Development of a New Acoustic System for Nondestructive Internal Quality Assessment of Fruits

Nhut-Thanh Tran[1(✉)], Cat-Tuong Nguyen[1], Huu-Phuoc Nguyen[1], Gia-Thuan Truong[1], Chanh-Nghiem Nguyen[1], and Masayuki Fukuzawa[2]

[1] Faculty of Automation Engineering, Can Tho University, Can Tho 94000, Vietnam
nhutthanh@ctu.edu.vn

[2] Graduate School of Science and Technology, Kyoto Institute of Technology, Kyoto 606-8585, Japan

Abstract. A new acoustic analysis system based on MEMS microphones has been developed for assessing the internal quality of fruits. Although acoustic analysis is one of the effective techniques for assessing the internal qualities such as firmness, maturity, hollowness and sweetness of fruits, it has not been widely applied for fruits quality assessment in practice because the conventional apparatus was complexed and bulky to suppress the effects of surrounding noise and to maintain a good frequency response of the system. This study aimed to achieve both noise suppression and good frequency response with a simple system structure using an ultra-low-cost MEMS microphone. By placing the MEMS microphone inside a specially-designed fruit holder and optimizing its arrangement with a tapping module, the effect of ambient noise was significantly suppressed compared with the MEMS microphone alone, realizing a drastic simplification of the system. The simple correlation analysis of watermelon sweetness and the received acoustic frequency revealed a high correlation coefficient of –0.82. This result not only demonstrates a high potential of the proposed system in non-destructive internal quality assessment of fruits, and also strongly suggests the possibility of further study on acoustic analysis based on machine-learning with large-scale data collected effectively by using the developed system.

Keywords: Acoustic Analysis System · Fruit Quality Assessment · MEMS Microphone · Watermelon Sweetness

1 Introduction

Watermelon is a popular edible fruit with high moisture content and vitamins. It is grown in many countries in the world, with more than 1,000 varieties. The quality of watermelon is assessed through several parameters. They are divided into two groups – external qualities such as size, shape, and skin defects, and internal qualities such as maturity, sweetness, nutrient, and hollowness [1]. The external quality parameters are exactly assessed by physical measurements or visual inspections. Although internal

N. Thai-Nghe et al. (Eds.): ISDS 2023, CCIS 1949, pp. 31–42, 2024.
https://doi.org/10.1007/978-981-99-7649-2_3

ones can be exactly evaluated by sampling and measuring destructively with specific devices, it is time-consuming and costly. Besides, an empirical method is also applied by thumbing or tapping on watermelons and listening to the reflected sound to predict the maturity or hollowness of watermelons. This empirical method is also applied to check the internal quality of other fruits such as durian, melon, coconut. However, this method is inaccurate and not suitable for applications of inline inspection.

Some non-destructive technologies for evaluating the internal quality of watermelons and other fruits have received considerable research attention in recent years, such as acoustic analysis, near-infrared (NIR) spectroscopy, machine vision, electronic nose, dielectric properties, nuclear magnetic resonance, and laser Doppler vibrometer [2, 3]. Among these technologies, acoustic analysis and NIR spectroscopy have received the most attention. Acoustic analysis is primarily used to evaluate some internal quality parameters of watermelon such as maturity, internal defects, firmness, while NIR spectroscopy is mainly used for assessing sweetness, maturity, and firmness [1]. Although NIR spectroscopy technology has been successfully applied to some thin-skin fruits, its application to watermelons and other thick-skin fruits is still limited due to light source penetration and overheating problems. Therefore, acoustic analysis technology is still more popular for evaluating the internal quality of thick-skin fruits because of cost-effectiveness and simple operation.

Various previous studies have successfully applied acoustic analysis technology for classifying the watermelon ripeness [4–7] and firmness [8]. This technology was also applied for evaluating the maturity or ripeness of durians [9, 10]. Khoshnam et al. implemented this acoustic technology to test the ripeness of the melon at different stages [11]. Although these studies have demonstrated the applicability of acoustic analysis in assessing the internal quality of watermelons and other fruits, the hardware design for the acoustic acquisition and insulator in these studies is not really suitable for practical applications. Therefore, it is necessary to renovate the hardware setup for practical application of inline inspection. In this study, a new acoustic analysis system based on a combination of an ultra-low-cost MEMS microphone and an optimal system arrangement is proposed for practical, high-reliability and cost-effective applications. Besides, the potential of the proposed system was demonstrated through the simple correlation analysis of watermelon sweetness and the received acoustic frequency.

2 Materials and Method

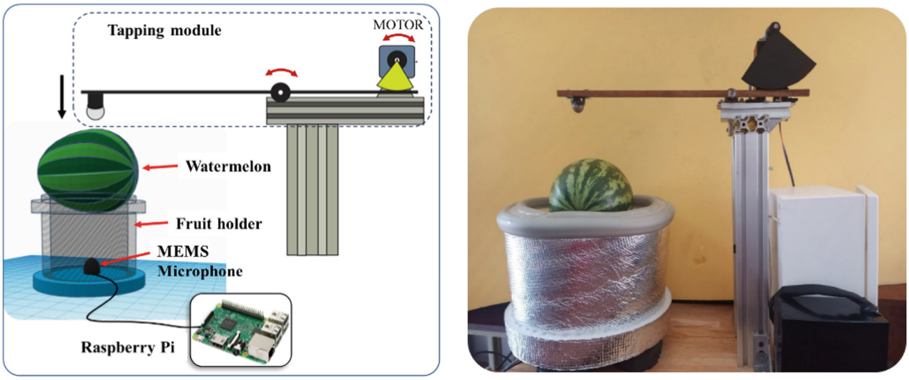
2.1 Proposed System

The proposed system was designed to include three main modules: a tapping module, a fruit holder with a MEMS microphone and acoustic insulators, and a sound recorder. The schematic diagram of the system and a picture of a prototype are shown in Fig. 1.

The tapping module aims to apply a constant impact force to a single point on the surface of a watermelon sample. It consisted of a wooden bar with a rubber ball (32 g) at one end, a motor with a disk cam on the shaft, and a support base. The constant impact force was produced by the free fall of the wooden bar lifted by the disk cam mechanism rotated by the motor.

The fruit holder is responsible both for holding the watermelon sample in the desired position and for preventing surrounding noises. It was made from a plastic bucket pasted with conventional plastic foam sheets as acoustic insulators on both sides of the bucket. A MEMS microphone was placed in an optimized position in the holder. One of the features of this system is to employ an ultra-low-cost MEMS microphone (Invensense INMP441) instead of expensive conventional microphones as in previous studies. Since this MEMS microphone integrated a signal conditioning circuit, a band-pass filter, and an analog-to-digital converter inside the package, it has clear advantages of giving a good performance of the analog system (i.e., 61 dB of SNR) and allowing the direct transfer of acoustic signal to the recorder as high-precision (24 bit) digital data. Some key features of this microphone are shown in Table1.

The sound recorder is a device to record the acoustic signal. In this study, it was constructed using a single board computer (Raspberry Pi) because it equips a I2S digital interface which is required to connect to the MEMS sensor directly. A recording application was used to record the acoustic signal, while a software for acoustic analysis was originally developed to be performed on the Raspberry Pi.



(a) (b)

Fig. 1. (a) Schematic diagram of the proposed acoustic analysis system and (b) a system prototype

Table 1. Key features of INMP441 MEMS Microphone

Feature	Description
Supply voltage	1.6–3.3 V
Frequency response	60 Hz to 15 kHz
Signal-to-noise ratio	61 dB (A-weighted)
Data Precision	24-bit
Current consumption	1.4 mA

2.2 Sample Preparation

A total of 18 watermelons (*Thanh Long F1 T522*) were harvested in Hau Giang province, Vietnam (Fig. 2). These fruits were 60 days after planting at harvest time. The average weight of these samples was around 3.0 kg. They were stored in a room with the temperature of 28 to 30 °C for 24 h before performing the experiments.

Fig. 2. Watermelon samples.

2.3 Acoustic Signal Acquisition and Analysis

In the experiment of acoustic signal acquisition, a watermelon was placed on the fruit holder with the horizontal stem–bloom orientation. Each watermelon was tapped six times at three positions around the middle area to get the acoustic signals of six watermelon samples. The recorded signals of the watermelon samples were converted to the frequency domain by the fast Fourier transformation algorithm. From the frequency-domain signal, a frequency with the largest amplitude of each watermelon sample, called f_{max}, was extracted.

2.4 Watermelon Sweetness Measurement

Figure 3 presents a procedure for measuring the sweetness of watermelon samples. After the acoustic signal acquisition process, the watermelons were cut into a slice with a thickness of 4 cm at the tapping region (at the middle of the watermelons). The watermelon samples were then peeled (about 1 cm) and squeezed to get the sample juice. Finally, the sweetness value of each sample was obtained by calculating the average of three measurement values of Brix with a pocket Brix-Acidity meter (model PAL-BX|ACID15 Master Kit, Atago Co., Ltd., Tokyo, Japan). This pocket meter has a sweetness measurement range from 0 to 90 ^{o}Bx with the resolution and accuracy of 0.1 and ± 0.2 ^{o}Bx respectively.

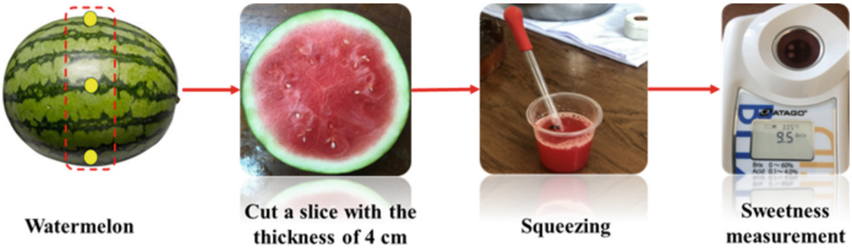


Fig. 3. The procedure for watermelon sweetness measurement

3 Results and Discussion

3.1 Functional Performance Testing

Performance of Acoustic Insulator

The performance of the acoustic insulator in the developed system was evaluated through two experiments (without and with insulator) under the common condition of surrounding noises. They include the wind noises of a ceiling fan and the sound of music being played at a high volume in a closed room. In the experiment without the insulator, the watermelon was placed on a table and next to the microphone, while the watermelon was placed on the designed fruit holder with the microphone inside in the experiment with the insulator. Figure 4 shows the recorded watermelon signals of the experiments without and with the insulator.

The result of the experiment without the insulator showed that the recorded signal exhibited the peaks at frequencies around 190, 245, 363, and 379 Hz, as shown in Fig. 4b. By using the designed fruit holder, most of the high-frequency peaks in the previous experiment were significantly suppressed. The recorded signal had only one dominant signal at a frequency of around 190 Hz (Fig. 4d). This frequency can be interpreted as the watermelon frequency when tapping and others can be done as noises. The experimental results of these two experiments demonstrated a good performance of acoustic insulation in the system using the designed fruit holder

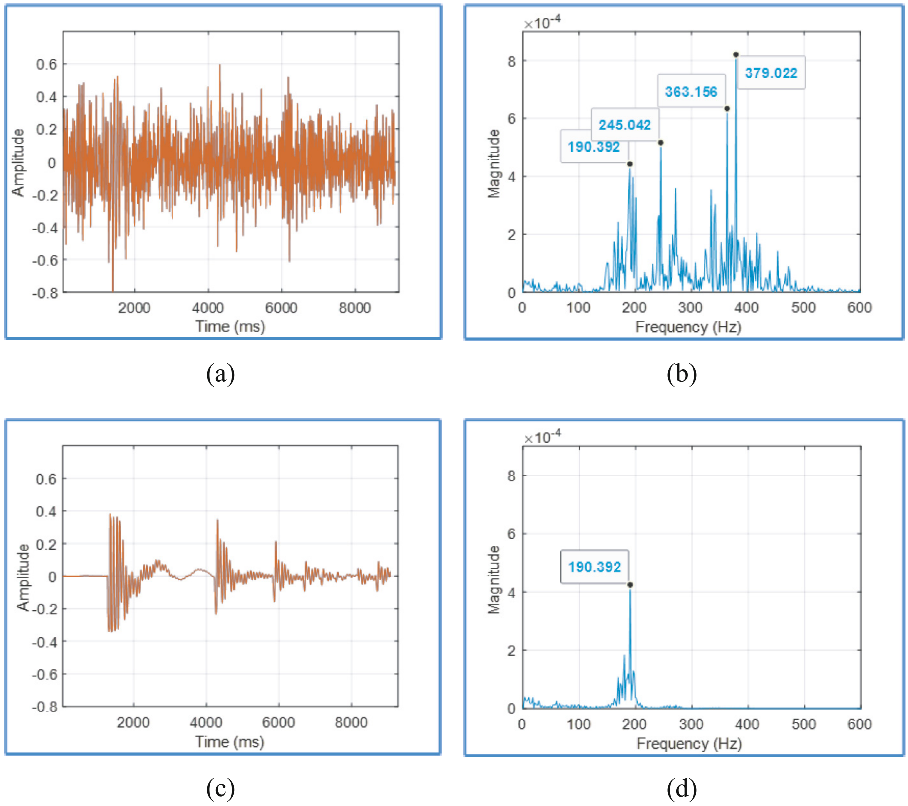


Fig. 4. Recorded watermelon signals in time and frequency domains (a) without and (b) with acoustic insulator.

Performance of INMP441 MEMS Microphone

To check the performance of the MEMS microphone, a conventional microphone (*Rode SmartLav Plus)* used in previous studies was used to compare the recording results. Figure 5 presents the acoustic signals of a watermelon in time and frequency domains, recorded with the two microphones. Although the recorded signal amplitude of the MEMS microphone was reduced by half compared to that of the conventional one (Figs. 5a and 5c), the f_{max} values were almost the same (Figs. 5b and 5d).

This result demonstrated that the MEMS microphone can completely be used to replace conventional microphones in assessing the internal quality of fruits based on acoustic analysis. The amplitude difference between the two microphones could be due to the position of the microphone installation and the tapping.

For evaluating the stability of the system, the acoustic signals of a watermelon sample were collected simultaneously by the MEMS and conventional microphones while this sample was tapped in 6 times at one position. The f_{max} values of these signals are shown in Table 2.

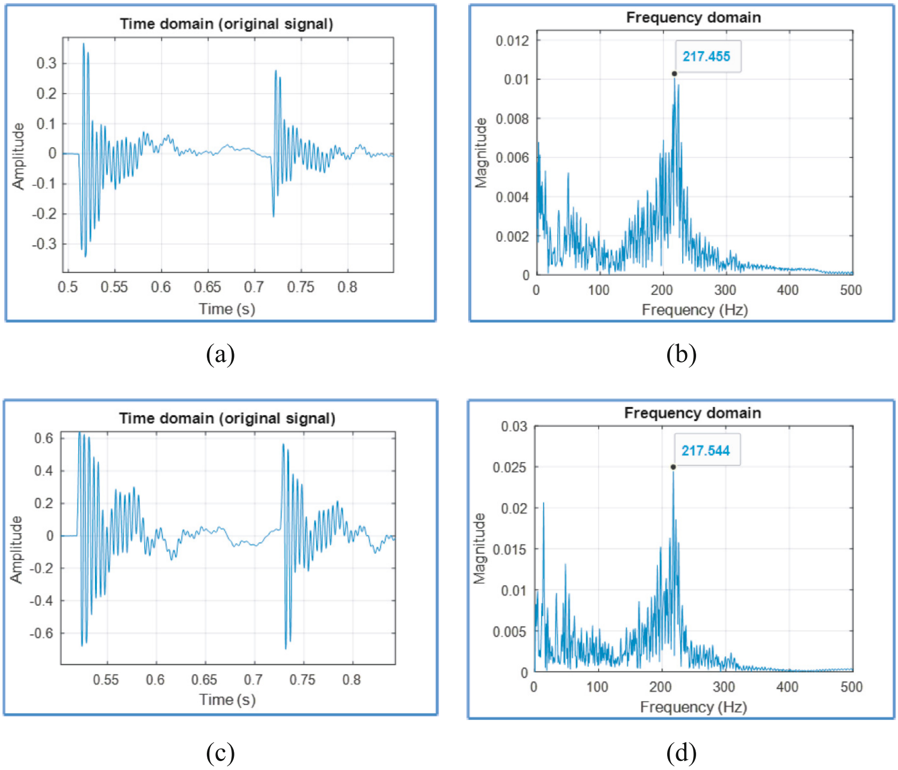


Fig. 5. Recorded acoustic signals in time and frequency domains of MEMS (a, b) and conventional (c, d) microphones.

Table 2. The f_{max} values of the sample tapped in six times at a one position

No	MEMS microphone (Hz)	Conventional microphone (Hz)	Difference (%)
1	220.7	217.2	1.59
2	216.8	217.9	0.51
3	220.2	217.9	1.04
4	217.4	217.5	0.05
5	217.3	217.9	0.28
6	219.7	220.1	0.18
Average	**218.68**	**218.08**	**0.61**

Table 2 shows that the recorded frequencies of the MEMS and conventional microphones in each tapping were almost the same because their differences were 1.59, 0.05, and 0.61% for the largest, smallest, and average ones, respectively.

The average f_{max} values of the two microphones in the six tapped times were 218.68 Hz and 218.08 Hz for MEMS microphone and conventional one. These results revealed that the operation of the MEMS microphone was appropriate and comparable to the conventional microphone and the functional performance of the acoustic system was reliable.

3.2 Application Performance Testing

Typical Acoustic Signal of Watermelon with Different Sweetness

To test the application potential of the developed system, the f_{max} values of the watermelon samples with different sweetness levels were analyzed. The f_{max} was obtained by using the developed system and their sweetness values were measured by the pocket meter. Figure 6 shows the recorded signals of three watermelon samples with the sweetness values of 7.63, 8.46, and 8.73 ^{o}Bx in time and frequency domains.

From Fig. 6, the f_{max} values of the watermelon samples with the sweetness values of 7.63, 8.46, and 8.73 ^{o}Bx were 227.3, 215.7, and 204.1 Hz, respectively. This result indicated that the watermelon sweetness value could be predicted based on its f_{max} value, and the higher the sweetness, the lower the frequency.

Simple Correlation Analysis

After eliminating a few outliers, seventy-one watermelon samples were used to examine the correlation between watermelon sweetness and its f_{max}. Statistical information about sweetness and f_{max} of these samples is presented in Table 3.

Table 3. Statistical information of 71 watermelon samples

Measure	Sweetness (^{o}Bx)	f_{max} (Hz)
Min	7.73	206.05
Max	9.13	261.72
Average	8.47	226.41
Standard deviation	0.36	13.45

The f_{max} values of the samples were from 206.05 to 226.41 Hz. The corresponding sweetness values of these samples ranged from 7.73 to 9.13 ^{o}Bx. There was an inverse correlation between the watermelon sweetness and its f_{max} value with a high correlation coefficient of −0.82, as shown in Fig. 7. This result was also consistent with the results of previous studies on predicting watermelon sweetness by f_{max} [2]. These results suggested that the proposed system had a great potential for predicting or classifying watermelon sweetness.

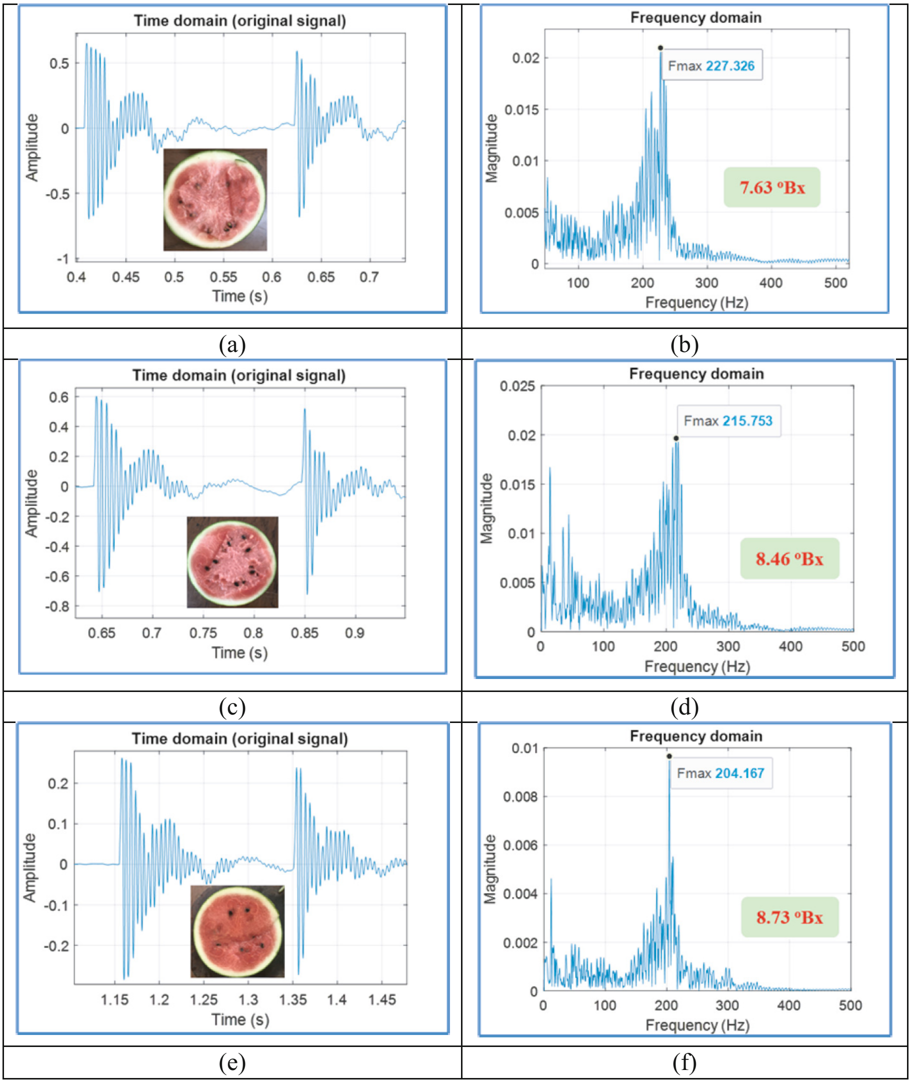


Fig. 6. Typical acoustic signals in time and frequency domains of watermelon samples with the sweetness values of 7.63 °Bx (a), 8.46 °Bx (b), and 8.73 °Bx (c).

3.3 Discussion

A cost-effective and high-performance acoustic analysis system was successfully developed. By placing the ultra-low-cost MEMS microphone inside the fruit holder made of common materials, the recorded acoustic signal was isolated from the noise of the environment. Moreover, with the optimized arrangement of the tapping module and the fruit holder, this developed system can be easily integrated into the conveyor system for automatic and inline assessment of fruit quality.

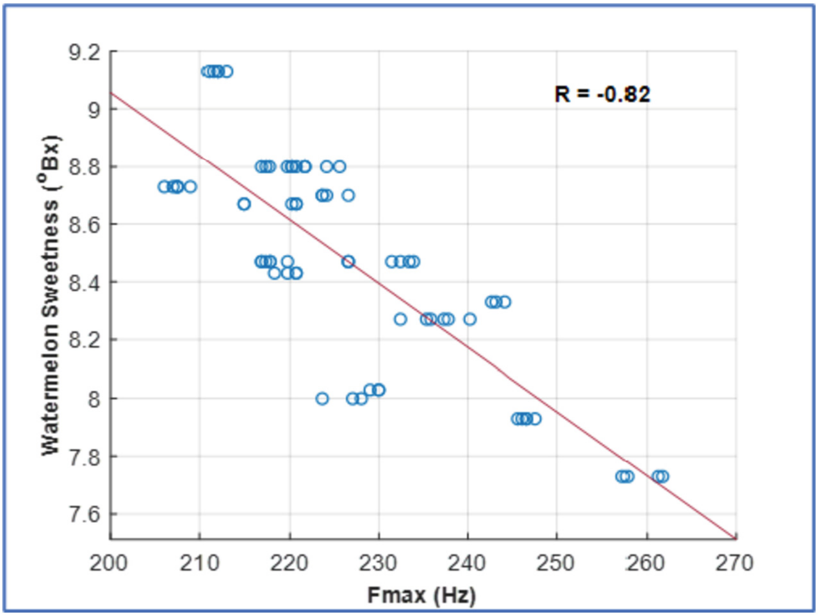


Fig. 7. Correlation analysis between f_{max} and watermelon sweetness

Besides, the limitations and further developments of this study are as follows:

- Need more samples with a wider sweetness range: In this study, watermelon samples were harvested at about 60 days after planting, so the sweetness range of these samples was not wide enough. In order to effectively apply the proposed system in practice, a larger number of watermelon samples should be collected and at different sweetness levels to increase the efficiency of watermelon prediction or classification based on its sweetness.
- Apply machine learning analysis: Instead of using conventional analytic solutions, machine learning algorithms need to be applied to improve the performance of prediction and classification models. With the proposed system, it will become simple to collect large-scale acoustic data from watermelons, which serves well for applying machine learning. Some recent studies have used machine learning algorithms for quality assessment of watermelons [6, 12, 13] and coconuts [14, 15].

4 Conclusion

In this study, a simple and low-cost acoustic analysis system based on an ultra-low-cost MEMS microphone and the special fruit holder for internal quality assessment of fruits was proposed and validated. By optimizing the arrangement of the system components, the received acoustic signal was not affected by the surrounding noise. The performance of the MEMS microphone was also comparable to that of the conventional microphone used in previous studies. A strong correlation result of watermelon sweetness and the received acoustic frequency not only demonstrated the feasibility of the proposed system for assessing the internal quality of fruits in practice, but also strongly suggested the possibility of further study on acoustic analysis based on machine-learning with large-scale data collected effectively by using the developed system.

Acknowledgments. This work was supported by JSPS Core-to-Core Program (grant number: JPJSCCB20230005).

References

1. Mohd Ali, M., Hashim, N., Bejo, S.K., Shamsudin, R.: Rapid and nondestructive techniques for internal and external quality evaluation of watermelons: a review. Sci. Hortic. (Amsterdam) **225**, 689–699 (2017). https://doi.org/10.1016/j.scienta.2017.08.012
2. Jie, D., Wei, X.: Review on the recent progress of non-destructive detection technology for internal quality of watermelon. Comput. Electron. Agric. **151**, 156–164 (2018). https://doi.org/10.1016/j.compag.2018.05.031
3. Abbaszadeh, R., Rajabipour, A., Delshad, M., Mahjub, M., Ahmadi, H., Laguë, C.: Application of vibration response for the nondestructive ripeness evaluation of watermelons. Aust. J. Crop. Sci. **5**, 920–925 (2011)
4. Chen, X., Yuan, P., Deng, X.: Watermelon ripeness detection by wavelet multiresolution decomposition of acoustic impulse response signals. Postharvest Biol. Technol. **142**, 135–141 (2018). https://doi.org/10.1016/j.postharvbio.2017.08.018
5. Baki, S.R., Yassin, I.M., Hasliza, A.H., Zabidi, A.: Non-destructive classification of watermelon ripeness using mel-frequency cepstrum coefficients and multilayer perceptrons. In: The 2010 International Joint Conference on Neural Networks (IJCNN), pp. 1–6. IEEE (2010)
6. Chawgien, K., Kiattisin, S.: Machine learning techniques for classifying the sweetness of watermelon using acoustic signal and image processing. Comput. Electron. Agric. **181**, 105938 (2021). https://doi.org/10.1016/j.compag.2020.105938
7. Zeng, W., Huang, X., Müller Arisona, S., McLoughlin, I.V.: Classifying watermelon ripeness by analysing acoustic signals using mobile devices. Pers. Ubiquitous Comput. **18**, 1753–1762 (2014). https://doi.org/10.1007/s00779-013-0706-7
8. Liza Pintor, A.C., Anthony Magpantay, M.A., Santiago, M.R.: Development of an android-based maturity detector mobile application for watermelons [Citrullus Lanatus (Thunb.) Matsum. & Nakai] using acoustic impulse response. Philipp. e-Journal Appl. Res. Dev. **6**, 44–56 (2016)
9. Phoophuangpairoj, R.: Durian ripeness striking sound recognition using N-gram models with N-best lists and majority voting. In: Boonkrong, S., Unger, H., Meesad, P. (eds.) Recent Advances in Information and Communication Technology. AISC, vol. 265, pp. 167–176. Springer, Cham (2014). https://doi.org/10.1007/978-3-319-06538-0_17
10. Terdwongworakul, A., Neamsorn, N.: Non-destructive maturity measurement of 'Montong' durian using stem strength and resonant frequency. Eng. Appl. Sci. Res. **33**(5), 555–563 (2013). https://ph01.tci-thaijo.org/index.php/easr/article/view/6017
11. Khoshnam, F., Namjoo, M., Golbakhshi, H.: Acoustic testing for melon fruit ripeness evaluation during different stages of ripening. Agric. Conspec. Sci. **80**(4), 197–204 (2015).https://hrcak.srce.hr/en/clanak/231272
12. Rajan, R., Reshma, R.S.: Non-destructive classification of watermelon ripeness using acoustic cues. In: Emerging Trends in Engineering, Science and Technology for Society, Energy and Environment, pp. 739–744. CRC Press (2018)

13. Choe, U., Kang, H., Ham, J., Ri, K., Choe, U.: Maturity assessment of watermelon by acoustic method. Sci. Hortic. (Amsterdam). **293**, 110735 (2022). https://doi.org/10.1016/j.scienta.2021.110735
14. Fadchar, N.A., Dela Cruz, J.C.: A non-destructive approach of young coconut maturity detection using acoustic vibration and neural network. In: 2020 16th IEEE International Colloquium on Signal Processing & Its Applications (CSPA), pp. 136–137. IEEE (2020). https://doi.org/10.1109/CSPA48992.2020.9068723
15. Caladcad, J.A., et al.: Determining Philippine coconut maturity level using machine learning algorithms based on acoustic signal. Comput. Electron. Agric. **172**, 105327 (2020). https://doi.org/10.1016/j.compag.2020.105327