



Application of Electrochemical Impedance Spectroscopy to Evaluate Ripeness and Storage-Induced Quality Changes in Nutmeg (*Myristica fragrans* Houtt)

Ronaldo Talapessy ^{a,*}, Gianita A. Salamena ^a, Pricillia J. Sabandar ^a, Tomoaki Ikegami ^b

^aDepartment of Physics, Faculty of Science and Technology, Pattimura University, Ambon, Indonesia

^bDepartment of Electronics and Information Technology, Kumamoto Prefectural College of Technology, Kumamoto, Japan

Abstract. *Nutmeg (*Myristica fragrans* Houtt) is an endemic fruit essential in the food industry; nevertheless, local farmers still rely on conventional methods to determine harvest time. The objectives of the research are to determine the freshness and ripening of nutmeg using the Electrochemical Impedance Spectroscopy (EIS) method. This study investigates the impedance of ripe and unripe nutmeg after five days of storage at 27°C and 4°C within a frequency range of 0–15 MHz. Ripe fruit has an impedance of 2-6 MΩ, lower than unripe fruit at 9-12 MΩ. The high and steady impedance at low frequencies indicated the low moisture content and preserved cellular integrity of the ripe fruit. In contrast, the impedance of unripe fruits decreases gradually, indicating greater permeability and tissue disintegration. Advanced tissue breakdown reduces impedance despite decreasing water content, and these electrical changes are associated with mass loss from respiration and dehydration. The weight of nutmeg remains stable at lower temperatures but decreases at room temperature. The findings demonstrate that EIS is a rapid and non-invasive technique for assessing nutmeg maturity and postharvest quality, supporting more accurate prediction and improved storage management.*

Keywords: *impedance; nutmeg; postharvest quality; fruit ripeness; non-destructive.*

Type of the Paper: Regular Article.



1. Introduction

Electrochemical impedance spectroscopy (EIS) is a non-destructive technique used to determine a material's properties. The observation of different material qualities, influenced by variables such as chemical composition, moisture content, and acidity (pH), and hydrogeology, is made possible by this technique [1–4]. Electrical impedance, a complicated quantity, represents a material's reactive and resistive characteristics when exposed to alternating current (AC). Important detailed information about a sample's resistive, magnetic, dielectric, and other physical properties can be obtained precisely and non-destructively using this method [5–8].

Applying an AC signal to a material at an appropriate frequency and observing the resulting voltage response is the basic principle of impedance measurement. The complex impedance can be determined by examining the voltage amplitude and phase. The non-invasive and non-destructive nature of this method, which maintains the sample's internal and external structure, is

one of its main advantages. Consequently, EIS is especially suitable for evaluating biological materials, such as food and fruits, where freshness is essential [9–14].

To create a spectrum representation that shows material behavior across a wide frequency range, EIS presents impedance data as a function of frequency. It has been widely used in food science and agriculture, especially to determine the ripeness and quality of crops. Previous research has shown that EIS is applied to various fruits and vegetables, including apples, lemons, citrus, papaya, and carrots [15–21]. To interpret the frequency-dependent electrical responses of biological tissues, the findings of EIS measurements are typically analyzed using equivalent circuit models or other mathematical techniques.

However, Nutmeg (*Myristica fragrans* Houtt), a fruit-bearing tree native to Indonesia's Maluku Islands and valued for its great economic significance, is the subject of analysis based on impedance and its components. Nutmeg is widely used in food products, cooking spices, and essential oil manufacturing. However, its quality and shelf life are greatly influenced by post-harvest factors, particularly fermentation and moisture content, which are not usually apparent through visual inspection. To support sorting procedures, monitor product quality, and prevent spoilage during storage and commercial distribution, impedance-based characterization methodologies must be developed.

It is expected that impedance measurement on nutmeg will yield more detailed information on the fruit's internal and external physiological state. Multi-frequency impedance measurements can be used to identify early indicators of deterioration caused by high humidity or microbial contamination and to differentiate the dielectric characteristics of various fruit components.

Nevertheless, the characterization of nutmeg's impedance creates new opportunities for food technology and precision agriculture. It provides a means to enhance post-harvest quality and advances scientific knowledge of the little-studied bioelectrical phenomena in tropical biological materials, as well as a real-time monitoring system for use during post-harvest handling and processing. Although recent studies have demonstrated the effectiveness of EIS for monitoring ripening and quality changes in other fruits, this technique has not been applied to nutmeg. Therefore, this study aims to measure the impedance of nutmeg fruit to determine its ripeness and freshness by observing the fruit's storage time after harvest. This study presents a preliminary investigation of impedance measurement of nutmeg during post-harvest storage, and its results can serve as a reference for further research in agricultural technology.

2. Materials and Methods

Nutmeg samples from nearby farms on Ambon Island were used in this investigation. Local farmers on Ambon Island, Indonesia, provided 20 nutmeg fruits, consisting of 10 ripe and 10 unripe samples (*Myristica fragrans* Houtt). Ripe and unripe nutmeg fruits were utilized as samples

and kept at room temperature (28°C) for five days. To determine changes in nutmeg quality, it was also stored for 10 days at room temperature and in a refrigerator set at 4°C.

The HIOKI 3532-80 LCR HiTester (Japan) was used to measure the impedance of nutmeg with two AgCl electrodes, each 3 mm in diameter, as shown in Fig. 1. Impedance spectra were recorded in the 150 Hz to 15 kHz frequency range after the electrodes were placed into the nutmeg samples, and an electric current of 1 mA with a potential difference of 3 V was applied. The impedance measurement data were obtained in real-time on a laptop [22].

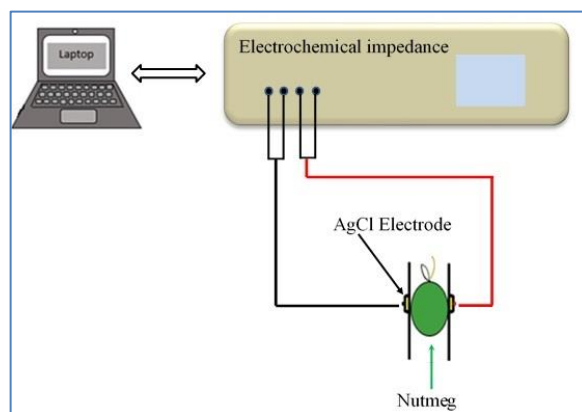


Fig. 1. Schematic of measurement

The magnitude of impedance represents the overall opposition of the sample to the applied alternating current (AC), which is calculated using Eq. (1). It combines both resistive (R) and reactive (X) components of the impedance and is expressed as:

$$|Z| = \sqrt{R^2 + X^2} \quad (1)$$

where R denotes the resistance in Ω and X represents the reactance in Ω .

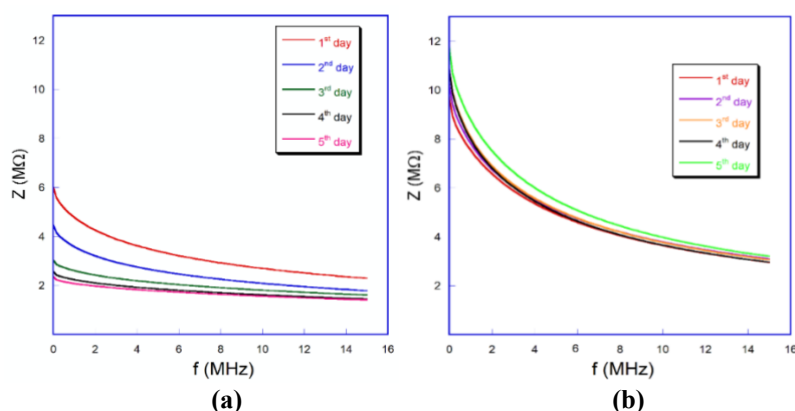


Fig. 2. Impedance of nutmeg stored for 5 days (a) ripe (b) unripe

3. Results and Discussion

Fig. 2 depicts the findings of impedance measurements conducted on ripe and unripe nutmeg fruits during a five-day observation period. The impedance of the samples at different maturity

levels and storage times is depicted by plotting the impedance magnitude (Z) versus frequency (f), which ranges from 0 to 15 MHz.

The initial impedance of ripe fruit on the first day was higher, reaching values between 11 and 12 M Ω at low frequencies, as shown in Fig. 2 (a). Meanwhile, the impedance of unripe fruit was lower, less than 6 M Ω , as shown in Fig. 2 (b). This high impedance suggests the presence of dense structures and decreased ionic mobility, which are frequently related to mature and dehydrated fruit tissues. Because living tissues exhibit capacitive characteristics, impedance continuously lowers as frequency increases on all days, exhibiting a typical dielectric relaxation trend [23]. The structure and water content of ripe nutmeg remained essentially stable over the five days, as indicated by the minimal difference in impedance values between days. The slight increase in resistance on the fifth day may be due to reduced ionic conduction channels caused by surface drying.

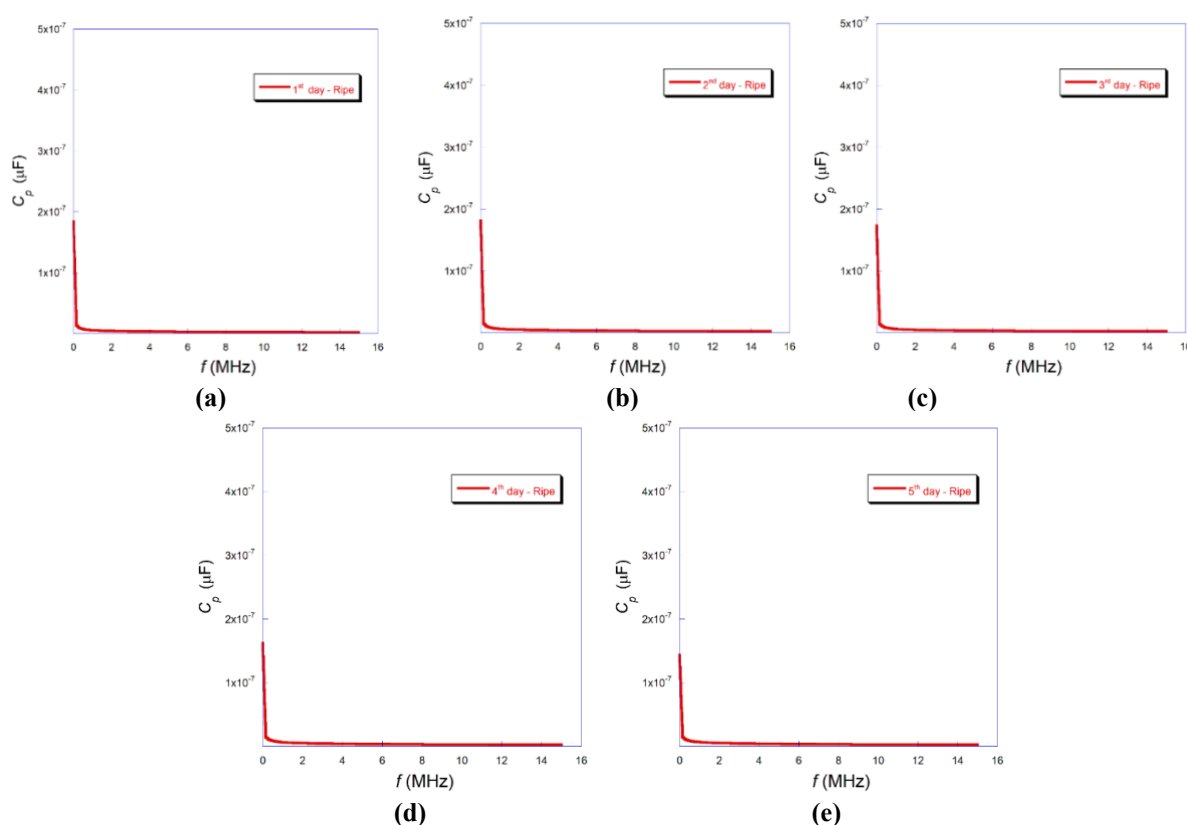


Fig. 3. Capacitance of ripe nutmeg on various days

However, on the first day at low frequencies, the unripe nutmeg samples exhibited significantly lower initial impedance values, approximately 6 M Ω . This lower impedance indicates higher water content and increased ionic conductivity within the immature fruit tissue. Notably, the impedance values gradually decrease over time, reaching below 2 M Ω on the fifth-day. This gradual decrease indicates a substantial change in the fruit's internal structure, likely caused by continued enzymatic activity, cell wall disintegration, and elevated tissue permeability. These alterations are common during the early phases of spoiling or postharvest physiological

maturation. The significant daily change highlights the instability and dynamic nature of the material during storage.

Measurement of impedance can distinguish ripe and unripe nutmeg. Higher and more consistent impedance values indicate intact structural and reduced moisture dynamics in ripe fruits. In contrast, rapid impedance reductions in unripe fruits indicate more active physiological changes and increased vulnerability to quality degradation. These results support the potential of EIS as a rapid and non-destructive method for evaluating nutmeg ripeness and postharvest quality. The results can also inform postharvest handling and storage strategies to prevent spoilage and preserve commercial value.

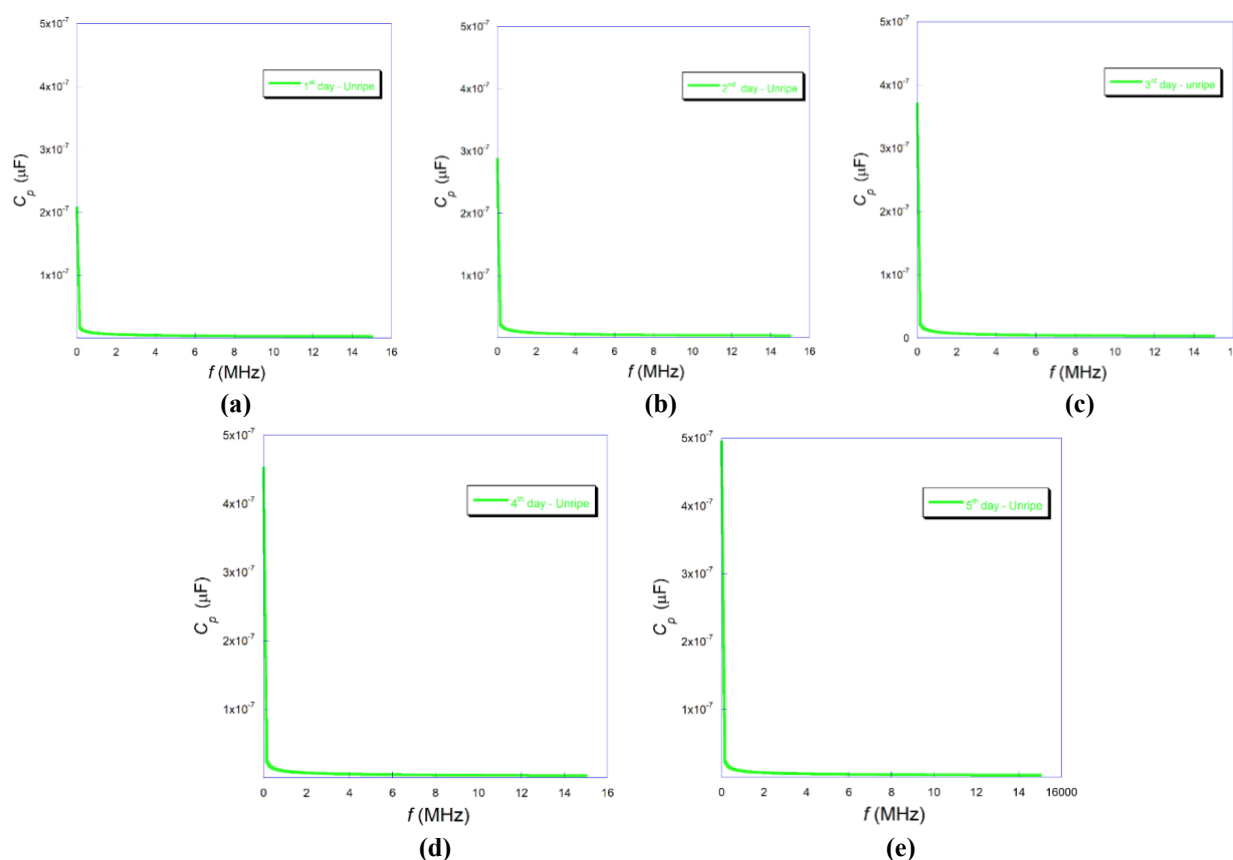


Fig. 4. Capacitance of unripe nutmeg on various days

Fig. 3 (a-e) represents storage of nutmeg over five days. Ripe fruit samples, which have high impedance values between 10 and 12 MΩ, show a noticeable decrease in capacitance. This behavior is explained by physiological changes associated with ripening, including tissue softening and a decrease in water content. At this stage, cellular membranes degrade, losing structural integrity and reducing the cell's ability to retain water and ions. Impedance increases because the fruit tissue becomes drier and more resilient as moisture loss and membrane disintegration progress. These deterioration processes diminish the fruit's capacity to retain electrical charge, which persists throughout storage. As a result, capacitance values progressively drop, consistent with the general drop in fluid content and cell structure degradation [24].

In contrast, capacitance reflects the amount of nutmeg that electric charge can store, which initially showed lower impedance values in the 2–6 M Ω range as shown in Fig. 4 (a-e). This aligns with the physiological properties of unripe fruit, which often include denser tissue, intact membranes, and larger water content. Enzymatic activity breaks down portions of the cell wall and membrane structures during the ripening process, releasing ions and increasing metabolic activity. These modifications redistribute ions and water, increasing the fruit tissue's capacity to hold an electric charge. The resulting rise in capacitance shows greater ionic mobility and transient structural changes that enhance charge retention [25].

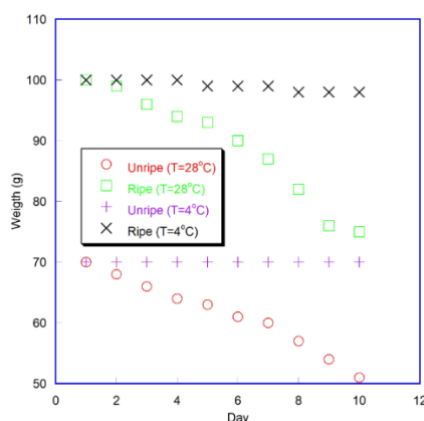


Fig. 5. Changes in nutmeg weight with respect to storage time and temperature

The relationship between the weight of nutmeg and storage duration was measured at 28 °C and 4 °C in a refrigerator. Fig. 5 shows that the weight of nutmeg remains stable at low temperatures, and decreases at room temperature. Water evaporation and respiration are the two main factors causing the fruit's bulk to decrease during storage [26]. Total weight decreases due to the fruit tissue's gradual water loss, and mass further decreases as respiration turns stored carbohydrates into gas (CO₂). Impedance increases as the fruit loses water through dehydration because the tissue becomes drier and the internal resistance rises.

4. Conclusions

This study proposes electrochemical impedance spectroscopy (EIS) technique as a practical and non-destructive method for assessing postharvest quality in nutmeg through measurement of impedance and its components, including frequency and capacitance. The results indicate that impedance can distinguish between ripe and unripe fruits during storage, reflecting differences in moisture content, membrane integrity, and physiological stability. These findings suggest that EIS may serve as a valuable tool for monitoring nutmeg quality and reducing postharvest losses in the horticultural supply chain. Further studies are necessary to develop practical tools for postharvest quality monitoring in agriculture.

Abbreviations

Not Applicable

Data availability statement

Data will be made available on request by readers.

CRedit authorship contribution statement

Ronaldo Talapessy: Conceptualization, Methodology, Collecting data, Analysis, Writing – review & editing. **Gianita Salamena:** Validation, Review draft manuscript. **Pricillia Jesica Sabandar:** Collecting data, project administration. **Tomoaki Ikegami:** Funding acquisition, Methodology, Validation.

Declaration of Competing Interest

The authors of this manuscript declare no conflict of interest or competing interest.

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References

- [1] Talapessy R, Ikegami T, Yoshida H. Development of Digital AC Resistivity Meter for Groundwater Survey. SEG Global Meeting Abstracts 2019;1–3. <https://doi.org/10.1190/segj2018-001.1>.
- [2] Grammatikos SA, Ball RJ, Evernden M, Jones RG. Impedance spectroscopy as a tool for moisture uptake monitoring in construction composites during service. Compos Part A Appl Sci Manuf 2018;105:108–117. <https://doi.org/10.1016/j.compositesa.2017.11.006>.
- [3] Sun F, Peng X, Bai X, Chen Z, Xie R, He B, et al. EIS analysis of the electrochemical characteristics of the metal-water interface under the effect of temperature. RSC Adv 2022;12:16979–16990. <https://doi.org/10.1039/d2ra01634f>.
- [4] Talapessy R, Ikegami T, Yoshida H. Measurement of apparent electrical impedance of soil with water flow inside. Water (Switzerland) 2020;12:2328. <https://doi.org/10.3390/W12092328>.
- [5] Ihara S, Islam MZ, Kitamura Y, Kokawa M, Lee YC, Chen S. Nondestructive evaluation of wet aged beef by novel electrical indexes: A preliminary study. Foods 2019;8:1–14. <https://doi.org/10.3390/foods8080313>.
- [6] Nakai T. Nondestructive detection of magnetic contaminant in aluminum casting using thin film magnetic sensor. Sensors 2021;21:4063. <https://doi.org/10.3390/s21124063>.
- [7] Andrews G, Neveling O, De Beer DJ, Chirwa EMN, Brink HG, Joubert TH. Non-Destructive Impedance Monitoring of Bacterial Metabolic Activity towards Continuous Lead Biorecovery. Sensors 2022;22:1–18. <https://doi.org/10.3390/s22187045>.
- [8] Abdollahi-Mamoudan F, Ibarra-Castaneda C, Maldague XPV. Non-Destructive Testing and Evaluation of Hybrid and Advanced Structures: A Comprehensive Review of Methods, Applications, and Emerging Trends. Sensors 2025;25:1–42. <https://doi.org/10.3390/s25123635>.
- [9] Talapessy R, Giawa DFB, Ikegami T. Investigation of Original Honey Based on Electrical Impedance. Indones J Appl Res 2023;4:225–233. <http://dx.doi.org/10.30997/ijar.v4i3.381>.
- [10] Ibba P, Falco A, Abera BD, Cantarella G, Petti L, Lugli P. Bio-impedance and circuit parameters: An analysis for tracking fruit ripening. Postharvest Biol Technol 2020;159:110978. <https://doi.org/10.1016/j.postharvbio.2019.110978>.
- [11] Grossi M, Riccò B. Electrical impedance spectroscopy (EIS) for biological analysis and food characterization: A review. J Sensors Sens Syst 2017;6:303–325.

- <https://doi.org/10.5194/jss-6-303-2017>.
- [12] Chin-Hashim NF, Khaled AY, Jamaludin D, Abd Aziz S. Electrical Impedance Spectroscopy for Moisture and Oil Content Prediction in Oil Palm (*Elaeis guineensis* Jacq.) Fruitlets. *Plants* 2022;11:3373. <https://doi.org/10.3390/plants11233373>.
 - [13] Cabrera-Lopez JJ, Velasco-Medina J. Structured Approach and Impedance Spectroscopy Microsystem for Fractional-Order Electrical Characterization of Vegetable Tissues. *IEEE Trans Instrum Meas* 2020;69:469–478. <https://doi.org/10.1109/TIM.2019.2904131>.
 - [14] Pathmanaban P, Gnanavel BK, Anandan SS. Recent application of imaging techniques for fruit quality assessment. *Trends Food Sci Technol* 2019;94:32–42. <https://doi.org/10.1016/j.tifs.2019.10.004>.
 - [15] Watanabe T, Ando Y, Orikasa T, Kasai S, Shiina T. Electrical impedance estimation for apple fruit tissues during storage using Cole–Cole plots. *J Food Eng* 2018;221:29–34. <https://doi.org/10.1016/j.jfoodeng.2017.09.028>.
 - [16] Rosiana E, Baskara HA, Setiawan J, Ardianto DA, Abdurrahman A, Maulana R, et al. Non-destructive Analysis of Pampelo Citrus Fruit Maturity with Impedance Spectroscopy Method. *Andalasian Int J Appl Sci Eng Technol* 2024;4:178–185. <https://doi.org/10.25077/aijaset.v4i2.144>.
 - [17] Sruthi S, Dhavse DR, Sarvaiya DJN. Quality Assessment of Fruits and Vegetables using Bio-impedance based Expert System. *Int J Innov Technol Explor Eng* 2020;9:965–970. <https://doi.org/10.35940/ijitee.h6735.069820>.
 - [18] Chowdhury A, Kanti Bera T, Ghoshal D, Chakraborty B. Electrical Impedance Variations in Banana Ripening: An Analytical Study with Electrical Impedance Spectroscopy. *J Food Process Eng* 2017;40:e12387. <https://doi.org/10.1111/jfpe.12387>.
 - [19] Fernández AO, Pinatti CAO, Peris RM, Laguarda-Miró N. Freeze-damage detection in lemons using electrochemical impedance spectroscopy. *Sensors (Switzerland)* 2019;19:1–12. <https://doi.org/10.3390/s19184051>.
 - [20] Ando Y, Maeda Y, Mizutani K, Wakatsuki N, Hagiwara S, Nabetani H. Impact of blanching and freeze-thaw pretreatment on drying rate of carrot roots in relation to changes in cell membrane function and cell wall structure. *Lwt* 2016;71:40–46. <https://doi.org/10.1016/j.lwt.2016.03.019>.
 - [21] Mekie TM, Desalegn G, Dessie AB, Abate TM. Market orientation and market participation of smallholder barely producers in North Gondar Zone: Implications for commercial transformation 2019;13. https://academicjournals.org/journal/AJAR/article-in-press-abstract/market_orientation_and_market_participation_of_smallholder_barely_producers_in_north_gondar_zone_implications_for_commercial_transformation.
 - [22] Talapessy R, Sujianti OK. Volume 2498 The 7 th International Conference on Basic Sciences 2023 A Simple Technique to Investigate Water Flow in Soil 2023;2498. <http://dx.doi.org/10.1063/5.0112532>.
 - [23] Rehman M, Abu Izneid BAJA, Abdullah MZ, Arshad MR. Assessment of quality of fruits using impedance spectroscopy. *Int J Food Sci Technol* 2011;46:1303–1309. <https://doi.org/10.1111/j.1365-2621.2011.02636.x>.
 - [24] Tıraş B, Dede S, Altay F. Dielectric Properties of Foods. *Turkish J Agric - Food Sci Technol* 2019;7:1805–1816. <https://doi.org/10.24925/turjaf.v7i11.1805-1816.2650>.
 - [25] Burubai W, Akor AJ, Igoni AH, Puyate YT. Effect of loading rate and pre-heating time on the strength properties of African nutmeg (*Monodora myristica*). *Int Agrophysics* 2007;21:317–322. https://www.researchgate.net/publication/26551718_Effect_of_loading_rate_and_pre-heating_time_on_the_strength_properties_of_African_nutmeg_Monodora_myristica.
 - [26] Kassebi S, Korzenszky P. The effect of post-harvest storage on the weight of Golden Delicious apples. *Sci Technol Innov* 2021;13:7–11. <https://doi.org/10.5604/01.3001.0015.5265>. <https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKew>

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