ($p<0.01$) of shaking frequency, shaking amplitude and the interactive effect of frequency and amplitude on ripe fruit removal. Comparison of mean values of the total detached ripe fruits at frequency-amplitude combinations is shown in figure 4. At the lowest frequency level (10Hz), significantly higher ($p<0.05$) fruit detachment occurred at higher shaking amplitudes, while at the other two frequency levels, the increase in fruit detachment at higher amplitudes was not as prominent.

Table 1. Analysis of variance of data on ripe fruit removal (%) at different levels of shaking frequency and amplitude

Source	df	Mean square	F
Amplitude	2	760.81	47.16**
Frequency	2	608.14	37.70**
Amplitude * Frequency	4	79.94	4.96**
Error	18	16.13	
Total	26		

** **Significant at p<0.01**

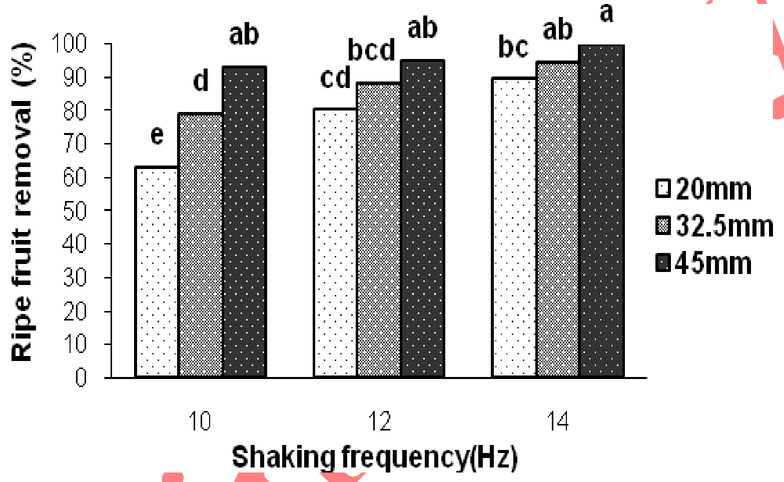


Fig. 4. The effects of shaking frequency and amplitude on ripe fruit detachment. Similar letters indicate no significant difference at p= 0.05

A linear multiple regression relationship correlating ripe fruit removal percentage (P_r) with shaking frequency (F, Hz) and shaking amplitude (A, mm) was derived (Equation 6) with the $R^2 = 0.798$.

$$P_r = 4.98\,F + 0.76\,A + 1.45 \qquad (6)$$

As shown in Table 2, the results of the analysis of variance for the effects of different levels of shaking frequency and amplitude on unripe fruit removal indicate a highly significant effect ($p<0.01$) of shaking frequency, but the effect of amplitude and the interactive effect of frequency and amplitude were not significant. This could be attributed to the fact that the dynamic force imparted to the fruit-stem or stem-branch junction by the forced vibration is proportional to the second power of frequency, where it is only a linear function of amplitude.

Comparison of mean values of the detached unripe fruit percentages at frequency-amplitude combinations are shown in Figure 5. It seems reasonable to assume that shake harvesting fig fruits at any shaking frequency - amplitude combination that results in more than 90 percent ripe fruit removal and less than 10 percent unripe fruit removal is justifiable. Therefore, by comparing Figures 4 and 5 it can be concluded that the only shaking frequency - amplitude combination meeting this criterion is the 10Hz x 45mm treatment with 93.3% ripe fruit and 9.4% unripe fruit removal.

Table 2. Analysis of variance of data on unripe fruit removal (%) at different levels of shaking frequency and amplitude

Source	Degree of freedom	Mean Square
Amplitude	2	12.83 ^{ns}
Frequency	2	137.47 **
Amplitude × Frequency	4	15.56 ^{ns}
Error	18	11.24
Total	26	

ns Non significant, ** Significant at p<0.01

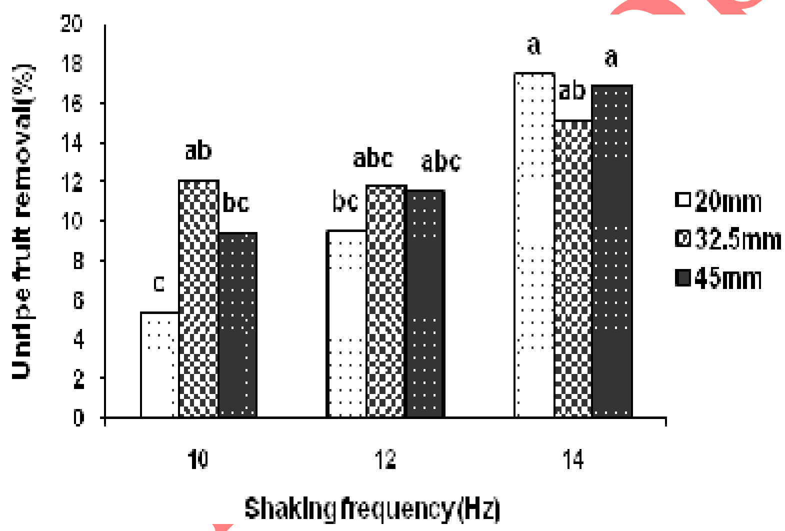
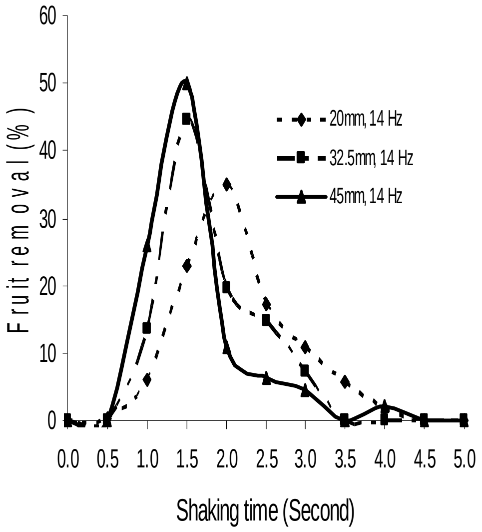
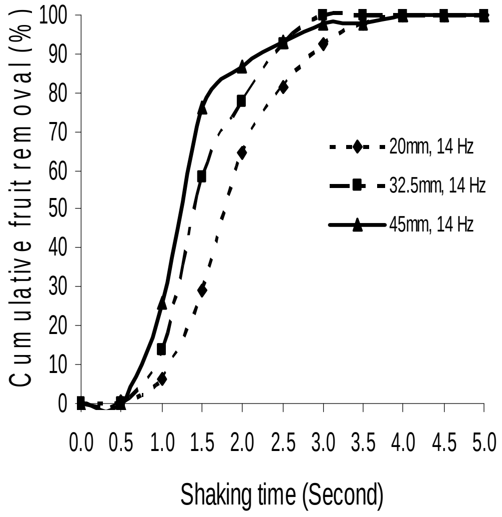


Fig. 5. The effects of shaking frequency and amplitude on unripe fruit detachment Similar letters indicate no significant difference at p= 0.05

The Effect of Shaking Time on Fruit Removal Rate

The representative patterns of instantaneous and cumulative fruit removal rates at the 14 Hz shaking frequency and three levels of shaking amplitude are shown in Figures (6a) and (6b), respectively. Figure 6a shows that at the two higher amplitude levels, the maximum fruit removal rate occurred 1.5 second after shaking started with the highest rate (50.2%) pertaining to the highest amplitude (45mm). At the lowest amplitude, the peak removal rate (35%), which is significantly smaller than those of the higher amplitudes, occurred after 2 seconds. This could be attributed to the higher inertial force imparted to the fruits when they were shaken at larger amplitudes.



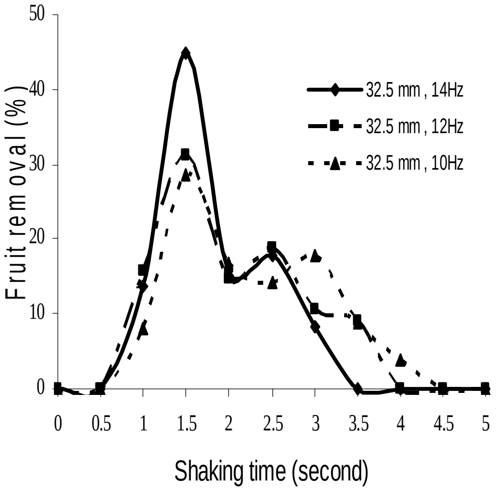


(a) **(b)**

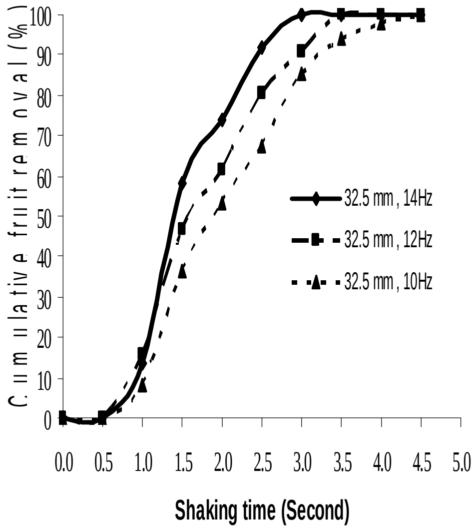
Fig. 6. Representative instantaneous (a) and cumulative (b) fruit removal rate curves at constant frequency (14 Hz) and three levels of shaking amplitude, during a 5 second shaking trial

The representative patterns of instantaneous and cumulative fruit removal rates at constant amplitude (32.5 mm) and three levels of shaking frequency are shown in Figures (7a) and (7b), respectively. The results showed that at all frequency levels, the highest rate of fruit detachment occurs about 1.5 seconds after starting the shaker with the highest rate (47%) pertaining to the highest frequency (14Hz), and the lowest rate (28.5%) at the lowest frequency (10Hz). This difference could be mainly attributed to the maximum and minimum inertial forces imparted to the fruits at these frequencies, respectively.

Figures 6b and 7b show that the cumulative fruit removal curves exhibit a near sigmoid shape, with an initial moderate slope corresponding to the start of the shaking followed by an exponential phase in which the greatest removal rate occurred. Finally, fruit removal continued with a decreasing trend until the end of the shaking. This is in agreement with the findings of Blanco-Roldan et al. (3), who reported that the process of oil olive fruit removal exhibited a sigmoid growth curve throughout the shaking time. The cumulative fruit removal curves show that almost 100% of the fruits were removed during the first 4.5 seconds of shaking. This suggests that for avoiding the destructive effects of shake harvesting such as excessive unripe fruit removal and tree damage, the shaking duration be limited to five seconds.



(a)



(b)

Fig. 7. Representative instantaneous (a) and cumulative (b) fruit removal rate curves at constant amplitude (32.5mm) and three levels of frequency, during a 5 second shaking trial

Analyzing the variances of data on fruit removal rates as presented in Tables 3 and 4 show that shaking amplitude and frequency both had significant effects ($p<0.01$) on the time necessary to achieve removal efficiencies of 60% and 90%, T60 and T90, respectively, with no significant interactive effect of frequency and amplitude. Comparison of mean values of T60 and T90 parameters at frequency-amplitude combinations are shown in Figure 8 and indicate that the shaking durations necessary for 60% and 90% fruit removal both follow a decreasing trend with increasing shaking amplitude and frequency. For example, T60 reduced from 1.85s at 20mm amplitude and 10Hz frequency to 0.9s at 45mm amplitude and 14Hz frequency and T90 reduced from 3.3s to 1.8s at the same amplitude and frequency combination.

Table 3. Analysis of variance of T60 at different levels of shaking frequency and amplitude

Source	Degree of freedom	Mean Square
Amplitude	**2**	**0.593****
Frequency	**2**	**0.507***
Amplitude × Frequency	**4**	**0.032**^{ns}
Error	**18**	**0.086**
Total	**26**	

^{ns} **Non significant, * Significant at p<0.05, ** Significant at p<0.01**

Table 4. Analysis of variance of T90 at different levels of shaking frequency and amplitude

Source	Degree of freedom	Mean Square
Amplitude	2	0.946**
Frequency	2	1.564**
Amplitude ×Frequency	4	0.053ns
Error	18	0.062
Total	26	

ns Non significant, ** Significant at p<0.01

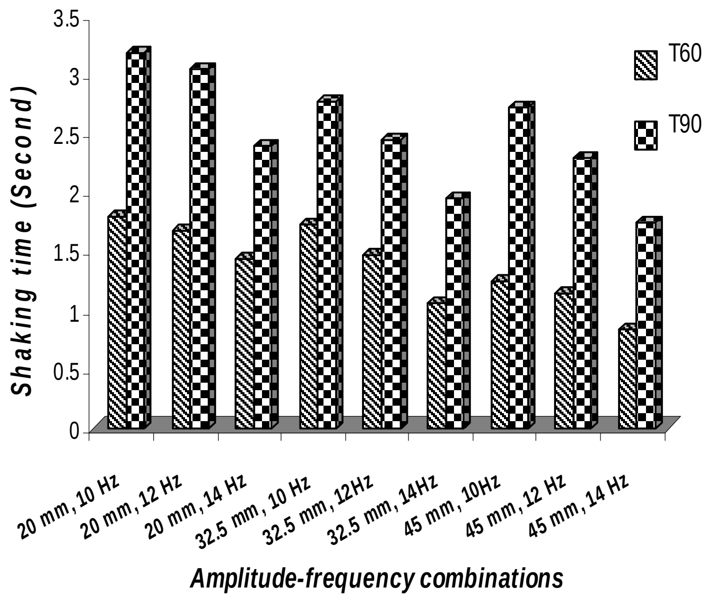


Fig 8. Comparison of mean shaking time required for 60% and 90% fruit removal at different combinations of shaking amplitude and frequency

Similar letters indicate no significant difference at p= 0.05

CONCLUSIONS

In this study, the effects of shaking frequency and amplitude on Estahban edible fig fruit detachment was investigated by using a 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 most suitable combination of shaking frequency and amplitude with 93% ripe fruit removal and 9% unripe fruit removal was determined at a 10 Hz frequency and 45mm amplitude. Comparison of mean values of T60 and T90 parameters, which represent the shaking duration necessary for 60% and 90% fruit removal, both followed a decreasing trend with increased shaking amplitude and frequency. This study suggests the feasibility of utilizing limb shakers as a practical approach for selective harvesting of ripe fruits.

Nomenclature

S_1	Input amplitude, mm	M_{uu}	Mass of unremoved unripe fruits, g
S_2	Output amplitude, mm	M_{ru}	Mass of removed unripe fruits, g
l_1	Input arm length, mm	T60	Shaking time for 60% fruit removal, s
l_2	Output arm length, mm	T90	Shaking time for 90% fruit removal, s
q_1	Input angle, radian	F	Shaking frequency, Hz
q_2	Output angle, radian	A	Shaking amplitude, mm

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تاثیر بسامد و دامنه ارتعاش بر جداسازی میوه انجیر سبز استهبان

فرزانه خورسندی[1]*، محمد لغوی[1]، و سعادت کامکار[1]***

[1] بخش مکانیک ماشین های کشاورزی، دانشکده کشاورزی، دانشگاه شیراز، جمهوری اسلامی ایران

چکیده - هدف از اجرای این تحقیق تعیین مناسب ترین بسامد و دامنه ارتعاش برای برداشت ارتعاشی انجیر سبز استهبان بوده است. در این بررسی از یک دستگاه شاخه تکان دستی مجهز به مکانیزم تغییر دامنه و بسامد ارتعاش استفاده گردید. از آزمایش فاکتوریل 3×3 بر پایه طرح کاملا تصادفی با سه سطح بسامد ارتعاش (10، 12 و 14 هرتز) و سه سطح دامنه ارتعاش (20، 32/5 و 45 میلی متر) به منظور بررسی اثر بسامد و دامنه ارتعاش بر جداسازی میوه انجیر استفاده شد. آنالیز واریانس و مقایسه میانگین داده های جداسازی میوه نشان داد که اثر بسامد و دامنه ارتعاش بر جداسازی میوه معنی دار می باشد. در سطوح بالای بسامد و دامنه ارتعاش درصد نسبتا بالای جدا شدن میوه های نارس (16/9%) در دامنه 45 میلی متر و بسامد ارتعاش 14 هرتز واقع گردید ولی دامنه ارتعاش 45 میلی متر و بسامد 10 هرتز با درصد بالای جداسازی میوه رسیده (93/3 %) و جداسازی قابل قبول میوه نارس (9/4%) توصیه میگردد. نرخ برداشت میوه در طول 5 ثانیه ارتعاش مداوم اندازه گیری و نتایج نشان داد که طول زمان بهینه مورد نیاز برای برداشت میوه هر شاخه 4 ثانیه می باشد. مقایسه میانگین های طول زمان برداشت 60 درصد (T60) و 90 درصد (T90) میوه در ترکیب های مختلف دامنه و بسامد ارتعاش حاکی از کاهش زمان لازم برای جداسازی با افزایش دامنه و بسامد ارتعاش می باشد. نتایج این بررسی نشان دهنده امکان برداشت انتخابی میوه انجیر در طی مراحل رسیدگی و خشک شدن بر روی شاخه با استفاده از شاخه تکان می باشد.

واژه های کلیدی: برداشت انجیر، بسامد ارتعاش، دامنه ارتعاش، نرخ جداسازی میوه

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* به ترتیب دانشجوی پیشین کارشناسی ارشد، استاد و استادیار

** مکاتبه کننده