Title: Nondestructive determination of the optimum eating ripeness of pears and their texture measurements using acoustical vibration techniques

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Abstract

We investigated the time-course changes in the elasticity index (EI) and the texture index (TI) of pears (*Pyrus communis* L.), namely, 'La France' during the postharvest period. EI was determined using a formula EI = $f_2^2 \cdot m^{2/3}$, where f_2 is the pear sample's second resonance frequency and *m* is the sample mass. A nondestructive vibrational method using a laser Doppler vibrometer (LDV) was used for measuring the pear samples' second resonance frequency (f_2). Changes in the EI of the pear samples showed bi-phasic decay. Along with sensory testing, we determined the period of optimum eating ripeness of the pear samples in terms of their EI to be $8.1\times10^4 – 1.5\times10^5$ kg$^{2/3}$ Hz^2. Pre-determined EI of pears enables consumers to predict the time range of optimum eating ripeness. An improved device for texture measurement was used for measuring time-course changes in the texture of pears. The texture was quantified with TI, which was determined for 18 frequency bands through integration of squared amplitudes of texture signals multiplied using a factor of a frequency band. The TI declined gradually over a wide frequency range as the pear samples ripened.

Keywords: Fruit ripening; Storage; Laser Doppler vibrometer; Piezoelectric sensor

1. Introduction

Pears continue to ripen after harvest. They must be stored for a particular period at a low temperature after harvest to be ripened to the desired texture; otherwise they fail to ripen properly (Chen and Borgic, 1985; Murayama et al., 1998). The quality for eating depends on the degree of ripeness. If the degree of ripeness could be determined nondestructively, it would be a useful indicator for distributors to determine when to ship the pears and for consumers to know the optimum timing for eating. The degree of ripeness of pears can be estimated from their firmness because pears lose firmness as they ripen (Terasaki et al., 2006).

Various techniques have been developed to evaluate the firmness of fruit nondestructively. One technique is measurement of the velocity of transmitting sound waves in fruit. Muramatsu et al. (1997a) showed that the velocity of sound waves decreases as kiwifruit ripen. Sugiyama et al. (1998) developed a portable firmness tester using the velocity of sound transmission in melons. This device was later improved for measuring pear firmness (Sugiyama, 2001). Another method is by measuring the mechanical resonance of a fruit sample (Abbott et al., 1968; Finney, 1971; Yamamoto et al., 1980, 1982; Abbott, 1994). Muramatsu et al. (1997b) showed that a method using a laser Doppler vibrometer (LDV) was advantageous for nondestructive measurement of fruit resonance. They determined the firmness using the formula EI = $f_2^{2} \cdot m^{2/3}$ (Cooke, 1972; Terasaki et al., 2001a), where f_2 is the second resonance of a fruit sample and m is the sample mass. The method using an LDV has been applied to monitoring the ripeness of kiwifruits (Terasaki et al., 2001b, 2001c) and pears (Terasaki et al., 2006).

Terasaki et al. (2006) measured the elasticity index of pears for different storage periods at low temperature (1 °C). However, the period of optimum eating ripeness of pears has not been determined clearly and nondestructively.

The first objective of the present study was to determine the period of optimum eating ripeness of pears nondestructively. Additional interest deal with was changes that occur in the texture of pears during the ripening stage. Food texture, such as crispness, is an important attribute of fresh produce. Consumers use such texture to evaluate the freshness of produce. For pears, texture is expected to change considerably as they ripen. Various methods have been used to measure physical properties of food such as texture. Measurement methods include both mechanical tests and sensory evaluation. Most acoustic studies of food texture measurement have involved the use of a method of recording the sound produced by mastication of food (Lee et al., 1990; Vickers, 1991; Dacremont, 1995). Early work on acoustic measurement of food texture was conducted by Drake (1963, 1965). He showed that crispier products generated louder sounds. A problem associated with this method is that intrinsic texture information can be lost because of the resonance of the palate or the mandible. Furthermore, the soft tissues in the mouth absorb or dampen higher-frequency sounds (Vickers, 1991). Vincent (1998, 2004) later introduced an engineering method to evaluate the texture of fruit and vegetables. Sakurai et al. (2005) developed a texture measurement device using a piezoelectric sensor. Later, Taniwaki et al. (2006b) improved the device and developed an octave multi-filter which enabled the calculation of the texture index of pears, apples and persimmons in the frequency domain. Mechanical and acoustic methods of measuring food texture have been well reviewed by Duizer (2001) and Roudaut et al. (2002). Sensory evaluation is another widely used method of evaluating food quality (Mehinagic et al., 2004). In this method, a panel evaluates food samples and grades them according to predetermined standards. Sensory evaluation results have been frequently correlated with those of instrumental methods (Harker et al., 2006).

The objectives of this paper were (i) to measure the changes in the elasticity index (EI) of pears in the postharvest ripening stage using a previously developed nondestructive method with an LDV, (ii) to determine the period of optimum eating ripeness of pears by using determined EI and sensory test, and (iii) to investigate the textural changes of pears during the ripening stage using an improved texture measurement device developed earlier by Taniwaki et al. (2006b).

2. Materials and Methods

2.1. Description of samples

Pear samples (*Pyrus communis* L.), namely ‘La France’, were used for our investigations. In all, 24 samples were harvested at a commercial orchard near Yamagata, Japan, on October 14, 2006 for use in our investigations. They were stored at 2 °C for 30 d, then at room temperature (ca. 20 °C, RH 50%) during measurements. Pears soften and reach a buttery and juicy texture after short-term storage at a low temperature (Murayama et al., 2002). The method of preparation of the samples for the texture measurement and for the sensory test is presented in Fig. 1. From each pear sample, a 20-mm thick slice was obtained along the equatorial plane. Half of the slice was used for texture measurement; the remainder was used for sensory test.

2.2. Sensory test

A sensory test was performed by panel of two experts. Each panelist graded the samples for hardness, crunchiness, thickness, sweetness, juiciness, acidity, and overall acceptability. The samples were rated using a scale of 1–5 (1, overripe; 3, ripe; and 5, immature). The samples were evaluated every two or three days for 16 d.

2.3. Elasticity index measurement

The elasticity index (EI) of each sample was determined nondestructively every two or three days immediately before the sensory test. The EI was determined according to the formula EI = $f_2^2 \cdot m^{2/3}$ (Cooke, 1972; Terasaki et al., 2001a) using the second resonance of the vibrational spectrum, i.e., f_2, and the mass of a sample m. The experimental setup, developed previously by Muramatsu et al. (1997b) to measure f_2 is presented in Fig. 2(a). A sample with a reflective film was set on an electrodynamic shaker (513-B; EMIC Corp., Tokyo, Japan); then the sample was excited for 10 s with swept sine wave signals (frequency, 0–2 kHz) that were generated using a PC. The vibrational response of the sample was sensed using a laser Doppler vibrometer (LDV, LV-1720; Ono Sokki Co. Ltd., Yokohama, Japan). The shaker vibration was monitored simultaneously with an acceleration pickup (NP-3211; Ono Sokki Co. Ltd., Yokohama, Japan). The signals from the LDV and the accelerometer were transmitted to the PC through a signal separator (D2VOX; IO DATA Device Inc., Kanazawa, Japan). A fast Fourier transform (FFT) algorithm (Spectra Pro; Sound Technology, Campbell, USA) was applied to the ratio of the response signals (X_{sample}) to the excitation signals (X_{input}) to obtain a vibrational spectrum of the sample. A typical vibrational spectrum of a pear sample is presented in Fig. 2(b).

2.4. Texture measurement

Figure 3(a) shows the experimental setup for measuring the texture of pear samples. Details of the texture measurement device have been reported by Taniwaki et al. (2006b). The device mimics the mastication process of human beings. Using a piezoelectric sensor (1 mm thickness, 10 mm diameter, 2Z10D-SYX; Fuji Ceramics Corp., Fuji, Japan), the device measures the acoustic vibrations generated during penetration of a probe into a sample. The detection range covers the entire audio frequency range (0–25600 Hz). The probe was a wedge that is 5 mm wide and 20 mm long with a tip angle of 30°. The probe was inserted into the mesocarp tissue of the samples. The probe penetration speed was 22 mm s^{-1}, which was inferred to lie within the speed range of typical human mastication (Roudaut et al., 2002). The data sampling rate was 80 kHz. A typical texture signal of a pear sample is presented in Fig. 3(b). Texture measurement was performed at nine points of the inner, middle, and outer parts of each sliced sample (Fig. 1) every two or three days along with the sensory test. The texture signals thus obtained were filtered using a half-octave multifilter (Taniwaki et al., 2006a, 2006b) for analyses in the frequency domain. We defined the texture index (TI) in terms of the "energy density" as

$$(f_l f_u) \cdot \frac{1}{n} \sum_{i=1}^{n} V_i^{\ 2},$$

where f_l represents the lowest and f_u the highest frequency of each frequency band determined using the half-octave multi-filter; in addition, V_i is the amplitude of the texture signal, and n is the number of data points (Taniwaki et al., 2008). This equation was applied to texture signal data of each frequency band.

3. Results

Figure 4 shows the time-course changes in the panel sensory test index of pear samples with respect to seven items (hardness, thickness, crunchiness, sweetness, juiciness, acidity, and overall acceptability). Hardness decreased linearly throughout the measurement period. Thickness and crunchiness decreased gradually until day 8 and stopped declining between day 8 and 13, then declined again thereafter. Sweetness, acidity, juiciness, and overall acceptability decreased gradually until day 8 and showed a temporary increase around day 12, then declined again thereafter. The optimum eating ripeness was determined to be day 6 from the overall acceptability index (= 3).

Figure 5 shows time-course changes in the averaged (a) and individual (b) EI of the pear samples. The overall decline pattern indicated quasi-exponential decay (r = 0.997). However, the results showed a bi-phasic decline pattern (until day 8 and thereafter).

Table 1 shows the coefficient of correlation between the sensory indices with respect to six items and EI. High correlations (significant at the 1 % level) were observed between the sensory indices and the EI. The results showed that the correlations were slightly higher for the physical attributes (hardness, crunchiness, thickness) than the chemical attributes (sweetness, acidity) and juiciness.

Figure 6 shows time-course changes in averaged TI at corresponding frequency band. The TIs between 100 and 1600 Hz were lower than those of other bands. The TI gradually decreased with time throughout the measurement period. The dominant decrease of the TI occurred during the first 6–8 d from 0 to 400 Hz, whereas TIs over 1600 Hz decreased between day 0 and day 4.

Figure 7 depicts the correlation between the sensory test indices (hardness, crunchiness, thickness) or EI, and TI. High correlations were observed throughout the audio-frequency band (0–17920 Hz) except for the highest frequency band.

4. Discussion

We used swept sine wave excitation for measuring the vibrational responses of the pear samples. The swept sine wave method is better for accurate determination of the resonance of the samples than the manual hitting method because the former enables the excitation energy to be concentrated within a small frequency band at a particular time. In contrast, using the latter method, the excitation energy is spread over frequencies of a wide range in a limited time period. Figure 5 depicts a bi-phasic decline pattern of EI. The time-course change in EI of individual samples more clearly showed the bi-phasic pattern. A similar pattern was observed for pears (Murayama et al., 2006) and kiwifruits (Terasaki et al., 2001b).

Table 1 shows that the EI was highly correlated with the sensory test indices. Therefore, the results are useful to determine the period of optimum eating ripeness. The nondestructively pre-determined period of optimum eating ripeness can be an excellent indicator of the quality for eating. Supposing that this period is defined in terms of the sensory test index of overall acceptability, which lies between 2.5 and 3.5, the corresponding EI can be derived as shown in Fig. 8. The EI for the period of optimum eating ripeness was calculated as 8.1×10^4 –1.5×10^5 $kg^{2/3}$ Hz^2.

The correlations between the sensory test indices and the EI (Table 1) showed that the mechanical attributes (hardness, crunchiness, thickness) were more highly correlated with the EI than chemical attributes (sweetness, juiciness, acidity). Therefore, the EI measured in the present study strongly reflected the mechanical property of pears. Sweetness and acidity are presumed to have no direct correlation with the elasticity index. However, high correlation between these indices indicated that sweetness and acidity increased along with the degree of firmness.

A significant decline in TI was observed for the first six to eight days in the frequency band up to 12 800 Hz, which corresponds to the first decline stage of EI presented in Fig. 5. High correlations were obtained in frequency bands up to 12 800 Hz (Fig. 7). “Crunchiness” showed higher correlation than “hardness” or EI with TI in the high-frequency region (2240–12800 Hz, $P < 0.001$). On the other hand, no significant difference was noted between crunchiness and hardness in the low frequency region (0–2240 Hz, $P = 0.052$). This suggests that the difference between the attributes “hardness” and “crunchiness” might be partly characterized by the frequency difference in the acoustic vibrations measured using our texture measurement device.

5. Conclusions

We used a previously developed nondestructive method using a vibrational technique and a texture measurement device that used an acoustic vibration method together with a sensory test to investigate the change in the physical properties of pears during the ripening stage. The results suggest that our EI method is useful for consumers and distributors to estimate the optimum eating ripeness of pears. Time-course changes in the texture of pears were measured. Our results suggest that the difference between the texture attributes is explainable in part by the frequency bands.

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Figure captions

Fig. 1: Preparation of the pear samples for sensory tests and texture measurements. Each sample was sliced along the equatorial plane. A half of the slice was used for the texture measurement; the remainder was used for the sensory test. The dots represent the points where the texture measurement device probe was inserted.

Fig. 2: (a) Experimental setup for the nondestructive measurement of the elasticity index of the pear samples. A sample was excited mechanically using a shaker that was driven by swept sine wave signals. The response at the opposite side of excitation was sensed using a laser Doppler vibrometer (LDV). (b) A typical response spectrum of a pear sample; f_2, the second resonance peak that was used for determining the elasticity index.

Fig. 3: (a) A schematic of the texture measurement device. A probe was inserted into a pear sample. Then the vibrations produced during penetration were sensed using a piezoelectric sensor. (b) A typical texture signal of a pear sample.

Fig. 4: Changes in the various items of the sensory test index of pear samples. Data show the averaged sensory test index evaluated by two panelists (Hanada and Tohro).

Fig. 5: Time-course changes in the (a) averaged elasticity index (EI) and (b) that of three individual samples determined by the method presented in Fig. 2. The bars represent the SE. The numbers along the curve represent the quantity of samples used for each measurement.

Fig. 6: The time-course changes in the averaged texture index (TI) of pears. The bars represent the SE (n = 27).

Fig. 7: The correlations between the texture index (TI) and the sensory test index or EI (n = 24, $P < 0.01$).

Fig. 8: The correlations between the sensory test index of overall acceptability and the elasticity index (EI) (n = 24, $P < 0.01$). Dotted lines are for determining the EI that corresponds to the period of optimum eating ripeness.

Figure-1

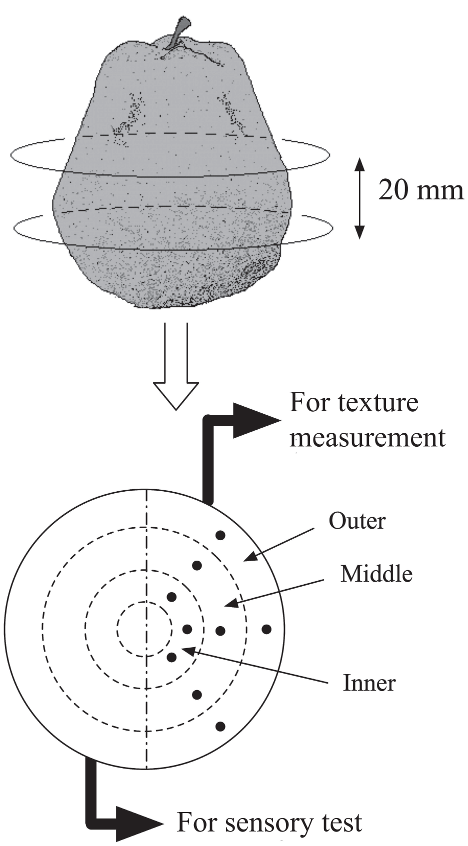
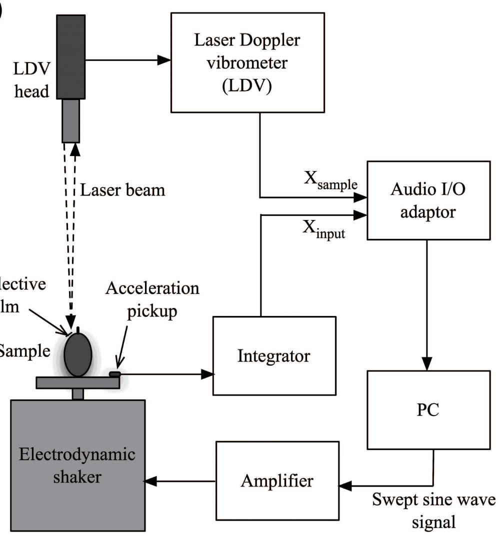

20 mm
For texture measurement
Outer
Middle
Inner
For sensory test

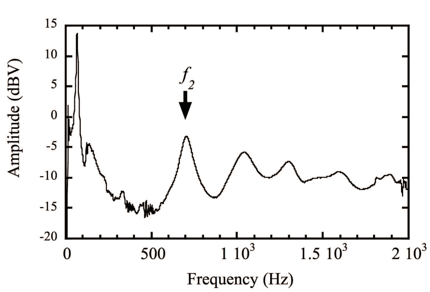
Figure-2

(a)



LDV head
Laser Doppler vibrometer (LDV)
Laser beam
X sample
X input
Audio I/O adaptor
Reflective film
Acceleration pickup
Sample
Integrator
PC
Electrodynamic shaker
Amplifier
Swept sine wave signal

(b)

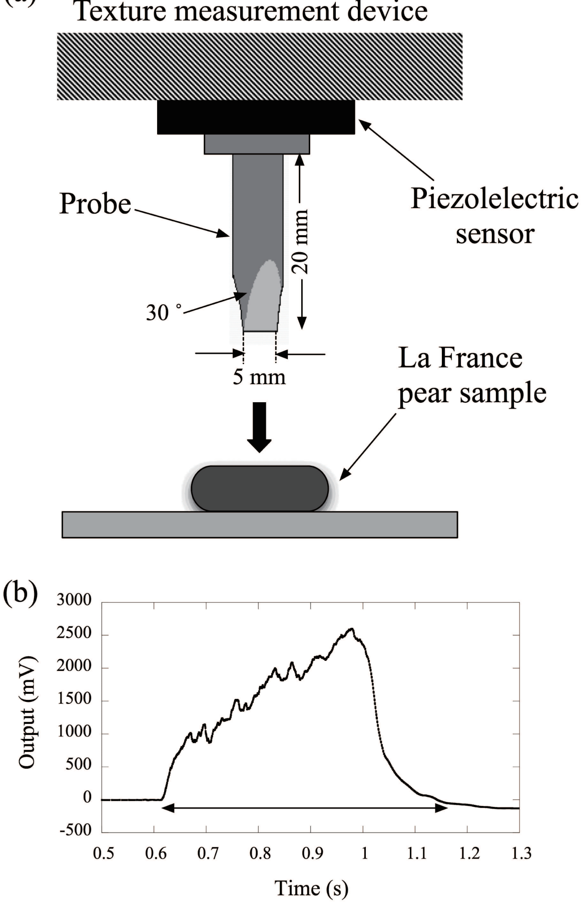


Amplitude (dBV)
Frequency (Hz)
f2
15
10
5
0
-5
-10
-15
-20
0
500
1 10^3
1.5 10^3
2 10^3

Figure-3

(a)

(b)



Texture measurement device
Probe
Piezolelectric sensor
20 mm
30 °
5 mm
La France pear sample
3000
2500
2000
1500
1000
500
0
-500
Output (mV)
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Time (s)

Figure-4

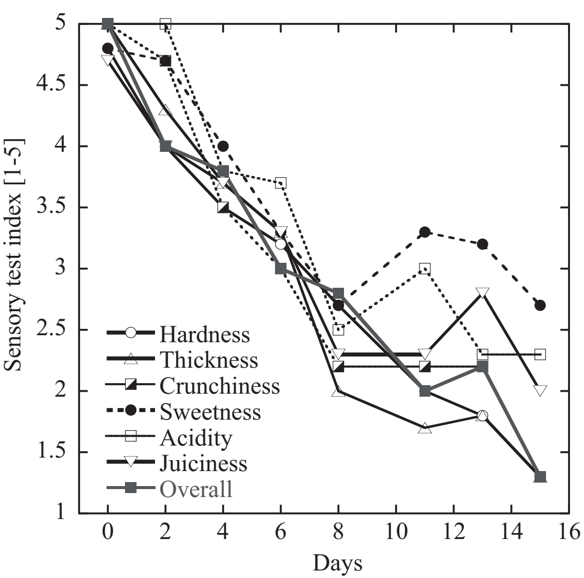
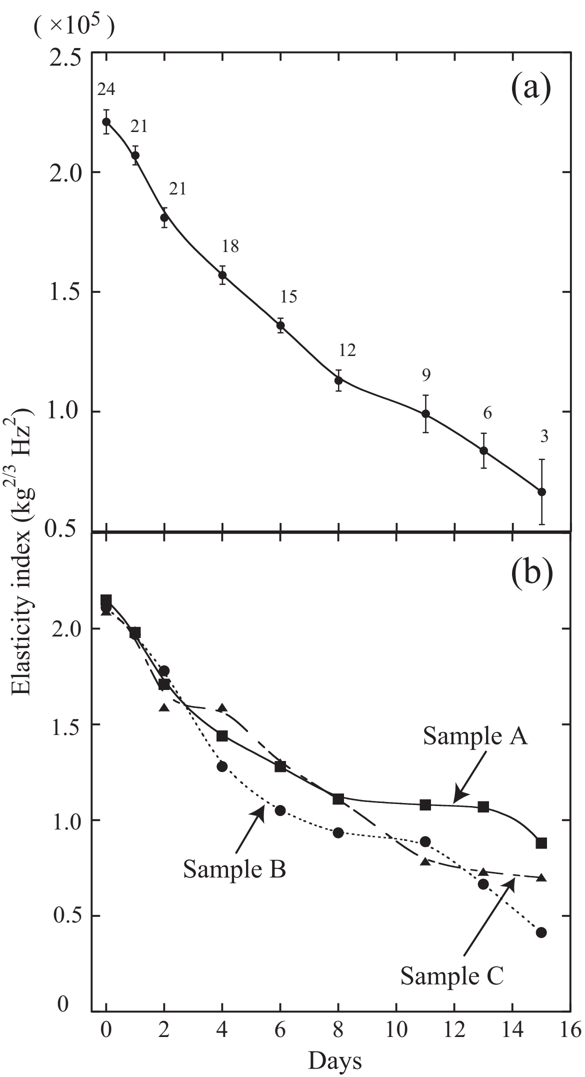
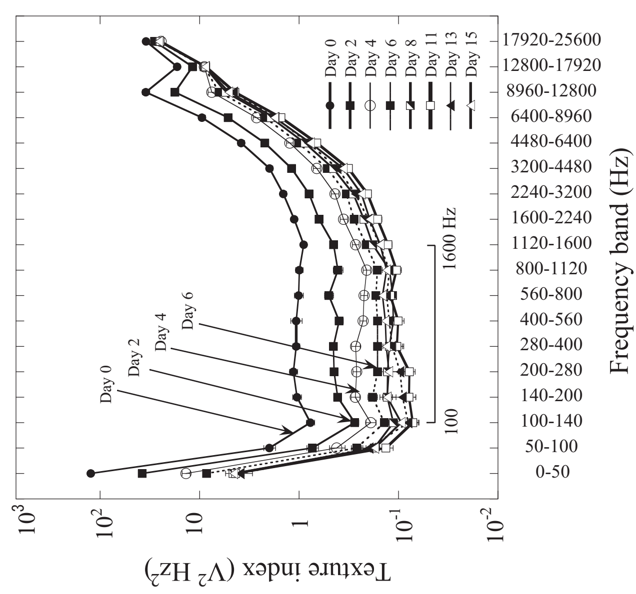

Sensory test index [1-5]
5
4.5
4
3.5
3
2.5
2
1.5
1
0
2
4
6
8
10
12
14
16
Days
Hardness
Thickness
Crunchiness
Sweetness
Acidity
Juiciness
Overall

Figure-5



(×10^5)
(a)
24
21
21
18
15
12
9
6
3
2.5
2.0
1.5
1.0
0.5
(b)
Sample A
Sample B
Sample C
2.0
1.5
1.0
0.5
0
0 2 4 6 8 10 12 14 16
Days
Elasticity index (kg^2/3 Hz^2)

Figure-6



Texture index (V² Hz²)
Frequency band (Hz)
0-50
50-100
100-140
140-200
200-280
280-400
400-560
560-800
800-1120
1120-1600
1600-2240
2240-3200
3200-4480
4480-6400
6400-8960
8960-12800
12800-17920
17920-25600
100
1600 Hz
Day 0
Day 2
Day 4
Day 6
Day 8
Day 11
Day 13
Day 15

Figure-7

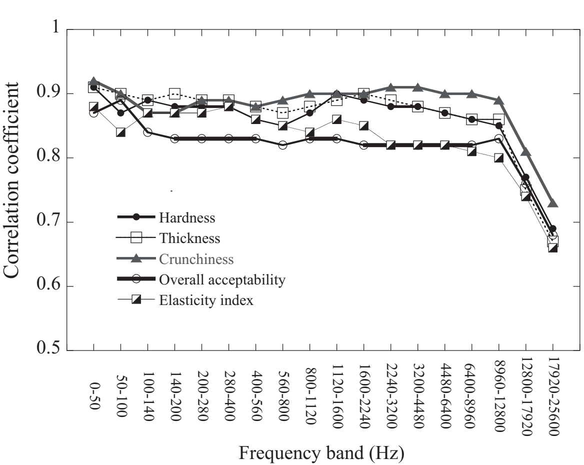

1
0.9
0.8
0.7
0.6
0.5
Correlation coefficient
Hardness
Thickness
Crunchiness
Overall acceptability
Elasticity index
0-50
50-100
100-140
140-200
200-280
280-400
400-560
560-800
800-1120
1120-1600
1600-2240
2240-3200
3200-4480
4480-6400
6400-8960
8960-12800
12800-17920
17920-25600
Frequency band (Hz)

Figure-8

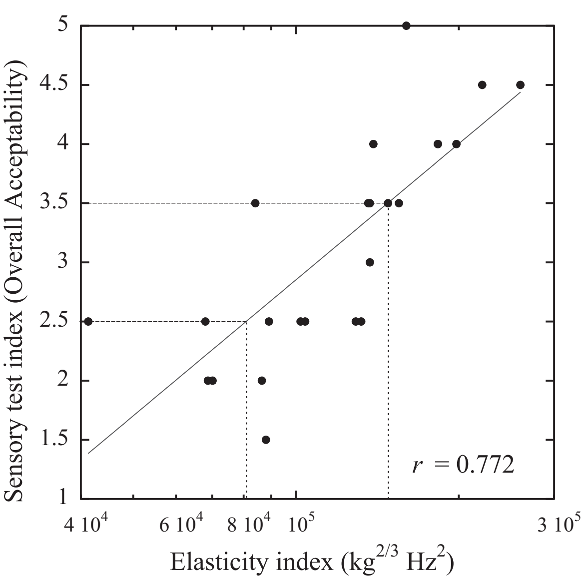

Sensory test index (Overall Acceptability)
5
4.5
4
3.5
3
2.5
2
1.5
1
r = 0.772
4 10^4
6 10^4
8 10^4
10^5
3 10^5
Elasticity index (kg^2/3 Hz^2)

Table-1

Table 1

The coefficient of correlation (*r*) between the sensory test index of various attributes and the elasticity index (EI).

Hardness	Crunchimess	Sweetness	Thickness	Juiciness	Acidity
0.874	0.836	0.861	0.767	0.772	0.793

$n = 24$, $P < 0.01$.