Acoustic Testing for Melon Fruit Ripeness Evaluation during Different Stages of Ripening

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Summary

Non-destructive impulse response technique was tested on two melon varieties ('Zard-Eyvanekey' and 'Sousky-Sabz') in five different stages of ripening. Resonance frequency and sound pressure level (SPL) from the impulse response were compared with mass, elastic modulus, soluble solids contents (TSS) and sensory evaluation. Among acoustic and destructive parameters, resonance frequency is an indicator to distinguish of different maturity stage of the melon in both varieties. The sound pressure level (SPL) was not a reliable parameter to evaluate melon ripeness. It was established that the impulse response technique is useful to decide fruit maturity stage and appropriate harvest time.

Key words

acoustic, impulse, response, non-destructive, melon, ripeness

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Introduction

Eating quality of melon depends mainly on harvest of mature melons at desired stage or ripeness. Generally, optimum eating quality requires adequate sugar and flavor development, and the centre meat with a melting texture that progress to a crisp texture toward the rind. Immature or underripe melons have less sugar and flavor development, and have a firmer texture than those at optimum ripeness. Flavor and texture degrade dramatically as melon progress from ripe to overripe. It is difficult to judge ripeness by external characteristics such as size, external color, stem condition or feel. Ripe melons should be firm, symmetrical, and fresh looking. Determining optimum melon maturity at harvest time, however, is a critical but difficult task, even for experienced growers.

Melons (*Cucumis melo* L.) are commercially important fruits, but their ripening has been relatively poorly studied compared to other fruits such as tomatoes, avocadoes or apples. A large number of diverse melon cultivars are available that exhibit variation in ripening characteristics. Early and late harvesting varieties are known for many fruits, but in melons a selection can also be made according to fruit color, shape or sweetness. There is also variation in the respiratory climacteric, which is probably a variety-dependent characteristic of melon (Nukaya et al., 1986; Hadfield et al., 1995).

Many people have claimed that the maturity and other qualities of certain fruits, such as apples, melons, and pineapples, can be determined by listening to the sound produced by striking them. Several researchers have tried to verify such claims by studying the acoustic responses of fruits. Hernández Gómez et al. (2006) evaluated the capacity of acoustic signal response to monitoring the mandarin fruit firmness change during storage. The results indicate that it might be possible to identify the ripeness state of an individual mandarin by using the present method, and that the nondestructive acoustic test could replace conventional compression test in order to determine mandarin fruit firmness and expected shelf- life (Gómez et al. 2006). Taniwaki et al. (2009) investigated time-course changes in the elasticity index (EI) and texture index (TI) of two persimmon cultivars during the postharvest period. EI was determined using the formula $EI = f_2^2\, m^{2/3}$, where f_2 is the second resonance frequency of a sample, and m is the mass of the sample. They found that changes in the EI of both cultivars showed quasi-exponential decays. An improved texture measurement device was used for measuring the TI of the cultivars. They determined the optimum eating ripeness of persimmons along with the sensory test in terms of their EI (Taniwaki et al., 2009). Zheng et al. (2014) addresses the problem of distinguishing between ripe and unripe watermelons using mobile devices. They found that through analyzing ripeness-related features extracted by thumping watermelons, collecting acoustic signals by microphones on mobile devices, this method can automatically identify the ripeness of watermelons. Experimental results show that this method is currently able to correctly classify ripe and unripe watermelons with an overall accuracy exceeding 89% (Zeng et al., 2014). To evaluate the firmness of fruits Macrelli et al. (2013) compared three novel stiffness indexes based on acoustic methods and involving Young's modulus and sound propagation velocity. The effectiveness of the considered indexes is tested by means of an experimental setup built with two piezoelectric transducers contacting several samples of kiwifruits during their ripening process. They found that stiffness indexes based on propagation delays are more rapid and reliable than those based on fruit resonance in assessing the ripeness degree (Macrelli et al., 2013).

Hongwiangjan et al. (2015) investigated the maturity assessment of pomelo using acoustic properties obtained from an impact of fruit, optical properties of the peel and variables related to oil glands from peel images. They found that the classification model based on the nondestructive variables showed that fruits could be separated into immature, early-mature and late-mature groups with an accuracy of 96.7% (Hongwiangjan et al., 2015). Mao et al. (2016) developed an acoustic device after investigating the influence of hitting ball and fruit tray on spectrum. They proposed three firmness indices to correlate with firmness of watermelon. They found that significant correlation was between firmness and these indices using linear regressive model and nonlinear model of artificial neural network (ANN) (Mao et al., 2016). An experimental system for nondestructive firmness evaluation, based on the flexible piezoelectric sensors, a microphone or and accelerometer was developed and tested on several fruit and other products, such as: apple (Yamamoto et al., 1980; Woensel et al., 1988; Armstrong et al., 1989; Chen et al., 1992; Chen 1993); tomato (Duprat et al., 1997; Schotte et al., 1999; Baltazar et al., 2008), avocado (Shmulevich et al., 2003); muskmelon (Sugiyama, 1994); watermelon (Stone et al., 1996; Diezma-Iglesias et al., 2004); pear (Jancsók et al., 2001; Wang et al., 2004); peach (Goliáš et al., 2003; Gómez et al. 2005); potato (Baritelle, 1997), and many others. Most of these researches used an experimental system for non-destructive firmness evaluation based on microphone techniques, which have successfully been used for several fruits and other products. De Belie et al. (2000) point out the advantage of the acoustic technique that is an overall measure and a very reproducible and sensitive method. With the acoustic impulse response technique the resonance frequency is obtained by performing a Fourier transformation on the recorded sound of an intact fruit. The sound is produced by impacting the fruit, which then vibrates and causes pressure waves in the air. For contact sensing typically sensors, such as accelerometers and piezoelectric films are used. For non-contact sensing a microphone or laser vibrometer is needed. The primary objective of the present work was to develop a nondestructive method based on impulse response technology for quality evaluation of two different melon varieties 'Zard-Eyvanekey' and 'Sousky-Sabz'.

Materials and methods

Sampling of melon

This research was conducted on 'Zard-Eyvanekey' and 'Sousky-Sabz' varieties obtained from a plantation in Garmsar township (35º13′20″ N, 52º20′26 E). They were carefully picked by hand during the summer and autumn in the early morning from the area of Davarabad, Garmsar, Iran. Fruits were selected according to color, size and lack of blemishes in order to obtain homogeneous samples. Before each test series, the melons were transferred to department laboratory at 18 to 22ºC temperature

Table 1. Date of harvesting and tests series

Stage	Operation	Date	Description
1	First series of test	Mid-August	Immature
2	Second series of test	Late-August	Early ripening
3	Third series of test	Mid-September	Moderately ripe
4	Forth series of test	Late-September	Ripe
5	Fifth series of test	Mid-October	Overripe

and kept for 24 hours. They were selected at five different stages of ripening (Table 1). All physical parameters were studied for 65 fruits from each variety. The experiments were conducted at Biophysical and Biological laboratory of University of Tehran, Karaj, Iran.

Determination of physical and mechanical properties and TSS

Mass (M) of the melons was measured with a precision balance with a sensitivity of 1 g and actual volume was determined by the water displacement technique. The true density (ρ) is the ratio of mass of melon to its actual volume. Three cylindrical cores were cut near the equator from one half of each melon, where the flesh tends to have the largest thickness, using a cylindrical borer through the flesh along the radial direction. Each 14 mm diameter cylindrical core was then cut into 14 mm long samples. The modulus of elasticity (E) of melon was evaluated using 20 samples by Universal Testing Machine (Santam, SMT-5). The machine was equipped with a load cell of 150 N at a compressive rate of 25.4 mm/min

For assessment of the total soluble solids (TSS or the 'Brix' refractometric measurement) a core (22 mm diameter or greater) was sampled from a randomly selected equatorial position on the fruit, and the rind and green inedible tissue (5 mm thickness) and placenta and seed were removed. All remaining edible mesocarp tissue was juiced.

Panel selection and training

The eating experience of a piece of fruit reflects physical characters such as texture, and chemical characters such as sweetness, acidity, and volatiles composition. Sensory analysis was performed for each harvest by 30-35 untrained assessors that are familiar with the product in question. The testers for the sensory evaluation were graduate students of the faculty of agricultural engineering and technology, university of Tehran, Iran. The flesh of fruit was cut into about 2x2 cm pieces and then samples were coded with 3-digit random numbers.

Presentation of samples was randomized among the panelists and sessions, and they were presented one at a time under moderate incandescent lighting. Assessors were instructed to clean their palates with a sip of room temperature water and it was a small time lag before each sample. Taste analysis acceptability (consumer-oriented testing method) scored on a scale of 1-5 where: 1, very bad; 2, poor; 3, fair; 4, good and 5, excellent were used to assess five attributes: flavor, bitterness, sourness, firm texture and juiciness. Finally the assessors determined the general acceptability (GA) and later the average of it was calculated.

Experimental equipment

The laboratory recording system used to acquire the acoustic impulse information is comprised of a melon-bed, an impactor (pendulum), sensing device, a lap-top computer and software to control the experimental setup and to analyze its results. During the test, the fruit (melon) was placed on a soft foam support in order to create free support conditions and not to disturb the vibration pattern. The frequency of all individual fruit was measured on the three positions along the equator approximately 120° between them. The impact needs a sufficient stroke, mass, velocity and right angle. The combination of these causes problems to miniaturise the little impactor. The impactor consists of a steel ball of diameter of 26 mm and a 256 mm long copper rod. The weight of the impactor was 72 g; the impact angle was of 70°.

Chen (1993) postulates as impact requirements that the impact force is high enough to excite the expected frequency range. He also mentions that the force should be low enough not to damage the fruit. He suggests that the mass, the initial contact velocity, the curvature in the contact area, and the elastic modulus of the impact material should be controlled (Chen, 1993).

The acoustic signal was sensed by a sound level meter (SLM) type 2270 B&K that have a prepolarised free-field 1/2" microphone type 4189 B&K with flat frequency response in human threshold of hearing range (20 to 20000 Hz) and sensitivity 50 mVPa^{-1}. The sound level meter is a measuring instrument

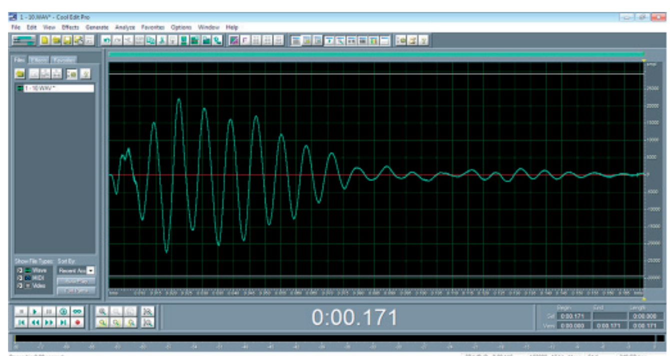

Figure 1. Waveform Display

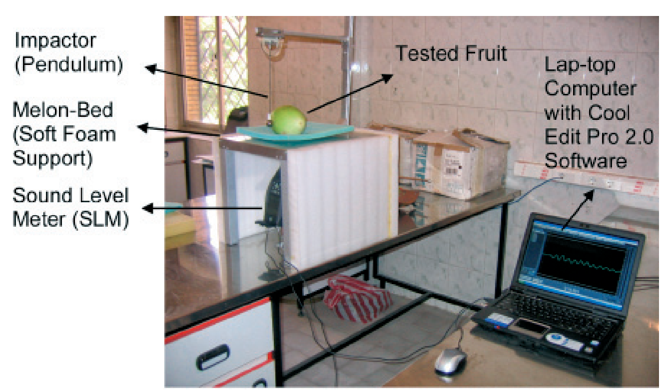

Figure 2. Setup of experiment for acoustic impact test

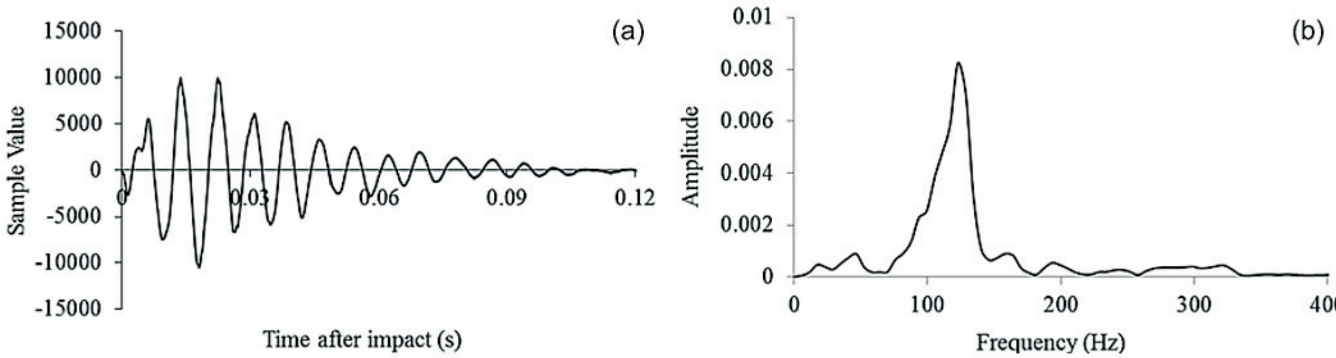

Figure 3. Typical acoustic signal of melon: (a) time domain, (b) frequency domain

used to measure sound pressure level. It was at a distance of 2-5 mm from the fruit surface when detecting the impulse acoustic response. User friendly Windows-based software, Cool Edit Pro 2.0 was used for the control of the process and the register of data, providing an easy output to be used with Microsoft Excel. The software shows the acoustic signal 'time versus sampling rate' for each test on the screen, and saves it in an ASCII file (Fig.1). Cool Edit Pro 2.0 is combination of digital recording and editing features. To start recording, we simply used /File/New to open a new file, then selected the sample rate, bit resolution, and number of channels (stereo or mono) that we wanted to use, pressed OK, and clicked on the Record button in the lower left area of the main window to begin. When we were done recording, we clicked on Stop and then saved our recording. We selected the sample rate 192000, resolution 16-bit, and channel mono. The Amplitude Ruler displayed the relative amplitude of a waveform over time. The ruler's display format can be set to either Samples (exact sample value of the data), a percentage (from -100% to 100%, where 100% is 0 dB) or as a normalized value (-1 to 1) in Waveform View. In Spectral View, the vertical ruler is always in frequency (Hz) format. The display format can easily be changed, using the left and right and dragging. Fig. 2 shows setup of experiment for acoustic impact test. The acoustic response of each melon was measured by hitting the fruit with an impactor and detecting the output sound by a sound level meter. The sound pressure level (SPL) was measured by sound level meter. A fast Fourier transform (FFT) of the signal was performed to determine the natural frequencies of the melons (Fig. 3). Analysis of variance (ANOVA) was applied to the data. Means corresponding to the different stages of evolution were compared using Duncan's multiple range tests ($p< 0.05$).

Results and discussion

During ripening, a fruit passes through a series of changes in color, texture and flavor indicating that compositional changes are taking place.

Table 2 shows changes in mass (M), true density (ρ), modulus of elasticity (E), total soluble solids (TSS), frequency (f) and sound pressure level (SPL) during the ripening of melon fruits. As it can be seen in table, melon mass, total soluble solid and sound pressure level increased during ripening period, while true density, modulus of elasticity and frequency decreased from immature fruits to over ripe fruits.

The Fig. 4 shows that the mass increased progressively in both varieties over the period of development and ripening as expected. However, the increasing rates were different during the harvesting stages in both varieties: faster rate in the initial stages and lower in the final stages. The mass of samples increased during the growing season rapidly; the mass of 'Zard-Eyvanekey' increased from 591.73 to 3913.15 grams (about 6.6 times) and the mass of 'Sousky-Sabz' from 569.52 to 3904.56 grams (about

Table 2. Changes of physical and mechanical properties and acoustic parameters of melon during harvesting (average values of 65 melons from each variety)

Variety	Maturity Stage	M (g)	ρ (kg/m^3)	E (MPa)	TSS (°Brix)	f (Hz)	SPL (dB)
Zard-Eyvanekey	First	591.8^e	901.84^a	0.466^a	4.93^d	132.25	49.21^c
	Second	1490.2^d	886.13^a	0.309^b	6.53^d	128.91	49.59^c
	Third	2978.8^c	863.16^b	0.211^c	9.43^c	119.14	54.19^b
	Fourth	3663.9^b	855.45^{bc}	0.199^{bc}	11.07^b	113.34	56.93^a
	Fifth	3913.1^a	842.33^c	0.149^d	13.03^a	111.33	57.74^a
Sousky-Sabz	First	569.5^e	908.11^a	0.417^a	4.83^d	128.91	49.66^d
	Second	1581.5^d	898.85^a	0.294^b	6.43^c	123.05	50.15^d
	Third	3016.6^c	878.34^a	0.226^{bc}	9.30^{bc}	119.14	53.23^c
	Fourth	3424.7^b	865.41^b	0.176^c	10.80^b	114.26	56.25^b
	Fifth	3904.6^a	860.03^{bc}	0.154^c	12.43^a	111.33	58.22^a

Means in the same column followed by different letters are significantly different according to Duncan's test ($p<0.05$).

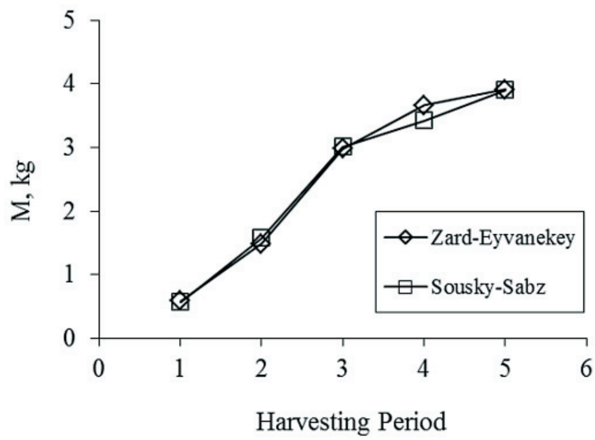

Figure 4. Mass changes during the fruit ripening of melon

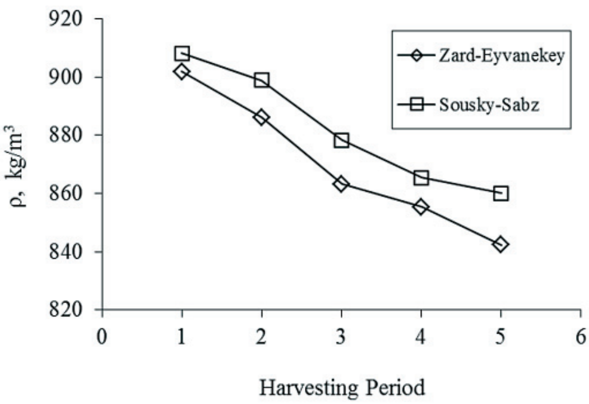

Figure 5. True density changes during the fruit ripening of melon

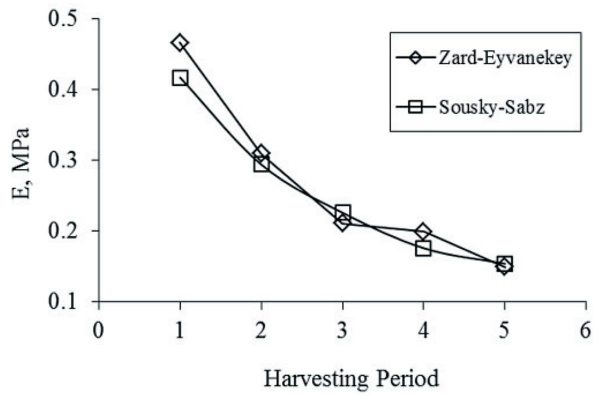

Figure 6. Modulus of elasticity changes during the fruit ripening of melon

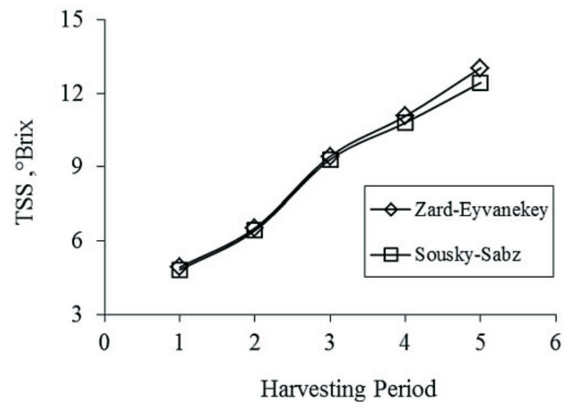

Figure 7. TSS changes during the fruit ripening of melon

6.8 times). The average of mass in the fourth harvest (ripened), 'Zard-Eyvanekey' and 'Sousky-Sabz' was estimated to be 3663.92 and 3424.70 grams, respectively. The 'Zard-Eyvanekey' mass was higher than the 'Sousky-Sabz' mass in full ripening, although the rate of increase of the mass was higher in 'Sousky-Sabz' variety.

The true density of two varieties had shown a decreasing trend. True density or 'Zard-Eyvanekey', was 901.84 kg m^{-3} in first stage and 842.33 kg m^{-3} in fifth stage (reduction 6.6%), whereas these values for 'Sousky-Sabz' were 908.11 kg m^{-3} and 860.03 kg m^{-3} (reduction 5.3%). The true density of (865.41 kg m^{-3}) was a little higher than of 'Zard-Eyvanekey' (855.45 kg m^{-3}) in full ripening (Fig. 5).

The elastic modulus values decreased in both varieties throughout ripening (Fig. 6). Its values fall from 0.466 to 0.149 MPa and from 0.417 to 0.154 in 'Zard-Eyvanekey' and 'Sousky-Sabz', respectively. Initial elastic modulus values of 'Zard-Eyvanekey' were higher than those of 'Sousky-Sabz'. This may be related to differences in physiological stage of ripeness, but also to the higher amount of cell wall polysaccharides in 'Zard-Eyvanekey' than in 'Sousky-Sabz' pulp. Both varieties have fruits with high elastic modulus at the first harvest date that shows compact and high density fruit. The rate of elastic modulus loss was also higher in 'Zard-Eyvanekey' than in 'Sousky-Sabz'. The elastic modulus of 'Zard-Eyvanekey' variety (0.199 MPa) estimated to be higher than in 'Sousky-Sabz' variety (0.176 MPa) in full ripening.

Melons are among the fruits with the highest sugar content. In melons, sweetness is the dominant consumer acceptance factor, and total soluble solids (TSS), as a measure of sweetness, is the most useful chemical measurement for assessing melon acceptability.

The total soluble solids (TSS) followed upward trends throughout ripening in both varieties as expected, though values were higher in 'Zard-Eyvanekey' variety than in 'Sousky-Sabz' variety. TSS of 'Zard-Eyvanekey' variety was initially at 4.93°Brix and reached a value of 13.03°Brix, these values were 4.83°Brix and 12.43°Brix in 'Sousky-Sabz' variety (Fig. 7).

The resonance frequency values of 'Zard-Eyvanekey' and 'Sousky-Sabz' varieties decreased during whole harvesting period from 132.25 to 111.33 Hz and from 128.91 to 111.33 Hz respectively. The average of resonance frequency in the fourth harvest (ripened) for 'Zard-Eyvanekey' and 'Sousky-Sabz' was estimated to be 113.34 and 114.26 Hz, respectively. Consequently, the resonance frequency of 'Zard-Eyvanekey' variety was a little

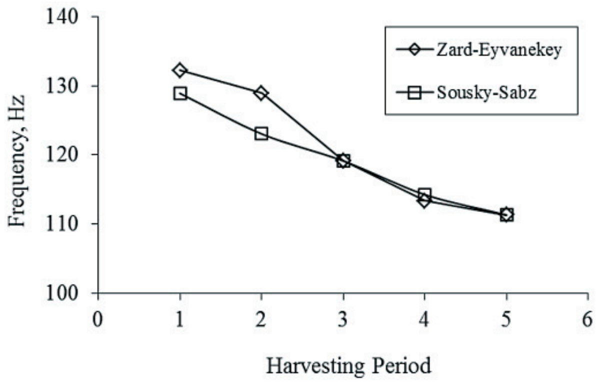

Figure 8. Frequency changes during the fruit ripening of melon

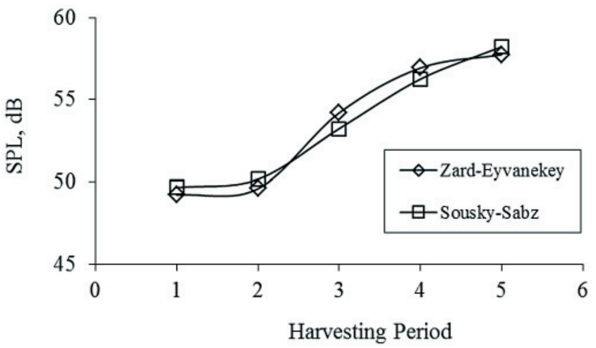

Figure 9. Sound Pressure Level (SPL) changes during the fruit ripening of melon

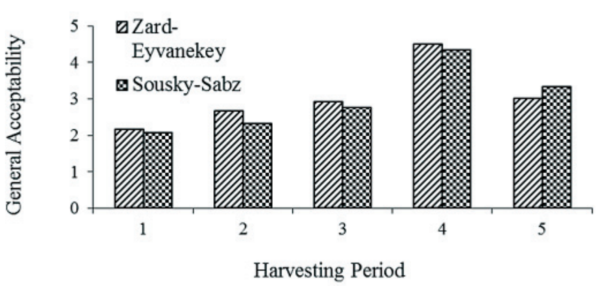

Figure 10. General acceptability changes in melon (average values)

lower than the resonance frequency of 'Sousky-Sabz' variety in full ripening (Fig. 8).

As mentioned, the resonance frequency decreased in both varieties during ripening. The other researchers kept samples in cold storage (optimum temperature and relative humidity) and found that resonance frequency decreases with fruit ripening. The samples have been provided with the uniform shape, size and color at the same time. The researches were done on specified samples under controlled conditions and generalization of the conclusions is difficult. In this work, the samples were prepared at several times and had non-monotonous shape, size and color. Furthermore, the control of many environmental and field factors is difficult and even impossible.

The response to vibrations in the fruits and vegetables depends on their elasticity modulus, mass and shape. This result means a diminution of 15.8% and 13.6% in the resonance frequency values respective to their initial values. This diminution is most likely caused by a different ripening rate of each variety, since it is assumed that the resonant frequency in fruits is changed mainly by ripeness. High frequencies were found from unripe fruit for both varieties. In general, it means that the more the fruit is ripened, the lower is its frequency. Chen (1993) found the measured frequencies to decrease with storage time and to be correlated with fruit firmness and sensory measurements.

As it can be seen in Fig. 9 the sound pressure level (SPL) varied and increased from 49.21 to 57.74 dB for 'Zard-Eyvanekey' variety and from 49.66 to 58.22 dB for 'Sousky-Sabz' variety during ripening of fruit. The average of sound pressure level in the fourth harvest (ripened) for 'Zard-Eyvanekey' and 'Sousky-Sabz' was estimated 56.93 and 56.25 dB, respectively. Consequently, the sound pressure level of 'Zard-Eyvanekey' variety was a little higher than the sound pressure level of 'Sousky-Sabz' variety. The variation in the distance between sound level meter (SLM) and melon surface affect the sound pressure level (SPL). This method is not very precise because of distance change (2–5 mm) of sound level meter from the melon surface. Therefore we found that it is not possible to measure ripeness accurately simply by determining the sound pressure level. Probably due to the increase of the mass of both varieties during the growing season, the sound pressure level of the process increased.

We concluded that the melon ripening is characterized by a progressive increase in the mass and TSS and a decrease in the resonance frequency and elastic modulus. The higher mass and TSS correspond to the sweeter melon and the higher resonance frequency and elastic modulus correspond to the firmer melon prior harvesting.

The sensory score for both varieties increased with the degree of ripeness to reach a maximum general acceptability at fourth stage, and thereafter decreased with further ripening. Consumers preferred the general acceptability of melon pieces from 'Zard-Eyvanekey' variety compared to 'Sousky-Sabz' variety (Fig. 10).

Due to the similar the taste and firmness of melon to cucumber at the first stage of harvesting (Mid-August, immature melon) to cucumber, the Garmsar farmers used the melons as a salad, and this would affect the assessors scoring. The assessors scoring were high in this stage. To solve this problem, we asked the assessors to compare the samples to ripe melon. The melons are not consumed at second stage of harvesting (Late-August, early ripening) because of rapid increase in the amount of TSS in respect to the first stage (The TSS of 'Zard-Eyvanekey' variety were 4.93° Brix and 6.53° Brix and in 'Sousky-Sabz' variety, these values were 4.83° Brix and 6.43° Brix) and water shortage. In the final stage of harvesting of both varieties assessors determined that although TSS increased, the firmness of tissue and consequently general acceptability decreased.

One of the main objectives in scientific research is the relationship between these phenomena. Correlation analysis was carried out to determine the strength of the relationship between each acoustic parameter with destructively measured ripeness indicators for both varieties (Table 3).

Table 3. Absolute value of correlation coefficients between acoustic parameters and other ripeness indicators of 'Sousky-Sabz' and 'Zard-Eyvanekey' melons

Variety		M	E	TSS	f	SPL	GA
Zard-Eyvanekey	M	1	0.929	0.965	0.986	0.957	0.522
	E		1	0.883	0.865	0.795	0.399
	TSS			1	0.978	0.961	0.400
	f				1	0.991	0.517
	SPL					1	0.508
	GA						1
Sousky-Sabz	M	1	0.969	0.977	0.961	0.890	0.632
	E		1	0.931	0.963	0.822	0.646
	TSS			1	0.979	0.963	0.642
	f				1	0.933	0.675
	SPL					1	0.678
	GA						1

M (Mass, kg), E (Elastic Modulus, MPa), TSS (Total Soluble Solids, °Brix), f (Resonance Frequency, Hz), SPL (Sound Pressure Level, dB) and GA (General Acceptability, without unit)

A very high correlation between resonance frequency and sound pressure level parameters and mass, total soluble solids (TSS) were obtained for both varieties.

The correlations between mass and TSS for both varieties are excellent, with a determination coefficient of 0.965 and 0.977 for 'Sousky-Sabz' and 'Zard-Eyvanekey', respectively, which means that more than 96% of the variation in mass is explained by TSS. Levels of correlation coefficient of 0.522 for 'Zard-Eyvanekey' variety and 0.632 for 'Sousky-Sabz' variety were found between the resonance frequency and general acceptability. The correlation coefficients were low because the resonance frequency had increase trend, while the general acceptability had increase trend until forth stage of ripening and then decreased.

Also, the elastic modulus and resonance frequency showed negative correlations with TSS, sound pressure level and general acceptability parameters in both varieties. The good correlation (R^2=0.865) was obtained for 'Zard-Eyvanekey' variety and excellent correlation (R^2=0.963) for 'Sousky-Sabz' variety between elastic modulus and resonance frequency. These findings can be explained by the high sensitivity of the acoustic method (resonance frequency) to elastic modulus of fruit.

Also, a strong correlation between resonance frequency and sound pressure level (R^2=0.991 for 'Zard-Eyvanekey' and R^2=0.933 for 'Sousky-Sabz') was observed. Statistical analysis of the data indicated high correlation between acoustic parameters and others ripeness indicators.

Our results showed that the value of resonance frequency is a useful indicator of maturity stage, as it decreases linearly throughout ripeness for both varieties.

The acoustic impulse response method is then an indirect way for non-destructive sensing of the melon ripeness. On the other hand, the data suggests that resonance frequency and elastic modulus can both be used to distinguish among fruits with diferent maturity and ripeness levels. During the all experiments no sign of bruising was observed on the melon's skin, confirming the nondestructiveness of this technique.

Conclusions

The major changes that occur during harvesting period of both varieties are reduction in true density and elastic modulus. The general acceptability of both melons determined by assessors and correlation coefficients between them are low because the resonance frequency had increase trend, while the general acceptability had increase trend until forth stage of ripening and then decreased. A very high correlations between resonance frequency and sound pressure level parameters and mass and total soluble solids (TSS) were obtained for both varieties. It is not possible to measure ripeness accurately simply by determining the sound pressure level (SPL). Experiments confirmed that non-destructive acoustic impulse response can be successfully used to distinguish different stage of ripeness.

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