1 Firmness evaluation of watermelon flesh by using surface elastic waves

2 Takashi Ikeda^{a*}, Pak-Kon Choi^b, Toshio Ishii^a, Ikko Arai^a, and Masako Osawa^c

3
4 ^aSchool of Agriculture, Meiji University, Kawasaki, Kanagawa 214-8571, Japan

5 ^bSchool of Science and Technology, Department of Physics, Meiji University, Kawasaki,
6 Kanagawa 214-8571, Japan

7 ^cHagihara Farm Co., LTD., Tawaramoto, Shiki, Nara 636-0222, Japan

8
9
10
11
12
13
14
15
16 *Corresponding author: Tel +81 044 934 7171, fax +81 044 934 7902

17 E-mail address: agrisys@meiji.ac.jp

ABSTRACT

We measured the velocity of surface elastic waves on watermelon flesh for firmness evaluation. The Rayleigh waves at frequencies ranging from 800 to 2400 Hz propagate on the flesh and are detected by a piezo-bimorph sensor in contact with the flesh. We determined the shear elasticity from the velocity for two types of Japanese watermelons, Maturibayashi777 and Wasenishsho, to be 1.18 and 0.74 MPa, respectively. These correlated well with a sensory firmness evaluation. The values of Young modulus obtained by the surface-wave measurements were nine times larger than those by the compression tests performed, which can be explained by the differences in measurement displacement and frequency. We also investigated the effect of storage on the surface-wave velocity for Maturibayashi777. The velocity decreased by about 10 % after ten days of storage. The present results suggest that this technique can be applied to estimating the elastic properties of various fruits.

Key words: Firmness, Poisson ratio, Rayleigh waves, Shear elasticity, Watermelon, Young's modulus

1. Introduction

There is an increasing need for better quality monitoring of watermelon. The major quality indices of watermelon are maturity, internal defects, and firmness/crispness. Various methods such as acoustic, electrical, magnetic, and X-ray techniques and near-infrared spectroscopy have been used to monitor these quality indices (Sun et al., 2010). In particular, the acoustic technique has been widely used. In the acoustic impulse response method for studying the natural frequency of watermelon with a pendulum hitting device, the sensory firmness or maturity is correlated with characteristic parameters composed of the resonant frequency of the detected sound waveform, and the mass and density of the watermelon sample (Clark, 1975; Yamamoto et al., 1981; Stone, et al., 1994; Wang et al., 1999). Sugiyama et al. (1994) found that the velocity of an acoustic impulse decreased as melons ripened. A portable firmness tester, incorporating an impact plunger and two microphones, was also developed to measure the velocity, which correlates well with the apparent elasticity (Sugiyama et al., 1998).

Internal defects (voids or hollows) of watermelon can be investigated by the acoustic impulse response method. Diezma-Iglesias et al. (2004) showed that the low-frequency spectral-band (85–160 Hz) parameter was the best indicator of internal defects, which was confirmed by vibrational analysis using finite element simulation (Diezma-Iglesias et al., 2005). It has been pointed out, however, that the acoustic impulse signal is sensitive to the angle and location of the impact on the fruit surface. Furthermore, the elasticity modulus of external rind is larger than that of internal flesh by one order of magnitude (Sadrnia et al., 2008), which is a hindrance to determining the mechanical properties of the flesh.

Ultrasonic techniques have also been applied to the monitoring of quality indices of fruits and vegetables during various pre- and postharvest processes (Mizrach, 2008). Mizrach et al. (2000) developed a continuous-touch system for non-destructive evaluation of tissue characterization and quality indices of various fruits during the

course of maturation, storage, and shelf life. In the through-transmission mode, the system consists of two ultrasonic transducers that are mounted in a structure that maintains a constant angle of 120° between the transducers' tips while in contact with a sample surface. The attenuation of ultrasonic waves with frequency of 50 kHz was found to change dramatically during storage, shelf-life, postharvest softening, and ripening of avocado, mango, and apple, whereas the change in ultrasonic velocity did not correlate with the physiochemical changes of the fruits (Mizrach et al., 1997, 1999; Kim et al., 2009).

We present here a new acoustic technique for the evaluation of the texture firmness of watermelon flesh. The technique was first developed by one of the authors for the estimation of elasticity in gelatin gels (Choi et al. 1999). Surface elastic waves at fixed frequencies ranging from 800 to 2400 Hz propagate on watermelon flesh. Detecting the propagation times of the surface waves at different positions gives the velocity, which, along with knowledge of the Poisson ratio, yields the shear elasticity of the flesh. Although the shear elasticity does not directly correspond to the sensory firmness, it provides a good representation of the firmness. Previous acoustic and ultrasonic techniques have not yielded the shear elasticity of fruits. In this paper, we examine two kinds of Japanese watermelons, namely Maturibayashi777 and Wasenissho varieties, which in sensory tests have relatively hard and soft flesh, respectively. The Maturibayashi777 variety has a crisper texture compared with Wasenissho. Compression tests were also made to obtain the Young's moduli and Poisson ratios for the two varieties, and these results were compared with those determined by surface wave measurements.

2. Material and methods

2.1. Material

Two Japanese watermelon varieties, Maturibayashi777 and Wasenissho, were

supplied by Hagihara Farm Co., Ltd. (Nara, Japan). The surface wave measurements were carried out within five days after harvesting. Each watermelon sample was cut in half along its stem axis just before the measurement. All measurements were performed over four summer seasons from 2008 to 2012.

2.2. Surface elastic waves

Surface wave propagation in soft materials was theoretically considered by Onodera and Choi (1998), who showed that surface elastic waves (Rayleigh waves) could propagate on materials with small shear elasticity and surface tension. The velocity V of the surface elastic waves is given by

$$V = \frac{0.87 + 1.12\sigma}{1 + \sigma} \sqrt{\frac{G}{\rho}}, \quad (1)$$

where G is the shear elasticity (rigidity), σ is the Poisson ratio, and ρ is the density. The theory was experimentally confirmed by Choi et al. (1999) in agarose gels. We can obtain the shear elasticity of watermelon flesh from the surface-wave velocity with knowledge of the Poisson ratio and the density by using eq. (1).

Figure 1 shows the experimental system we used for measuring surface waves in watermelon flesh. The surface elastic waves were excited by an oscillator (a metal bar with a length of 25 mm and diameter of 4 mm) connected to a shaker (Mini Shaker 4810, Bruel & Kjaer, Naerum, Denmark). The edge of the oscillator gently touched the cut surface of the watermelon flesh. A pulsed-wave signal with a duration of 20 cycles at 800–2400 Hz was applied to the oscillator by using a function generator (WF1944A, NF Corporation, Tokyo, Japan) and a power amplifier (PM4400, Marantz, Tokyo, Japan). We detected the pulsed waves using a piezo bimorph sensor (Fuji Ceramics, Shizuoka, Japan) with a size of $10 \times 10 \times 1$ mm³. The signal was amplified and filtered with a preamplifier equipped with a band-pass filter (SR560, Stanford Research Systems, CA, USA), and was displayed on an oscilloscope (54616B, Hewlett Packard, CA, USA). At

the beginning of the measurements, the distance between the oscillator and the bimorph sensor was set at approximately 5 mm. Signals were recorded with 2 mm increment of propagation distance by moving the sliding stage supporting the bimorph sensor. The time shifts of the detected peaks were plotted as a function of the propagation distance between the oscillator and the sensor, from which the surface wave velocities were obtained. The measured propagation distance was about 10 mm, and in this small region of the watermelon flesh we could determine the elastic properties. The accuracy of the velocity measurement is 4 %, but the positional variation of velocity in a piece of watermelon is much larger. The measurements (2.2.1, 2.2.3, 2.2.4) were made near the center of a half-cut flesh where seeds were scarce. The measurements of dependence on sample thickness (2.2.2) were made with cut-out samples.

2.2.1 Dependence of the surface-wave velocity on frequency

The frequency dependence of the surface-wave velocity was measured at 800, 1200, 1600, 2000, and 2400 Hz for the Maturibayashi777 variety. The data sizes were 20–25 from samples of five watermelons for each frequency.

2.2.2 Dependence of the surface-wave velocity on sample thickness

Rayleigh-wave propagation assumes that the medium is an infinite half-space; this assumption may not be valid if the sample thickness is small. We measured the dependence of the surface-wave velocity on the sample thickness for the Maturibayashi777 variety. The sizes of the flesh samples were almost 50 mm in width, 150 mm in length, and 5–90 mm in thickness. The flesh portions were taken from near the center of the fruit. The edge of the flesh sample was cut with a slope to prevent reflected waves. Wherever possible, seeds were not included in the samples to reduce their effect on the measurement.

2.2.3 Dependence of surface-wave velocity on watermelon variety.

To investigate the difference in firmness between the two varieties, the surface-wave velocity was measured at frequencies of 800 and 2000 Hz for eight Maturibayashi777 and four Wasenisho watermelons. The measurements were made near the center of the half-cut flesh where seeds were scarce. Four to ten data points were obtained for each watermelon, which were harvested during a different summer season from those used in the experiments of 2.2.1 and 2.2.2.

2.2.4 Effects of storage on the surface-wave velocity

We examined the effects of storage time on the surface-wave velocity for Maturibayashi777. The velocity was measured at frequencies of 800, 1200, 1600, 2000, and 2400 Hz two or three days after harvesting. The data size was 25 from five watermelons. The velocity was also measured 12 or 13 days after harvesting. In the latter case, the data size was 47 from ten watermelons. When stored, the samples were in a refrigerator at 5 °C.

2.3 Compression tests

We used compression tests to determine the Poisson ratio and Young's modulus of the two watermelon varieties. Figure 2 shows the experimental system for measuring the Poisson ratio. After cutting a cubic sample (approximately $25 \times 25 \times 25$ mm³) of flesh, we put it on the stepping-motor controlled three-dimensional sliding stage (Suruga Seiki, Shizuoka, Japan) with a resolution of 4μm. While compressing the sample in the vertical direction in steps of 0.25 mm, the change in horizontal length of the sample was measured by using a displacement sensor (Digimatic indicator 1D-C112XB, Mitsutoyo Co., Tokyo, Japan) with a resolution of 1 μm. One side of the sample was fixed, and the displacement of the other side was measured. The maximum compression length was 3

mm. The Poisson ratio σ of the sample was obtained from

$$\sigma = \frac{\Delta d / d}{\Delta l / l} \quad (2),$$

where d and l are the horizontal and vertical lengths of the watermelon sample, and Δd and Δl are the changes in d and l by compression, respectively. The data sizes were 21 for two Maturibayashi777 watermelons and 12 for one Wasenisho watermelon.

For measurement of the Young's modulus, a watermelon sample was placed on an electronic balance (the weight resolution is 0.1 g) that was fixed on the stage indicated in Fig. 2. Seven samples (25–35 mm in size) were cut from Maturibayashi777 and three from Wasenisho watermelons. The displacement sensor was removed for these measurements. Compression tests were carried out with a compression speed of 0.1 mm s⁻¹. The maximum displacement of the compression was about 1 mm, corresponding to a strain of about 3 %. The gravity weight indicated on the balance was recorded as a function of time, yielding a stress–strain curve. A maximum pressure corresponding to 0.6 kg was applied to the cubic sample. The Young's modulus E is directly obtained from the gradient of the stress–strain curve, which was revealed to be nearly a straight line. The shear elasticity G is related to the Young's modulus by the following relation:

$$G = \frac{E}{2(1 + \sigma)} \quad (3)$$

2.4 Sensory evaluation of the firmness.

A sensory evaluation of the firmness was conducted with a panel of 78 members ranging from 18 to 24 years of age to taste the flesh of the two watermelon varieties and describe their firmness. We cut the watermelon flesh radially into equal slices, and provided equal amounts of the flesh to each panel member. The panel members evaluated the flesh texture by using a five-point scale, with a larger number representing harder texture. To partially conceal the purpose of our study from the

panel members and avoid biasing their responses, we drew up a questionnaire that included four questions, three of which were in regard to insignificant items unrelated to our study.

3. Results

The dependence of the surface-wave velocity on frequency is shown in Fig. 3 for the Maturibayashi777 variety. The error bars represent the standard error in the mean (the standard deviation divided by the square root of the data size) for data sizes of 20–25 at each frequency. The velocities at frequencies of 800, 1200, 1600, 2000, and 2400 Hz were nearly constant, indicating that the velocity had no frequency dependence.

The dependence of the surface-wave velocity at 800 Hz on the sample thickness is shown in Fig. 4 for the Maturibayashi777 variety. The surface-wave velocity increases with increasing thickness up to around 30 or 40 mm, then the velocity remains nearly constant for thicknesses over 40 mm.

We measured the surface-wave velocity in the flesh of the two watermelon varieties. Figure 5 shows the variation of surface-wave velocity at frequencies of 800 Hz (Fig. 5a) and 2000 Hz (Fig. 5b), for eight Maturibayashi777 watermelons (a–h) and four Wasenishsho watermelons (A–D). The error bars represent the standard deviations for 4–10 measurement points. The data sizes were 56 for Maturibayashi777 and 24 for Wasenishsho. The averaged velocities and standard errors at 800 Hz were respectively 31.2 and 0.61 m s⁻¹ for Maturibayashi777, and 25.0 and 1.3 m s⁻¹ for Wasenishsho. At 2000 Hz, the average velocities and standard errors were respectively 29.9 and 0.74 m s⁻¹ for Maturibayashi777, and 25.8 and 0.93 m s⁻¹ for Wasenishsho. The average velocity for Maturibayashi777 is larger than that for Wasenishsho by 16 % at 800 Hz and 25 % at 2000 Hz.

We investigated the effect of storage on the surface-wave velocity for

Matsuribayashi777 watermelon at several frequencies ranging from 800 to 2400 Hz. Figure 6 shows the surface-wave velocity as a function of frequency for different storage times, i.e., 2 or 3 days after harvesting, denoted by the closed circles, and 12 or 13 days after harvesting, denoted by the open triangles. The error bars represent the standard errors. The results showed a decrease in the velocity by an average of 10.2 % after 10 days of storage.

Compression tests yielded values of the Poisson ratio σ and Young's modulus E_{comp} of the watermelon flesh. Table 1 summarizes the values of the density (Abbaszadeh et al., 2014; Foong and Lim, 2010), Poisson ratio, average surface-wave velocity, shear elasticity G calculated from the surface-wave velocity by using eq. (1), Young's modulus E_{surface} calculated from G by using eq. (3), and Young's modulus E_{comp} obtained from the compression tests. For Matsuribayashi777, the values of Young's modulus $E_{\text{surface}} = 2.60$ MPa and $E_{\text{comp}} = 0.29$ MPa differ by one order of magnitude; this is discussed below. The standard deviations of the Poisson ratio were 0.033 and 0.076 for Matsuribayashi777 and Wasenissho, respectively. The standard errors in the mean (S) of E_{surface} were 0.4 MPa for both varieties. Approximately 60% of the error source in E_{surface} is due to uncertainty of the Poisson ratio.

Figure 7 shows the results of the panel's sensory evaluation of the flesh texture firmness. The horizontal axis represents a five-point scale with rank 1 indicating the softest texture and rank 5 the hardest. Of the 78 panel members, 94 % ranked the texture of Matsuribayashi777 as 4 or 5, while only 10 % gave Wasenissho such high scores.

4. Discussion

We assumed that the surface waves propagating on a watermelon are purely elastic and are Rayleigh waves. Rayleigh waves propagate on an infinite half-space and are non-dispersive (Landau and Lifshitz, 1986). The frequency dependence of the

surface-wave velocity as shown in Fig. 3 indicates no dispersion of the surface elastic waves in the frequency range from 800 to 2400 Hz. This suggests that the assumption of Rayleigh wave propagation is valid in the present experiments.

If the sample thickness is not large enough to satisfy the condition of an infinite half-space, the surface-wave velocity does not follow eq. (1). The energy of surface elastic waves extends beneath the surface to a depth of about one wavelength. The wavelength of surface waves at 800 Hz on a watermelon is calculated from the velocity of 31 m s^{-1} to be 39 mm, which corresponds to the transition value of the thickness over which the velocity is nearly constant (Fig. 4). When the thickness is smaller than approximately 40 mm, a wave reflection occurs at the sample bottom, which disturbs Rayleigh-wave propagation. These are called Lamb waves, the velocity of which is frequency dependent and to which eq. (1) cannot be applied. The present results shown in Figs. 3 and 4 were obtained with half-cut watermelons, and the thickness at the measuring points was over 100 mm, assuring that Rayleigh waves propagated on the watermelon in the experiments described in 2.2.1 and 2.2.2.

Because the Rayleigh-wave velocity at higher frequency reflects elastic properties from shallower regions, the lack of frequency dependence (Fig. 3) demonstrates that the elastic properties are homogeneous in the region from the surface to a depth of at least 39 mm.

The difference in the surface-wave velocity between the two varieties is distinct, as shown in Figs. 5, although the variation of the velocity among different samples is not small. The surface-wave velocity is larger for Maturibayashi777 than for Wasenisho. The shear elasticity G is obtained from the surface-wave velocity and the density. The Young's modulus E_{surf} is then calculated from the values of G and the Poisson ratio obtained from the compression test. Miyazato et al. (1994) observed the Poisson ratio to be 0.4 for a whole watermelon, a value that is much larger than the present results of 0.10 for Maturibayashi777 and 0.15 for Wasenisho (Table 1). They used samples that

included green rind, whereas the present measurements targeted only flesh samples. This caused the large difference in the value of the Poisson ratio. Even if we assume the Poisson ratio to be 0.4 in calculating V , its value changes by only 15 %. Therefore, the resulting V is quite insensitive to the value of the Poisson ratio. Incidentally, from the average of measurements on four samples, we confirmed that the surface-wave velocity on the green rind of watermelon is 90 m s^{-1} at 800 Hz, a value that is three times larger than that on the flesh.

Sadrnia et al. (2008) reported the value of the Young's modulus of watermelon flesh from a compression test experiment. They obtained values of 0.40–0.54 MPa, depending on the variety. These values are in good agreement with the present values of E_{comp} in Table 1. The values of E_{surf} estimated from the surface-wave velocity are larger than those obtained from the compression test E_{comp} by a factor of nine for both varieties (Table 1). This discrepancy is explained by a difference in the measuring techniques as follows. The displacement amplitude of the surface elastic waves is on the order of 10 μm , which will likely not destroy the fiber structure of watermelon. However, the displacement of the compression test is a maximum of 1 mm, which may destroy the microscopic fiber structure. This is expected based on the outpouring of liquid from the flesh tissue during the compression test. The small value of the Poisson ratio that is observed might be the result of fiber destruction. At the microscopic level, plastic deformation occurs in the compression test. Thus, the surface-wave measurements may determine the Young's modulus in the elastic deformation range, whereas the compression test may measure the Young's modulus in the plastic deformation range. It is reasonable, therefore, that the former is larger than the latter. The ratio of the Young's moduli between the two varieties is nearly the same for both measuring methods, which supports our speculation. The Young's modulus for Maturibayashi is larger than that for Wasenisho by 50 % for the two measuring techniques.

Another difference in the Young's modulus obtained by using the two measuring

techniques is attributed to the fact that the surface-wave method is dynamical, whereas the compression test is quasi-static measurement. The frequency of the surface waves is 800–2400 Hz, which is higher by three orders of magnitude compared with the compression tests. It has been demonstrated that dynamic elasticity measurements give larger values of elastic modulus compared with quasi-static methods for apples (Finney, 1967) and watermelons (Shiga et al., 1978). This frequency dependence is caused by viscoelastic characteristics of fruit sample. Shiga et al. (1978) reported that the elastic modulus from dynamic measurements at 127 Hz was 2.4 times as large as that from quasi-static measurement.

The panel's sensory evaluation of the flesh texture firmness (Fig. 7) demonstrated that Maturibayashi777 had a harder texture than the Wase-nissho variety. Considering the results of the compression tests and the sensory evaluation, we can conclude that the surface-wave velocity is a good measure of the firmness of the watermelon flesh.

Firmness reflects the changes in tissue texture during the course of growth, maturation, and storage (Mizrach et al., 1994; Stone et al., 1994; Taniwaki et al., 2009). The present results in Fig. 6 indicate that the surface-wave velocity decreased by 10.2 % after ten days of storage. This corresponds to a decrease by 20 % in the Young's modulus. Mizrach (2000) used ultrasonic techniques at frequencies of 50 and 100 kHz to monitor the maturity of avocado and mango. Ultrasonic attenuation was influenced by the oil content at harvest and by the dry matter content at full ripening in the avocado fruits. Based on their observations in the course of storage, Mizrach (2000) stated that the ultrasonic attenuation method could be used as a non-destructive technique for firmness monitoring. Conversely, the ultrasonic velocity showed no relation to quality-related properties of the fruits.

We have made a preliminary ultrasonic measurement of watermelon flesh. An ultrasonic pulse excited at 100 kHz was not detected by a receiving transducer placed at the opposite face of a rectangular sample of flesh with a thickness of 50 mm. The

ultrasonic attenuation was so large in watermelon flesh that the ultrasonic measurement was impossible.

The frequencies of the surface elastic waves employed here are in the range of 800–2400 Hz, much lower than ultrasonic frequencies, at which surface-wave attenuation is lower. Surface-wave properties are dominated by shear elasticity, which is closely related to firmness. Thus, the technique of surface elastic waves can be used as a firmness monitoring tool in various fruits.

5. Conclusions

Surface elastic waves were applied to the evaluation of fruit firmness for the first time. The velocity of the surface elastic waves on watermelon flesh was measured for two watermelon varieties: Maturibayashi777 and Wasenisho. The velocity for Maturibayashi777 was found to be larger by 25 % than that for the Wasenisho variety, indicating that Maturibayashi777 has a harder texture. The results of compression tests and sensory evaluation of the firmness supported this conclusion. The present dynamical measurement, however, provided a larger value of Young modulus than that by the quasi-static compression tests. The surface-wave velocity for Maturibayashi777 showed a decrease of 10.2 % after ten days of storage. This technique may provide a novel firmness-monitoring tool for watermelon and fruits with a thin peel such as tomato and apple.

Acknowledgements

We thank Mr. Kouta Funayama and Ms. Miwa Kosuge for their technical assistance. This work was supported by a Research Project Grant from the Institute of Science and Technology, Meiji University, and was also supported by the Research for Promoting Technological Seeds program from the Japan Science and Technology Agency.

References

- Abbaszadeh, R., Rajabipour, A., Sadrnia, H., Mahjoob, M.J., Delshad, M., & Ahmadi, H., (2014), Application of modal analysis to the watermelon through finite element modeling for use in ripeness assessment. *J. Food Eng.* 127, 81-84.
- Choi, P.K., Jyounouchi, E., Yuuki, K., & Onodera, Y., (1999), Experimental observation of pseudocapillary and Rayleigh modes on soft gels. *J. Acoust. Soc. Am.* 106, 1591-1593.
- Clark, R.L., (1975), An investigation of the acoustic properties of watermelon as related to maturity. ASAE Meeting Paper 75. 6004.
- Diezma-Iglesias, B., Ruiz-Altisent, M., & Barreiro, P., (2004), Detection of internal quality in seedless watermelon by acoustic impulse response. *Biosys. Eng.* 88, 221-230.
- Diezma-Iglesias, B., Ruiz-Altisent, M., & Jancsok, P., (2005), Vibrational analysis of seedless watermelons: Use in the detection of internal hollows. *Span. J. Agri. Res.* 3, 52-60.
- Finney, E.F. Jr., (1967), Dynamic elastic properties of some fruits during growth and development. *J. Agric. Eng. Res.* 12, 249-256.
- Foong, S.K., & Lim, C.C., (2010), Can you tell the density of the watermelon from this photograph? *Physics Education* 45, 352-355.
- Kim, K., Lee, S., Kim, M., & Cho, B., (2009), Determination of apple firmness by nondestructive ultrasonic measurement. *Postharvest Biol. Technol.* 52, 44-48.
- Landau, L.D., & Lifshitz, E.M., (1986), *Theory of elasticity*. Butterworth-Heinemann, Oxford.
- Miyazato, M., Chen, J.Y., Ishiguro, E., & Nanba N., (1994), Studies on the nondestructive measurement of Poisson's ratio of watermelon (I) –Model development-. *Mem. Fac. Agr. Kagoshima Univ.* 30, 97-104.
- Mizrach, A., (2000), Determination of avocado and mango fruit properties by ultrasonic

383 technique, *Ultrasonics* 38, 717–722.

384 Mizrach, A., (2008), Ultrasonic technology for quality evaluation of fresh fruit and
 385 vegetables in pre- and postharvest processes. *Postharvest Biol. Technol.* 48,
 386 315–330.

387 Mizrach, A., Galili, N., Teitel, D. C., & Rosenhouse, G., (1994), Ultrasonic evaluation of
 388 some ripening parameters of autumn and winter-grown galia melons. *Sci. Hortic.* 56,
 389 291–297.

390 Mizrach, A., Flitsanov, U., & Fuchs, Y., (1997), An ultrasonic nondestructive method for
 391 measuring maturity of mango fruit. *Trans. ASAE.* 40, 1107–1111.

392 Mizrach, A., Flitsanov, U., El-Batsri, R., & Degani, C., (1999), Determination of avocado
 393 maturity by ultrasonic attenuation measurements. *Sci. Hortic.* 80, 173–180.

394 Mizrach, A., Flitsanov, U., Akerman, M., & Zauberman, G., (2000), Monitoring avocado
 395 softening in low-temperature storage using ultrasonic measurements. *Comput.*
 396 *Electron. Agric.* 26, 199-207.

397 Onodera, Y., & Choi, P.-K., (1998), Surface-wave modes on soft gels. *J. Acoust. Soc. Am.*
 398 104, 3358-3363.

399 Sadrnia, H., Rajabipour, A., Jafari, A., Javadi, A., Mostofi, Y., Kafashan, J., Dintwa, E.,
 400 & De Baerdemaeker, J., (2008), Internal bruising prediction in watermelon
 401 compression using nonlinear models. *J. Food Eng.* 86, 272-280.

402 Shiga, T., Hikida, Y., & Chuma, Y., (1978), Vibrational and impact response properties of
 403 agricultural products for non-destructive evaluation of internal quality (II)
 404 -Viscoelasticity of watermelons-, *J. Jpn. Soc. Agric. Machin.* 40, 375-380. (in
 405 Japanese)

406 Stone, M.L., Armstrong, P.R., Zhang, X., Brusewicz, G.H., & Chen, D.D., (1994),
 407 Watermelon maturity determination in the field using acoustic impulse impedance
 408 techniques. *Trans. ASAE.* 39, 2325-2330.

409 Sugiyama, J., Katsurai, T., Hong, J., Koyama, H., & Mikuriya, K., (1998), Melon

410 ripeness monitoring by a portable firmness tester. Trans. ASAE. 41, 121-127.

411 Sugiyama, J., Otobe, K., Hayashi, S., & Usui, S., (1994), Firmness measurement of
412 muskmelons by acoustic impulse transmission. Trans. ASAE. 37, 1235-1241.

413 Sun, I.T., Huang, K.H., Xu, H., & Ying, Y., (2010), Research advances in nondestructive
414 determination of internal quality in watermelon/melon. J. Food Eng. 100, 569-577.

415 Taniwaki, M., Hanada, T., Touro, M., & Sakurai, N., (2009), Non-destructive
416 determination of the optimum eating ripeness of pears and their texture
417 measurements using acoustical vibration techniques, Postharvest Biol. Technol. 51,
418 305-310.

419 Wang, S., Jiao, Q., & Ji, J., (1999), An impulse response method of nondestructive
420 inspection of the ripeness of watermelon. Trans. CSAE. 15, 241-245.

421 Yamamoto, H., Iwamoto, M., & Haginuma, S. (1981), Nondestructive acoustic impulse
422 response method for measuring internal quality of apples and watermelons. J.
423 Japan. Soc. Hort. Sci. 50, 247-261.

Table 1. Density, Poisson ratio, surface-wave velocity (V), shear elasticity (G), and Young's modulus (E_{surf}) and (E_{comp}) for the flesh of the Maturibayashi777 and Wasenissho watermelons.

Watermelon Variety	Density* ¹ (kg m ⁻³)	Poisson ratio	V * ⁴ (m s ⁻¹)	G * ⁵ (MPa)	E_{surf} (MPa)	E_{comp} (MPa)
Maturibayashi777	970	0.10* ²	31.2	1.18	2.60* ⁶	0.29* ⁸
Wasenissho	970	0.15* ³	25.0	0.74	1.71* ⁷	0.19* ⁹

*¹ obtained from Foong and Lim (2010)

*² S (standard error in the mean) =0.01, *³ S =0.02

*⁴ surface-wave velocity at 800 Hz

*⁵ calculated from the surface-wave velocity by using eq. (1)

*⁶ S =0.4, *⁷ S =0.4, *⁸ S =0.002, *⁹ S =0.014

Figure 1. An experimental system for measuring the surface-wave velocity on watermelon flesh.

Figure 2. The experimental compression test system used for measuring the Poisson ratio and Young's modulus. For the measurement of the Young's modulus, the sample is placed on an electronic balance, and the displacement sensor is removed.

Figure 3. The frequency dependence of the velocity of surface elastic waves on the central part of the flesh in half-cut Maturibayashi777 watermelons. Data for each frequency were collected for 5 fruits (each with 4–6 measurements). Error bars indicate the standard errors.

Figure 4. The thickness dependence of the surface-wave velocity for the watermelon flesh of Maturibayashi777. The frequency for this experiment was 800 Hz. Samples were taken from the central part of the fruits.

Figure 5. The surface-wave velocity at frequencies of (a) 800 Hz and (b) 2000 Hz for the Wasenisho and Maturibayashi777 watermelon varieties. Letters on the abscissa refer to the sample identifier (A–D for Wasenisho and a–h for Maturibayashi777). The error bars represent the standard deviations for 4–10 samples.

Figure 6. The surface-wave velocity for Maturibayashi777 watermelon flesh sample at 2 or 3 days after harvesting (solid line) and 12 or 13 days after harvesting (dashed line). The error bars indicate the standard errors.

461 Figure 7. The distribution of a five-point-scale sensory test of firmness for the two
462 watermelon varieties. Rank 1 indicates the softest texture, and rank 5 the hardest. The
463 panel was comprised of 78 individuals between 18 and 24 years of age.
464

Figure 1. An experimental system for measuring the surface-wave velocity on watermelon flesh.

Figure 2. The experimental compression test system used for measuring the Poisson ratio and Young's modulus. For the measurement of the Young's modulus, the sample is placed on an electronic balance, and the displacement sensor is removed.

Figure 3. The frequency dependence of the velocity of surface elastic waves on the central part of the flesh in half-cut Maturibayashi777 watermelons. Data for each frequency were collected for 5 fruits (each with 4–6 measurements). Error bars indicate the standard errors.

Figure 4. The thickness dependence of the surface-wave velocity for the watermelon flesh of Maturibayashi777. The frequency for this experiment was 800 Hz. Samples were taken from the central part of the fruits.

Figure 5. The surface-wave velocity at frequencies of (a) 800 Hz and (b) 2000 Hz for the Wassenissho and Maturibayashi777 watermelon varieties. Letters on the abscissa refer to the sample identifier (A–D for Wassenissho and a–h for Maturibayashi777). The error bars represent the standard deviations for 4–10 samples.

Figure 6. The surface-wave velocity for Maturibayashi777 watermelon flesh sample at 2 or 3 days after harvesting (solid line) and 12 or 13 days after harvesting (dashed line). The error bars indicate the standard errors.

Figure 7. The distribution of a five-point-scale sensory test of firmness for the two watermelon varieties. Rank 1 indicates the softest texture, and rank 5 the hardest. The panel was comprised of 78 individuals between 18 and 24 years of age.