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DIPLOMA THESIS ASSIGNMENT

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Detection of damaged apple tissue by using electrical capacitance measurements

Supervisor

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1. Nelson, S.O., Trabelsi, S., 2012. Factors influencing the dielectric properties of agricultural products and food materials. ASABE paper No. 12–1338239. ASABE, St. Joseph, Michigan, USA.
2. Skierucha, W., Wilczek, A., Szyplowska, A., 2012. Dielectric spectroscopy in agrophysics. Int. Agrophys. 26, 187–197.
3. Watanabe, T., Ando, Y., Nakamura, N., Orikasa, T., Shiina, T., Nagata, M. 2019. Electric and mechanical detection of changes in heated apple flesh. J. Food Eng., 261, 26-31.

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Summary:

This thesis investigates the relationship between electrical capacitance measurements and damaged apple tissue. The aim is to design a measurement tool for detecting tissue damage based on electrical capacity, offering a faster and more objective assessment method compared to traditional techniques. Through rigorous experimentation, the study demonstrates the effectiveness of capacitance measurement in identifying damaged tissue, with results showing a significant correlation between capacitance fluctuations and tissue damage severity. The findings highlight the potential for enhancing apple quality assessment practices and post-harvest handling procedures. Overall, this research contributes valuable insights to agricultural science and food technology, paving the way for improved quality control measures in the apple industry.

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1. Introduction

1.1 General Overview

Research into the dielectric properties of agricultural products has long captured the attention of numerous scientists, primarily driven by the need for efficient methods to assess grain moisture content. The exploration of these properties dates back over 80 years, marked by pioneering investigations into resistance measurements and the utilization of DC current for moisture determination in grains. Subsequent advancements saw the adoption of AC current methodologies.

One significant milestone in this journey was the seminal work of Dunlap and Makover in 1945, where they conducted early experiments focusing on carrots. Operating within a frequency range spanning from 18 kHz to 5 MHz, their study delved into the intricate interplay between dielectric constant, electrical conductivity, product dimensions, humidity levels, frequency variations, and temperature changes. Notably, they observed a consistent dielectric constant and electrical conductivity within grain samples until reaching an 8% humidity threshold, beyond which both properties exhibited a rapid increase.

These findings underscored the complex dynamics governing dielectric behavior in agricultural produce, laying a foundation for further research and practical applications in moisture estimation and quality assessment across various crops and commodities. The legacy of such pioneering investigations continues to inform contemporary efforts aimed at enhancing agricultural productivity and post-harvest management through innovative dielectric-based techniques and technologies.

1.2 Statement of problem

Concern about the quality of fruits is increasing all over the world. The concept of quality in food with understanding and taste the consumer has a direct relationship. Consumer perception is based on the five senses and therefore best measured by the five senses take place. The high quality guarantee of fruits is an issue that is directly related to People's health is related. People pay more attention to the quality guarantee of fruits and hope to have high quality fruits buy. Product quality management is very important in promoting the consumption of fruits and vegetables and providing high quality products. In order to achieve this goal, quality management tools should be designed or developed coordinately delivers the fruit from the farm to the consumer. Many different techniques have been developed and used to measure the quality characteristics of fruits. Some of them in in order to identify the physical aspects of the samples (such as strength, skin color, shape and size, defects and damages) and the rest are based on chemical identification (such as the amount of main compounds, chemical residues and absorption of radiation in wavelengths). One of the limitations of these techniques is that they can only measure one of the qualitative parameters to identify, therefore, to obtain complete information about the quality of the fruit, a set of sensors should be used (Hussain, M.I., 2021). Since many quality factors of agricultural products are related to their physical characteristics, the development of methods Non-destructive is necessary to measure handling based on these characteristics. Methods are non-destructive that do not have photo physical, thermal, chemical, mechanical and photochemical destructive effects on the sample. These methods have been studied to deal with two major problems in the fruit industry:

- Identifying the optimal time to pick the product
- Controlling the fruit softening process to provide consumers with high quality aroma

Non-destructive measurement of the internal quality of fruits, causing better presentation of products to consumers, more profitability and improvement Competition becomes industrial (Lee, Y. and T. Watanabe, 2022). Apple is one of the most important fruits of the temperate region and one of the most important strategic fruits of some countries. In an apple tree, if 5-8% of blossoms turn into fruit, the production will be economical. Fertility age is 2-6 years depending on the variety and base used, and the economic lifespan of apple trees is 50 years on average. The quality of apple fruit is a complex feature and includes all the attributes that cause the quality and marketability of the product and is subject to many factors such as size, color, texture, aroma and taste and appearance of the product. Physiological effects of apples before and after harvesting have a significant effect on the quality of the fruit and lead to a decrease in the yield and marketability of the fruit and an increase in fruit waste, causing heavy damage to gardeners every year, but with a proper nutritional program and Proper management can control and reduce the amount of damage (López-Hortas, L., 2019).

Physiological effects of apples:

- Pre-harvest complications include sunburn, cracking, and fruit drop
- Post-harvest complications include bitter spot, cork spot, surface burn of the fruit, water bite and browning of the fruit flesh.

1.3 Importance of Research

Most of the non-destructive methods that have been invented so far are expensive and complicated, or in they are not applicable. So, you should look for a cheap and simple way to diagnose it was a product. The capacitive dielectric method seems to be quite ideal in this regard. This idea is over the basis of the change of the dielectric properties of the fruit during ripening has been proposed. Dielectric constant in Different levels of handling using the capacitive method of measurement and its relationship with handling can be in this method; the product is placed between the capacitor electrodes as a dielectric material the amount of handling is determined (Ando, Y., et al., 2019). A device based on this method can replace experts and it is not necessary to have an expert in each unit for fruit grading be present and a non-expert person able to grade with the help of a capacitance measuring device it will be fruits. Also, this device can be used to control the process of artificial delivery of fruits He used apples in cold store (K. Mizutani, and N. Wakatsuk, 2014). Experts according to the color of the apple skin and the amount they determine the softness of the degree of ripeness of the apple and control the conditions manually. This People have to open and close the cold storage door to inspect the fruits, which causes them to escape Ethylene in the air and the change in temperature and humidity of the cold room are the result of heat transfer (Asaka, M. and R. Hayash, 1991).

1.4 Aims and Goals

Our purposes that a discernible relationship exists between fluctuations in electrical capacitance measurements and the presence of damaged apple tissue. We propose that these fluctuations, particularly notable peaks observed within the capacitance data, align with instances of tissue damage. Our conjecture is grounded in the understanding that alterations in tissue integrity, induced by mechanical stress or external factors, can manifest as detectable changes in electrical properties. Central to our hypothesis is the concept of the unloading phase during mechanical testing. We anticipate that this phase, characterized by the release of mechanical stress applied to the apple tissue, will coincide with distinct peaks in the capacitance data. These peaks, we believe, represent moments when the tissue undergoes structural alterations or experiences localized damage, thereby influencing its electrical capacitance properties.

By exploring this hypothesis, we aim to validate the utility of electrical capacitance measurements as a non-destructive and measurement tool for identifying and characterizing tissue damage in apples. If our hypothesis holds true, it would signify a significant advancement in quality assessment methodologies for perishable agricultural products, offering potential applications in post-harvest handling, storage optimization, and quality control processes (Diezma-iglesias, B.; Ruiz-Altisent, M., 2004).

Through rigorous experimentation and statistical analysis, we endeavor to elucidate the intricacies of the relationship between electrical capacitance fluctuations and tissue damage occurrences. By substantiating our hypothesis with empirical evidence, we aspire to contribute valuable insights to the fields of agricultural science and food technology, ultimately enhancing the efficiency and reliability of apple quality assessment practices.

Objectives:

- Designing a tool to check the amount of apple tissue damage based on electrical capacity.
- Finding the relationship between the dielectric properties of apple fruit with mechanical properties and properties of Chemicals of apple fruit.
- Apple tissue damage detection by designed tool.

2. Theory and Literature Review

2.1 Introduction

Texture testing, or tissue testing, has a long-standing history as a technical examination method used to gauge the mechanical and physical characteristics of raw materials. It's particularly handy for scrutinizing food structures and ensuring quality control from start to finish. This method is incredibly versatile, finding application in a wide range of food types like baked goods, cereals, sweets, snacks, dairy products, fruits, vegetables, gelatins, meats, poultry, fish, pasta, and even animal feed.

Texture, essentially the feel of a surface, can be measured using mechanical methods, typically in terms of force. One fascinating area where texture testing is applied is in assessing the hardness of apple fruit. Here, non-destructive instrumental methods are key (Mohsen, M, 2022). They help evaluate texture quality, predict optimal harvesting times, categorize fruits based on processing stages, and identify any external or internal flaws.

Different techniques are used to measure apple flesh hardness, including acoustic and mechanical vibration methods, as well as optical ones like hyperspectral scattering imaging, near-infrared analysis, and ultrasound. While traditional destructive tests are still used as a benchmark, non-destructive methods have gained popularity due to their accuracy and speed, making them ideal for online use. These advancements highlight the ongoing progress in texture testing, making it an indispensable tool across various industries.

2.2 Quality Indexes of Apple Hardness

Apples are grown in many countries and global production has seen a rapid increase of more than 86 million tons in 2018. It adapts well in areas where the air temperature is close to freezing in winter. Apple harvesting time is important for storage because early harvesting affects the taste, color, size and storage ability, and late harvesting causes the apples to soften and reduce shelf life. Pressure testing is used to measure hardness to determine the harvest date. Nowadays, fruit quality is one of the main concerns of consumers, and evaluating fruit quality is a vital issue in post-harvest transportation (Oikawa, A., et al, 2011).

Texture, along with appearance, taste and nutritional properties, is one of the main quality indicators of fresh and processed agricultural products. And it is one of the key indicators for evaluating the quality and maturity of agricultural products. Knowledge about the properties of agricultural products is important for all investors in the production chain, including producers, post-harvest, processors, sellers and consumers, wholesalers and retailers, and agricultural insurance agents. For fresh foods such as fruits and vegetables, texture characteristics are widely used as criteria for transportation, storage, and consumer acceptance. In apples, textural features include crispness, juiciness, hardness, hardness, and it seems that its taste and appearance are dominant quality features. These properties are essential to add value to fruits. Non-destructive methods for assessing the internal quality of agricultural products can be used for online applications (Phothiset, S. and S. Charoenrein, 2014).

2.2.1 Hardness

Hardness is one of the reasonable textural characteristics to determine the quality of products. Freshness plays an important role in the choice of apples by customers. Additionally, hardness is related to both the juiciness and freshness of the apple. The hardness of the fruit is a more important indicator than the amount of sugar and acid. Strength is one of the parameters for calculating Streif index (Sekozawa, Y, 2003).

2.2.2 Strength

Various indicators such as apple appearance and size, total soluble solids (TSS), acid content, starch, flesh hardness, flesh color, seed color, background color, core water, and internal ethylene concentration to determine fruit maturity and among other uses will be But hardness is an important factor in determining harvest time. Hardness and other properties of fruits and vegetables are related to each other. For example, hardness of meat has a direct relationship with freshness and ripeness, and softness has an inverse relationship with them. Gentleness has a direct relationship with softness and an inverse relationship with hardness (Hampel, U., 2007).

Hardness loss is closely related to low juice content and is the most important change during long-term cold storage. Apple hardness is also related to the rheological properties of its skin and flesh. The softening of apple fruit after harvest is a serious problem for gardeners and storekeepers. Loss of hardness occurs for reasons such as fruit anatomy and cell packing, changes in cell walls and membranes, changes in cell turgor, and the role of ethylene and other growth regulators. One of the indicators for evaluating the quality of apple texture is the Strife index.

2.3 Non-destructive measurement methods

Non-destructive methods and advanced systems to detect the strength of fruit tissue. It is used to measure certain properties and components of materials without damaging and changing their function and structure. The advantage of the non-destructive method is that, unlike the usual and destructive method, the tested substance is safe and available. Non-destructive testing aims to replace old techniques (Alvarez, M., W. Canet, and M. López, 2002).

2.3.1 Non-destructive tests

The non-destructive technologies used in the evaluation of apple hardness are divided into three categories:

- Acoustic vibration
- Optical
- Electrical resistance and capacity

In 1997, Abbott et al announced techniques for estimating and measuring the most properties of fruits and vegetables, such as density, mechanical, electromagnetic and electrochemical properties. This article can be used as a good reference for measuring the properties of fruits and vegetables. Garcia et al (2005) reviewed non-destructive fruit hardness sensors in a paper. According to their classification, stiffness estimation methods include measurement of indices extracted from force-deformation curves, analysis of impact forces, acoustic responses to vibrations and impact, rebound technique, NMR methods, and measurement of optical properties. Harker et al. in 2010 described the basic knowledge of fruit texture. Then, it is explained in detail about texture recognition and measurement methods and factors affecting it and fruit texture disorders.

2.3.1.2 Acoustic, vibration and mechanical methods

Acoustic emission is an important index to evaluate the quality of food texture properties. Therefore, the acoustic properties of snack and fresh food products are equally important. The acoustic method can also be used to calculate the elasticity coefficient corresponding to the Young's modulus. The use of acoustic emission methods to evaluate food quality is divided into two groups, destructive and non-destructive. Chewing sound analysis, compression test and whole test are some of these destructive tests. In non-destructive testing and fruit tissue strength detection systems, the sample is usually excited by an impact or forced module. Then, the contact or non-contact module receives the signal and delivers the signal to the signal processing module. Since hardness is one of the textural properties of fruits and related to its juiciness and crispness. In this section, the subject of textural properties is discussed. Monitored changes in apple tissue quality after harvest using acoustic shock response technique (Costa, F., et al, 2011).

2.3.1.3 Optical methods

Some methods of measuring hardness and other textural properties of agricultural products are based on optical techniques. For example, Xueming et al. evaluated the hardness of pears based on their absorption and scattering characteristics using an automated integrated spherical system (Hu, D., et al., 2015).

2.3.1.4 Electrical resistance and capacitance measurement

The electrical capacitance properties of fruits are usually used to measure the volume or density or to detect the moisture content of agricultural products. Masah et al applied electrical resistance to evaluate the quality of apple fruit after harvest. This method can be used to measure the hardness of the fruit. Bhosale and Sundaram proposed a non-destructive method for predicting the hardness of apples by measuring electrical capacitance properties. Acoustic loudness measurements were used for reference. They do this by using parallel non-contact plates (Massah, J., F. Hajiheydari, and M. Haddad Derafshi, 2017). As mentioned, one of the non-destructive methods of evaluating the quality of fruits is the use of a capacitor. The capacitor consists of the assembly of two circular electrodes, between which an insulating material called dielectric is placed, in such a way that the electric charge on electrodes is saved. The electrical energy storage potential of a capacitor, capacitance, is expressed in terms of a unit called Farad. A capacitor of one faraday can store one coulomb charge in one volt. A farad is a large and defining unit the capacity is very high. Therefore, smaller units are used in capacitors. The capacity of capacitor with parallel plates is calculated in Farad (Lee, Y., et al., 2019).

2.4 Permittivity

Permittivity, often denoted by the symbol ε_r (epsilon), is a fundamental property of materials that describes how they respond to electric fields. It quantifies the ability of a material to permit the displacement of electrical charge within it when subjected to an electric field. In simpler terms, it indicates how much the electric field is weakened or "permitted" to penetrate the material. (Weber, B., et al., 2012)

- **Definition:** Permittivity is defined as the ratio of the electric flux density to the electric field strength in a material.
- **Influence:** Polarization is one of the factors that influence permittivity, which in turn affects various electrical properties of materials, including capacitance and the propagation of electromagnetic waves.
- **Frequency Dependency:** In many materials, particularly dielectrics, permittivity isn't constant but fluctuates with the frequency of the applied electric field, a phenomenon termed frequency dispersion. This variation occurs due to the material's response to the

electric field being influenced by the movement of charges or dipoles within it, which operate on different timescales. At low frequencies, charges or dipoles may adequately respond to the field, resulting in high permittivity. Conversely, at higher frequencies, they may lack sufficient time to respond fully, leading to a decrease in permittivity. The dependence between permittivity and frequency reflects how materials respond to electric fields at varying frequencies. Permittivity quantifies a material's capacity to allow the flow of an electric field, indicating the extent to which the electric field within the material diminishes compared to that in vacuum. Essentially, it elucidates the degree to which an external electric field induces an electric displacement field within the material. Understanding this frequency dependency is crucial in engineering applications, especially in the design of electronic devices and communication systems. It allows engineers to predict and account for how materials will behave under different frequencies, ensuring the reliability and efficiency of the constructed systems (D. Halliday, R. Resnick, J. Walker, 49, 2001). And also the Debye equation is a model used to describe the frequency dependence of permittivity in dielectric materials. It is named after the Dutch physicist Peter Debye, who proposed it. The Debye equation is given by:

- $\varepsilon(\omega)$ is the complex permittivity at angular frequency ω.
- ε_∞ is the permittivity at infinite frequency (high frequency limit).
- ε_s is the static or low-frequency permittivity.
- ω is the angular frequency of the applied electric field.
- i is the imaginary unit.
- τ is the characteristic relaxation time of the material.

$$\varepsilon_r' = \varepsilon_{r\infty} + \frac{\varepsilon_{rdc} - \varepsilon_{r\infty}}{1 + (\omega\tau)^2}$$

$$\varepsilon_r'' = \frac{(\varepsilon_{rdc} - \varepsilon_{r\infty})(\omega\tau)}{1 + (\omega\tau)^2}$$

Equation 1. Debye equations

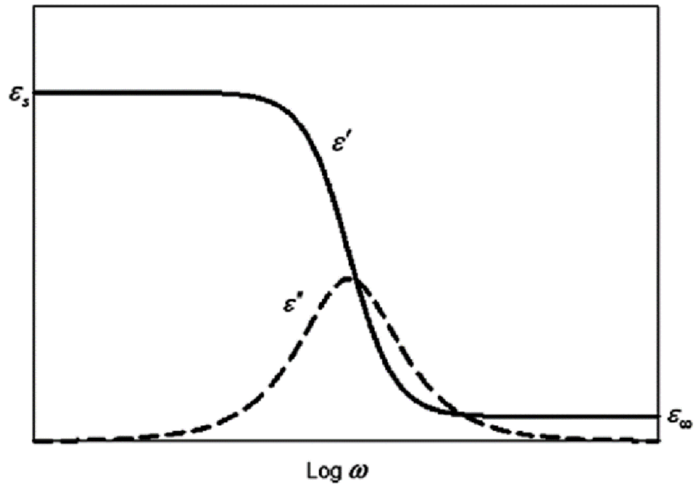


Figure 1. Permittivity and Polarization mechanisms – pure polar material

2.4.1 Complex Permittivity

Complex permittivity extends the concept of permittivity to include both the real and imaginary components, representing the capacitive and resistive behaviors of a material, respectively.

- **Real Component (ε'):** This component represents the ability of a material to store electrical energy (capacitive behavior) and is related to the dielectric constant.
- **Imaginary Component (ε"**): This component represents the energy dissipated as heat (resistive behavior) when an electric field is applied to the material.
- **Relation to Loss Factor:** The loss factor (tan (δ)) is the ratio of the imaginary part of the complex permittivity (ε") to its real part (ε'), providing a measure of the material's lousiness (Juansah, J., et al., 2012).

2.5 Loss Factor (Dissipation Factor or Loss Tangent)

The loss factor, often represented by tan(δ) or sometimes simply referred to as the dissipation factor, is a measure of how much energy is lost as heat when an electric field is applied to a material. It quantifies the loss of energy in the material due to factors such as electrical resistance and dielectric relaxation (Euring, F.; Russ, W.; Wilke, W, 2014).

- **Definition:** The loss factor is the ratio of the imaginary part of the complex permittivity to its real part.
- **Significance:** A high loss factor indicates that a material dissipates a significant amount of energy when subjected to an electric field, which can be important in applications such as capacitors and dielectric heating.
- **Interpretation:** A loss factor close to zero suggests a material with low loss and good electrical insulation properties, while a high loss factor indicates a material that absorbs more energy and may not be suitable for certain applications.

2.6 Polarization mechanisms

In this research we focus on exploring polarization mechanisms, especially within the 1 kHz to 10 MHz frequency range. These mechanisms are crucial for understanding the electrical behavior of materials, particularly dielectrics, under varying frequencies. The research aims to elucidate the influence of dipolar relaxation, Maxwell-Wagner-Sillars polarization, and electrode polarization on impedance measurements. By analyzing these phenomena, the study seeks to enhance understanding of electrical properties for practical applications, such as assessing and characterizing agricultural products or fruit quality (Wang, G., et al., 2021).

2.7 Capacitance

Capacitors consist of two parallel conducting circular electrode (metal) that do not touch each other and are separated from each other (1mm distance) by an insulating material called a “dielectric”. When a voltage is applied to circular electrode, electric current flows that charges one electrode with a positive charge according to the supply voltage and the other electrode with an opposite and equal negative charge. Then the capacitor has the ability to store the electric charge Q (unit in coulombs) of the electron.

When the capacitor is fully charged there is a potential difference d between the electrodes, and the larger the area of the electrodes and/or the smaller the distance between them (known as insulation) the greater the electrical charge the capacitor can hold and the greater its capacitance. The ability of capacitors to store this electric charge (Q) between their electrodes is proportional to the voltage V applied to a capacitor of known capacitance in Farads. Note that C is always positive and never negative. The greater the applied voltage, the greater the charge stored on the capacitor electrodes. Likewise, the smaller the applied voltage, the smaller the load (F. Liu et al, 2020). As a result, the actual charge Q on the capacitor electrodes is calculated as follows

Equation 2. $$\boldsymbol{Q = C \cdot v}$$

Where: $\boldsymbol{Q}$ is charge I = $\boldsymbol{C}$ is capacitance (F). $\boldsymbol{V}$ Is voltage in units of volt (V).

Since the capacitance shows the ability of the capacitor (capacity) to store an electric charge on its electrodes, one farad can be defined as: "the capacity of a capacitor that requires a charge of one column to create a potential difference of one volt between its electrodes" which Originally defined by Michel Faraday. So the larger the capacitance, the higher the amount of charge stored on the capacitor for the same amount of voltage.

A capacitor's ability to store charge on its conductive electrodes gives it its capacitance value. Capacitance can also be determined from the dimensions or area A of the electrodes and the characteristics of the dielectric material between the electrodes. The size of the dielectric material is given by the gap (ε), or dielectric constant.

2.8 Previous Studies

Electrical impedance measurements were used to assess the amount of bruising sustained by a 'Granny Smith' apple, and to monitor the development of the bruises over time. A bruise index was developed to quantify the severity of bruising. It was found that the bruise index could distinguish apples bruised to different levels and that there was no significant change in the impedance properties of the apple after the initial damage had occurred. The method described here may have a potential use in assessing fruit bruises (Cox, M.A., M.I.N. Zhang, 1993). Plots of reactance against resistance at 36 spot frequencies between 50 Hz and 1 MHz traced a semicircular arc, which contracted in magnitude after bruising. A number of characters are tics of these curves were then related to bruise weight. The change in resistance that occurred as a result of fruit impact (ΔR50Hz) was the best predictor of bruise weight, with r2 values up to 0.71. The influence of apple cultivar and temperature on electrical impedance may cause difficulties when implementing these measurements in a commercial situation. However, further development of electrical impedance spectroscopy methodologies may result in convenient research techniques for assessing bruise weight without having to wait for browning of the flesh (Jackson, P.J. and F.R. Harker, 2000).

An overview of non-destructive detection in quality of post-harvest fruit was presented in (GAO, H., F. Zhu, and J. Cai., 2010), and the research and application were discussed. This paper elaborated the fruit quality detection methods which were based on one of the following properties: optical properties, sonic vibration, machine vision technique, nuclear magnetic resonance (NMR), electronic noses, electrical properties, computed tomography. At last, the main problems of non-destructive detection in application were also explained.

In another research discs of apple tissue were compressed to 75% of their original height. Throughout compression, the force-distance curve was collected and the electrical impedance of the discs was measured at two frequencies of alternating current—1 kHz and 1 MHz. Electrical impedance was separated into its resistive and reactive components, and at these particular frequencies changes in resistance predominated. Measurements at 1 kHz indicate the resistance of extracellular regions of the discs (ruptured cells as well as those regions external to the plasma membrane), while measurements at 1 MHz indicate the resistance of the entire disc (combined intracellular and extracellular regions). Juice was released from the discs as a result of damage to cells and the extrusion of cellular fluid into intercellular air spaces. This resulted in a decline in electrical resistance at 1 kHz, but little change to the resistance at 1 MHz. Changes in juice release as determined by electrical measurement were related to the mechanical properties of the discs. Generally, the release of juice occurred after the inflection point on the force-distance curves, but much earlier than mechanical failure (indicated by maximum force). The extent of tissue damage was determined from the relative decrease in resistance at 1 kHz, and was found to vary among apple cultivars and in response to fruit ripening (Harker, f.r., et al., 2003).

Mass, volume, electrical and mechanical properties of four apple cultivars after high hydrostatic pressure (HHP) treatment were investigated. Volume changes were greater than those of mass after HHP treatment. Electric properties were measured by electrical impedance spectroscopy, and their frequency dependences were analyzed using the Cole-Cole plot and cell-based electrical circuit model (modified Hayden model). The analyzed electric parameters showed differences among the cultivars, indicating cell membrane damage after HHP treatment. HHP treatment also affected the mechanical properties such as breaking stress and strain, indicating changes in cell structure. However, the mechanical properties after HHP treatment of 'Shinanogold' and 'Fuji' fruit were retained to a greater extent than those of 'Jonathan' and 'Jonagold' despite cell membrane destruction. This study is the first to reveal cultivar differences in the physical property changes after HHP treatment and their tolerances to treatment.

O'Toole, M.D concluded that Bio impedance spectroscopy is the electrical impedance of a biological sample measured over a range of different frequencies. Over the kHz to MHz range, the characteristic shape of the spectra is denoted as the β dispersion, and is the result of the polarization of cell boundaries presenting a capacitance that contributes to the overall flow of electrical current in the sample. This implies that the curve of the dispersion could be a marker for breakdown behaviors and cell vitality within the fruit, as variations in the cell walls (looseness or cell death) will present different overall capacitances. In this paper, we present some early results exploring the relation between the bio impedance spectra and variations in the fruit quality of apples, caused by different growing conditions, irrigation, stress, and injury. We use a novel measurement technology termed Magnetic Induction Spectroscopy which uses magnetic fields and induced eddy-currents to ascertain a relative conductivity measure over a frequency range from 50 kHz to 2.5 MHz. The significant advantage of this approach is that it is non-contact, opening the possibility of future in-field or process-line operation.

Skierucha (A. Wilczek, 2012) presents scientific foundation and some examples of agrophysical applications of dielectric spectro- scopy techniques. The aim of agrophysics is to apply physical methods and techniques for studies of materials and processes which occur in agriculture. Dielectric spectroscopy, which describes the dielectric properties of a sample as a function of frequency, may be successfully used for examinations of properties of various materials. Possible test materials may include agrophysical objects such as soil, fruit, vegetables, intermediate and final products of the food industry, grain, oils, etc. Dielectric spectroscopy techniques enable non-destructive and non-destructive measurements of the agricultural materials, therefore providing tools for rapid evaluation of their water content and quality.

There are a limited number of researches in the field of dielectric spectroscopy of agricultural objects, which is caused by the relatively high cost of the respective measurement equipment. With the fast development of modern technology, especially in high frequency applications, dielectric spectroscopy has great potential of expansion in agrophysics, both in cognitive and utilitarian aspects(Mitcham, E.J., 2019).Dielectric properties of materials are defined, and the major factors that influence these properties of agricultural and food materials, namely, frequency of the applied radio-frequency or microwave electric fields, and water content, temperature, and density of the materials, are discussed on the basis of fundamental concepts. The dependence of measured dielectric properties on these factors is illustrated graphically and discussed for a number of agricultural and food products, including examples of grain, peanuts, fruit, eggs, fresh chicken meat, whey protein gel, and a macaroni and cheese preparation. General observations are provided on the nature of the variation of the dielectric properties with the major variables (Ruelas-Chacon, X.; Contreras-Esquivel, J.C., 2017).

3. Materials and Methods

3.1 Apple samples

In this study, our research focused on apples purchased from the Billa shop. Following our experimental plan, we conducted the study over two distinct days. On the first day, we utilized a total of four apples, comprising one Golden apple and three Red delicious apples. Similarly, on the second day, our experimentation involved four red delicious apples exclusively.

To ensure consistency and accuracy in our analysis, each apple was halved precisely down the middle, resulting in two equal-sized portions. This method enabled us to conduct our experiments with standardized apple samples, facilitating reliable comparisons and data collection across the different varieties tested.

Figure 2: Golden Apple

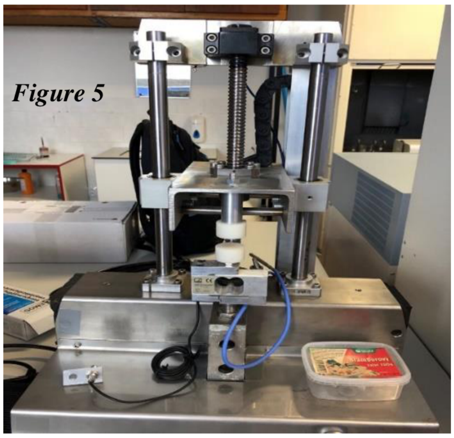
Figure 3: Red Delicious

3.2 Electrical capacitance measurements (By using The LCR Bridge)

In this study, we measured electrical capacitance using an important tool, as illustrated in Figures 4 to 7. This capacitive tool configuration features two parallel circular electrodes composed of metal (L: 30mm, D: 20mm), separated by an insulating layer. The operational principle of this sensor revolves around the modulation of capacitance induced by the dielectric properties of materials in proximity to the electrodes (Song, H.-Y.; Jo, W.-S.., 2013).

Figure 4: LCR Meter (GW Instek LCR-8101G)

Process of setup:



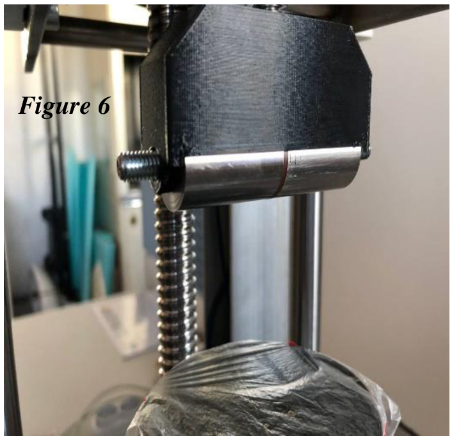
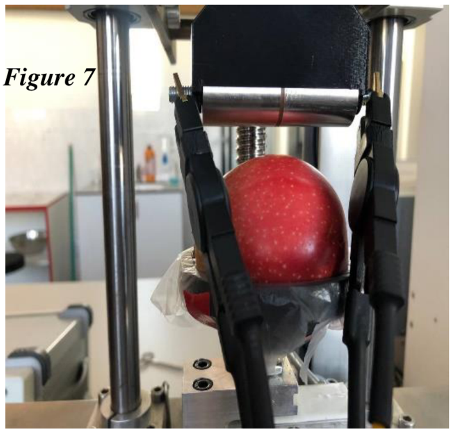
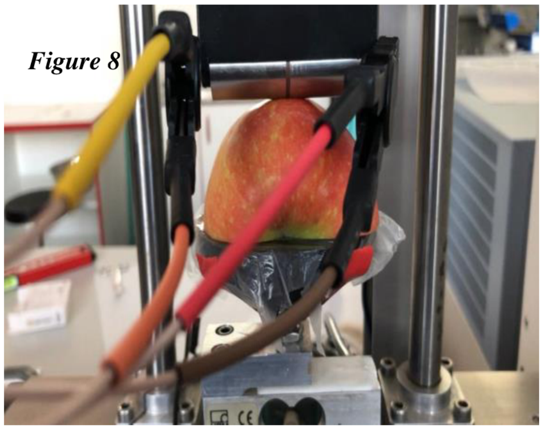


Figure 4, 5, 6, and 7: Process of capacitance measurements set up





To evaluate the electrical characteristics of the materials under investigation, half of an apple was strategically positioned on a plastic plate, and efforts were made to establish contact between the surface of the apple and the electrodes of the capacitive sensor (Chauhan, O.; Raju, P., 2011, Barcelon, E. G., Tojo, 1999).

The capacitance measurements were performed employing an LCR meter (GW Instek LCR-8101G) operating at a frequency 1 kHz to 10 MHz .This frequency setting was chosen to ensure optimal sensitivity to the electrical properties being examined. It’s noteworthy that all measurements were conducted under controlled environmental conditions, with the ambient temperature maintained at room temperature (22±2°C). These standardized conditions aimed to minimize external influences on the measurements and ensure the reliability and reproducibility of the experimental outcomes (Suchanek, M.; Kordulska, M., 2017).

3.3 Physical measurements

The physical properties of the apples were also measured to evaluate their correlation with the electrical capacitance. The diameter, weight, and density of the apples were measured using a digital Vernier caliper, and electronic measuring balance (Zhao, Y.L.; Wang, L.; Zhang, X.Y., 2019).

Figure 9: Electronic Measuring Balance

Figure 10: Digital Vernier Caliper

Golden apple 1, sample 1&2		
Weight	0.124	kg
Height	64.19	mm
Width	64.76	mm
Red Delicious 1 – sample 3&4 (small)		
Weight	0.134	kg
Height	61.02	mm
Width	64.84	mm
Red Delicious 2 – sample 5&6		
Weight	0.217	kg
Height	76.16	mm
Width	78.9	mm
Red Delicious 3 – sample 7&8		
Weight	0.195	kg
Height	67.4	mm
Width	75.96	mm

Table 1: Apple characteristics for first day

Red Delicious 1, sample 1&2		
Weight	0.194	kg
Height	70.24	mm
Width	76.44	mm
Red Delicious 2 – sample 3&4		
Weight	0.18	kg
Height	65.44	mm
Width	70.27	mm
Red Delicious 3 – sample 5&6		
Weight	0.196	kg
Height	72.36	mm
Width	74.38	mm
Red Delicious 4 – sample 7&8		
Weight	0.211	kg
Height	71.36	mm
Width	78.62	mm

Table 2: Apple characteristics for second day

3.4 Statistical Analysis

In our study, we employed various statistical methods to analyze the data collected from both the mechanical testing machine and the LCR Bridge. Firstly, we used descriptive statistics to summarize the data's characteristics, calculating measures like mean, median, standard deviation, and range for variables such as time, force, deformation, capacitance, and loss tangent (Guo, Z.; Wang, M.; Barimah, A.O. 2020). Then, we delved into correlation analysis to explore relationships between different variables, focusing on the association between mechanical properties (force, deformation) and electrical capacitance measurements. Additionally, we identified peaks in the capacitance data through visual inspection of graphs, considering these peaks as potential indicators of tissue damage for further analysis (Nelson, S.O.; Guo, W.C.; Trabelsi, S., 2007). Finally, we conducted a comparative analysis, comparing the occurrence of peaks in capacitance data with events observed in mechanical testing data to validate the hypothesis that peaks in capacitance measurements coincide with instances of tissue damage (Abbott, J. A., Lu, R., Upchurch, B. L., & Stroshine, R. L, 1997).

4. Results and Discussion

4.1 Dynamics of Force Variability over Time

In our study, we used a test machine to examine apples and collected data on time, force, and deformation. Upon reviewing the data, we observed significant fluctuations in force over time, indicating potential moments of damage to the apples. This variability in force allowed us to pinpoint when damage might have occurred. Initially, the force readings remained low, near zero, suggesting stability in the apples' condition. However, as pressure was applied by the machine, the force increased, peaking at 50 N, before rapidly decreasing.

We also noted variations in how different apples responded to the testing. Sometimes, changes in force on the chart helped us determine precisely when and how much force led to damage. However, in other cases, discerning such changes was challenging, possibly due to minor damage or no damage at all. We also observed an anomaly with the Golden apple, particularly in sample 1, where no fluctuations were evident on the chart despite visible skin damage, possibly due to the softness of the Golden apple's skin. Following our analysis of the initial testing day, we documented significant fluctuations across the samples. Moreover, we meticulously recorded specific moments and forces associated with damage, presenting this information in the table provided below:

	Damaged apples(first day)							
	Time(Sec)				Force(N)			
Samples	First(damage)	Second(damage)	Third(damage)	Fourth(damage)	First(damage)	Second(damage)	Third(damage)	Fourth(damage)
1	-	-	-	-	-	-	-	-
2	6500.616	-	-	-	-30.288	-	-	-
3	7945.506	7959.492			-21.188	-32.833		
4	8714.955	8732.159	8748.922	8758.693	-11.82	-21.822	-34.021	-41.955
5	9464.206	-	-	-	-43.835	-	-	-
6	9715.4	-	-	-	-33.036	-	-	-
7	10381.845	-	-	-	-38.426	-	-	-
8	10694.089	-	-	-	-25.551	-	-	-
Samples	Damaged apples(Second day)							
	Time(Sec)				Force(N)			
1	4020.285	-	-	-	-31.853	-	-	-
2	4358.058	-	-	-	-32.638	-	-	-
3	4729.795	-	-	-	-28.591	-	-	-
4	4904.287	-	-	-	-31.886	-	-	-
5	5231.737	-	-	-	-16.833	-	-	-
6	5455.181	5481.599	-	-	-15.972	-37.482	-	-
7	5758.545	-	-	-	-38.066	-	-	-
8	5957.456	-	-	-	-42.556	-	-	-

Table 3. Detection of time and force

Damaged apples (first day): The analysis of the tissue damage data, as detected through electrical capacitance measurement, reveals distinct patterns across the different apple samples. Let's delve into each sample and compare their characteristics and response to external forces:

Sample 1:

We did not observe any fluctuation on the chart, and there was only significant damage on the skin, which may be attributed to its soft texture. This suggests that the structural integrity of the apple remained intact, indicating a higher resistance to external forces compared to other samples.

Sample 2:

Tissue damage occurred at approximately 6500.616 second with a force of -30.288N. This single instance of damage suggests that the apple experienced a significant impact, leading to structural damage.

Sample 3:

Two distinct instances of tissue damage were identified. The first occurred at 7945.506 second with a force of -21.188N, followed closely by a second instance at 7959.492 second with a force of -32.833N. Despite the proximity in time, the forces applied during these instances varied, indicating different levels of impact.

Sample 4:

This sample exhibited four separate moments of tissue damage, each with increasing force. The first instance occurred at 8714.955 second with a force of -11.82 N, followed by subsequent instances at 8732.159 (-21.822N), 8748.922 (-34.021N), and 8758.693 (-41.955N). The progressive increase in force suggests a cumulative effect leading to extensive tissue damage.

Sample 5:

Tissue damage was observed at a single instance, occurring at 9464.206 second with a force of -43.835N. Despite occurring once, the high magnitude of force indicates significant structural damage to the apple.

Sample 6:

A single instance of tissue damage was noted at 9715.4 second with a force of -33.036N. Similar to Sample 5, this suggests a significant impact leading to tissue damage.

Sample 7:

The moment of tissue damage was identified at 10381.845 second with a force of -38.426N. This single instance suggests a notable impact leading to structural damage to the apple.

Sample 8:

Tissue damage occurred at 10694.089 second with a force of -25.551N. Despite occurring once, the force applied indicates significant damage to the apple tissue.

Damaged apples (second day): The second day of testing provided further insights into the detection of damaged apple tissue through electrical capacitance measurement. Here's a breakdown of the results for each sample:

Sample 1:

Damage was detected at approximately 4020.285 second with a force of -31.853N. This indicates a significant impact on the apple's structural integrity.

Sample 2:

Tissue damage occurred at around 4358.058 second with a force of -32.638N. Similar to Sample 1, this suggests a substantial impact leading to damage.

Sample 3:

Damage was observed at 4729.795 second with a force of -28.591N. This indicates a moment of structural compromise in the apple tissue.

Sample 4:

Tissue damage occurred at approximately 4904.287 second with a force of -31.886N. Like the previous samples, this suggests a significant impact leading to damage.

Sample 5:

Damage was detected at 5231.737 second with a force of -16.833N. Despite a lower force compared to other samples, this still indicates structural damage to the apple tissue.

Sample 6:

Two instances of tissue damage were observed. The first occurred at 5455.181 second with a force of -15.972N, followed by a second instance at 5481.599 second with a force of -37.482N. This suggests multiple impacts leading to damage.

Sample 7:

Damage was noted at 5758.545 second with a force of -38.066N. This indicates a significant impact leading to structural damage.

Sample 8:

Tissue damage occurred at 5957.456 second with a force of -42.556N. This represents a substantial force applied to the apple, resulting in damage.

4.1.1 Variability in Susceptibility to Damage: Samples with more instances of tissue damage are generally considered more susceptible. For instance, Sample 4 and Sample 6 had multiple instances of damage on both days, indicating potentially higher susceptibility compared to those with fewer instances, such as Sample 5 and Sample 8, which had only one instance each on both days. Higher forces applied during instances of damage suggest greater susceptibility. Samples with higher forces, such as Sample 5 on the first day and Sample 8 on the second day, are likely more susceptible to damage compared to those with lower forces. Variability in the forces applied during instances of damage within a sample may indicate inconsistent susceptibility. For example, Sample 3 exhibited two instances of damage on the first day with varying forces, suggesting different levels of resistance to impact. Samples with a progressive increase in force during multiple instances of damage may suggest a cumulative effect leading to extensive tissue damage and potentially higher susceptibility. Sample 4 demonstrated this pattern on the first day. The detection of damage on both days may also indicate the resilience or vulnerability of the apple tissue. Samples that showed damage on both days may suggest higher susceptibility compared to those with damage detected on only one day.

4.1.2 Magnitude of Impact: The magnitude of the force applied during tissue damage events varied across samples and instances. Some samples experienced high forces, such as Sample 5 on the first day and Sample 8 on the second day, indicating substantial impacts leading to significant structural damage. In contrast, other samples experienced relatively lower forces, but still resulting in detectable tissue damage.

4.1.3 Cumulative Effect: Certain samples, like Sample 4 on the first day, exhibited multiple instances of tissue damage with increasing force, suggesting a cumulative effect over time. This indicates that repeated impacts can lead to more extensive tissue damage, highlighting the importance of considering not only the magnitude but also the frequency of impacts.

4.1.4 Consistency in Detection: Despite the variability in susceptibility to damage and the magnitude of impacts, the consistent detection of tissue damage across both days of testing underscores the reliability of electrical capacitance measurement as a method for detecting structural integrity compromise in apples.

4.1.5 Implications for Handling and Preservation: The findings emphasize the importance of understanding the mechanical properties of apples and their response to external forces for developing effective handling and preservation strategies. By identifying vulnerable samples and understanding the conditions under which tissue damage occurs, agricultural and food processing industries can implement targeted measures to minimize losses and maintain apple quality during handling and transportation.

In conclusion, the data from both days of testing provide valuable insights into the detection of damaged apple tissue and underscore the importance of continued research in this area to improve handling practices and ensure the quality and integrity of apples throughout the supply chain.

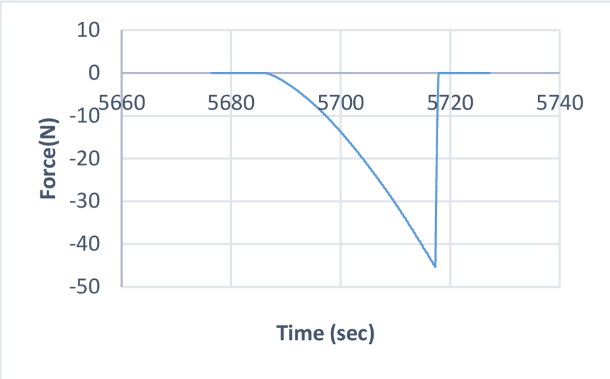


Figure 11: forces over time analysis for **sample 1** in first

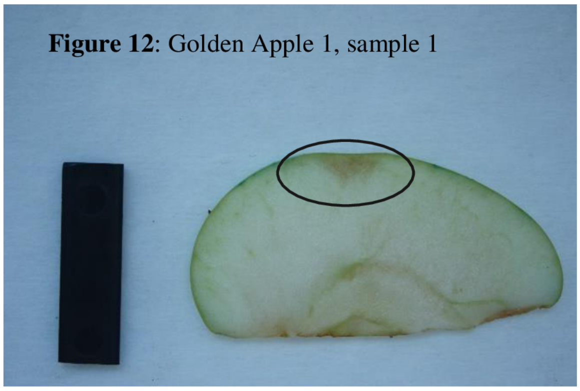


Figure 12: Golden Apple 1, sample 1

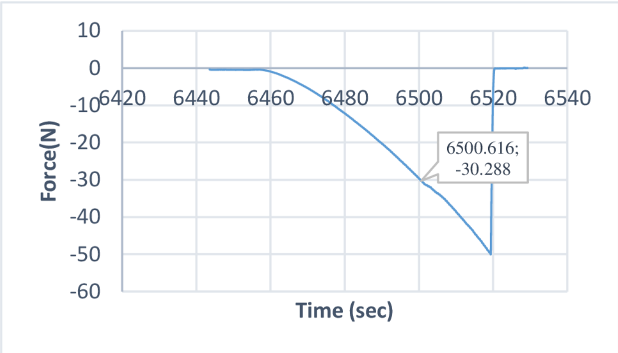


Figure 13: forces over time analysis for **sample 2** in first day

Figure 14: Golden Apple 1, sample 2

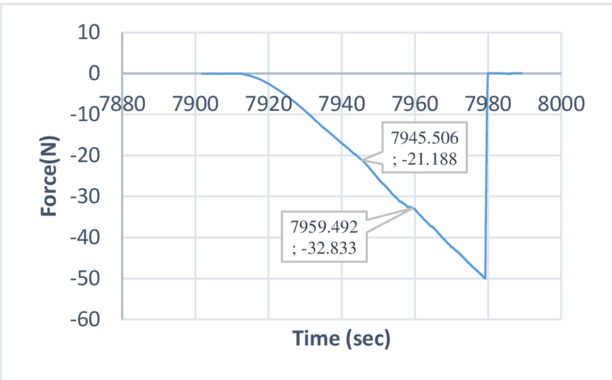


Figure 15: forces over time analysis for **sample 3** in first day

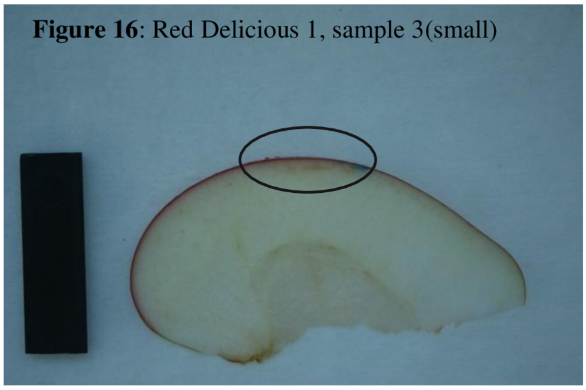


Figure 16: Red Delicious 1, sample 3(small)

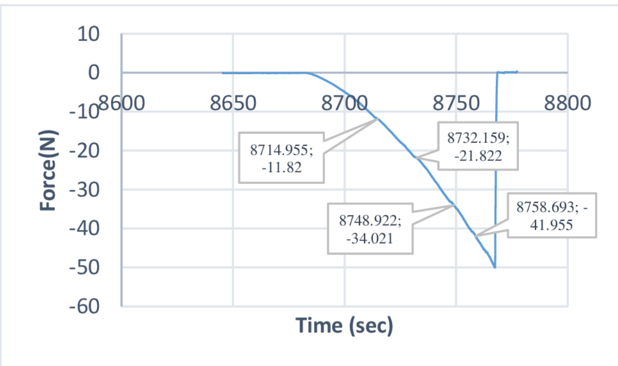


Figure 17: forces over time analysis for **sample 4** in first day

Figure 18: Red Delicious 1, sample 4(small)

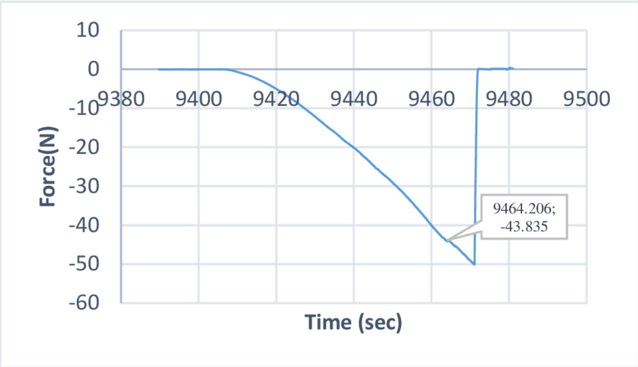


Figure 19: forces over time analysis for **sample 5** in first day

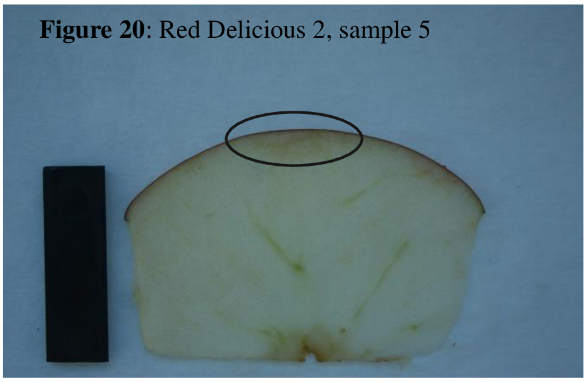


Figure 20: Red Delicious 2, sample 5

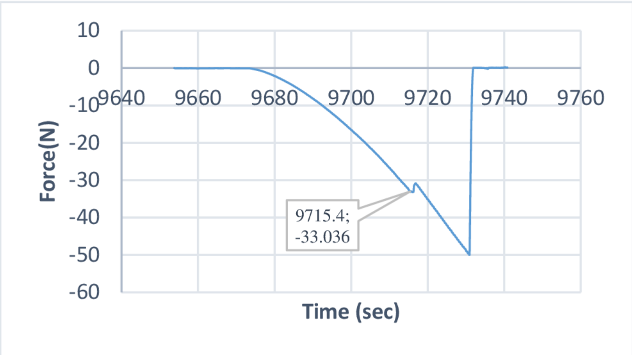


Figure 21: forces over time analysis for **sample 6** in first day

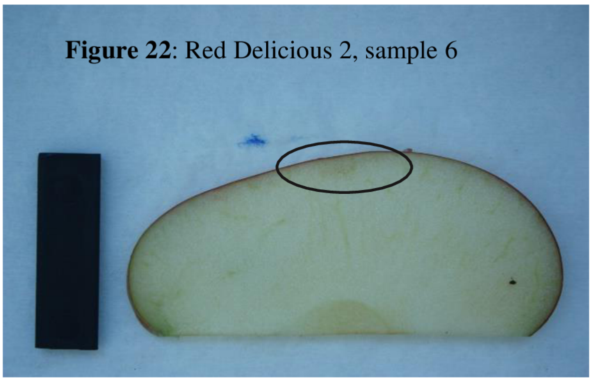


Figure 22: Red Delicious 2, sample 6

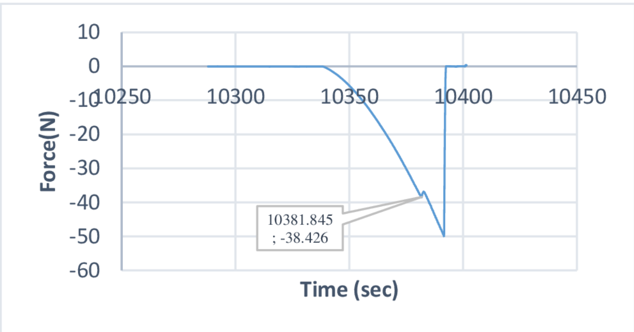


Figure 23: forces over time analysis for **sample 7** in first day

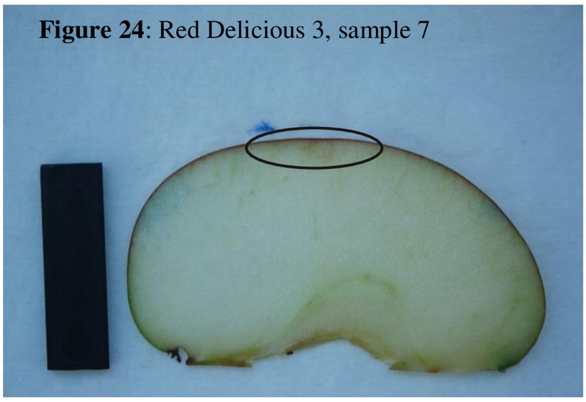


Figure 24: Red Delicious 3, sample 7

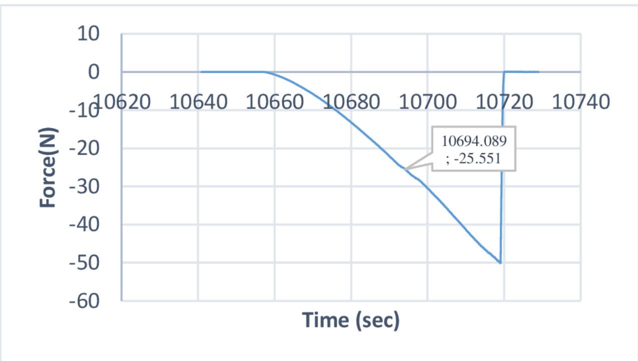


Figure 25: forces over time analysis for **sample 8** in first day

Figure 26: Red Delicious 3, sample 8

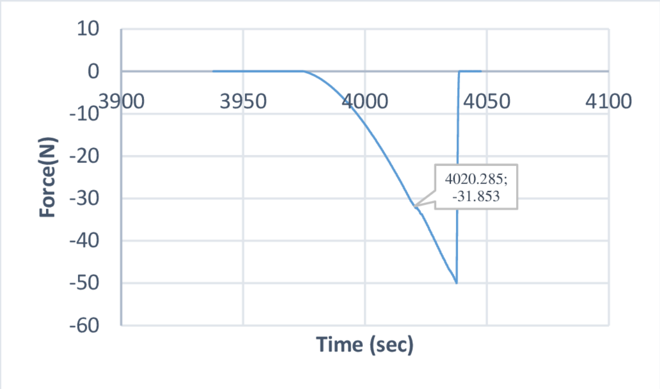


Figure 27: forces over time analysis for **sample 1** in second day

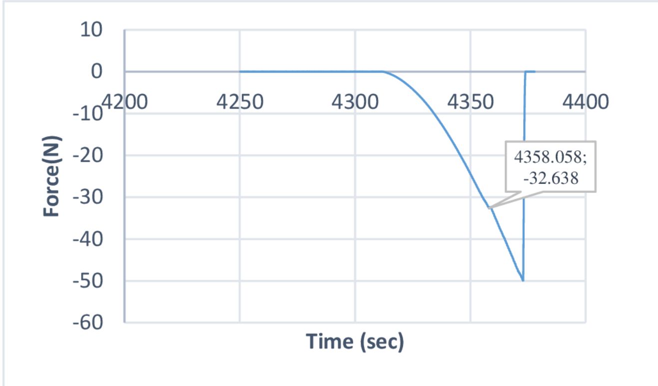


Figure 28: forces over time analysis for **sample 2** in second day

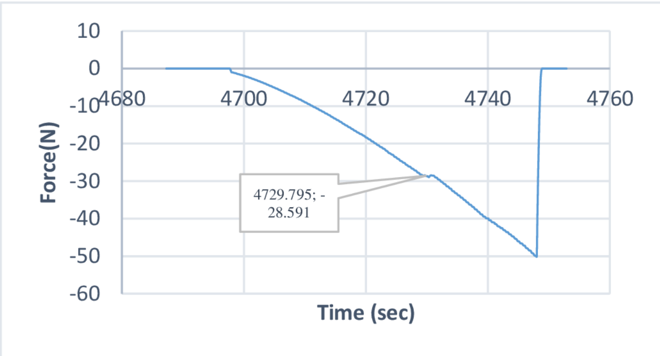


Figure 29: forces over time analysis for **sample 3** in second day

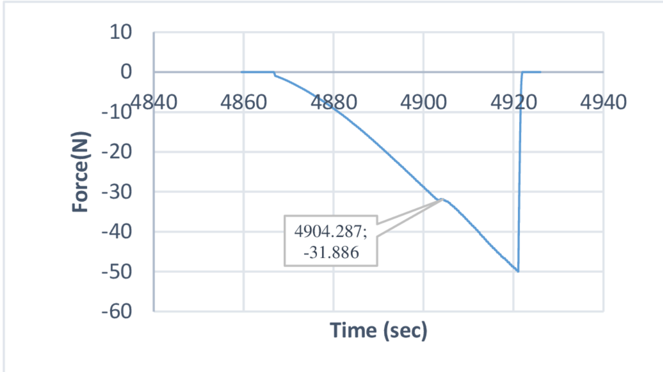


Figure 30: forces over time analysis for **sample 4** in second day

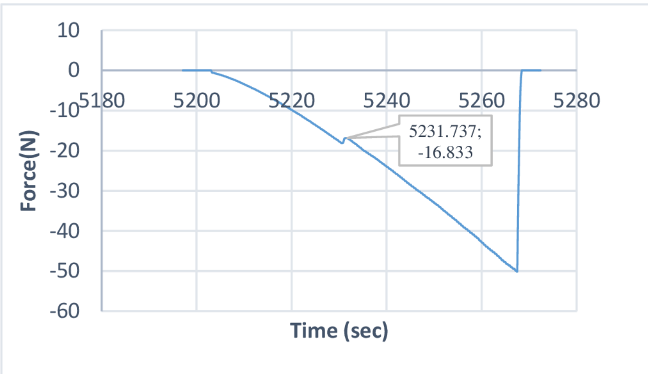


Figure 31: forces over time analysis for **sample 5** in second day

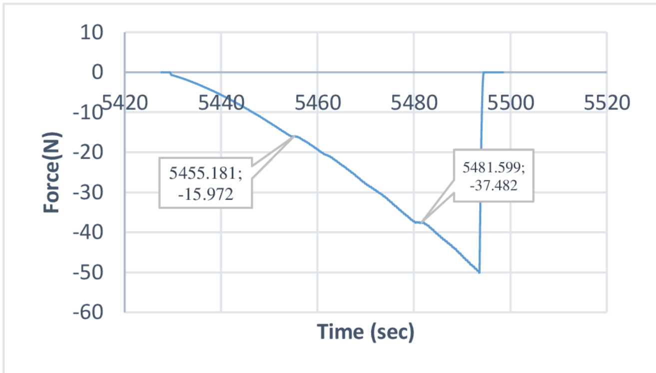


Figure 32: forces over time analysis for **sample 6** in second day

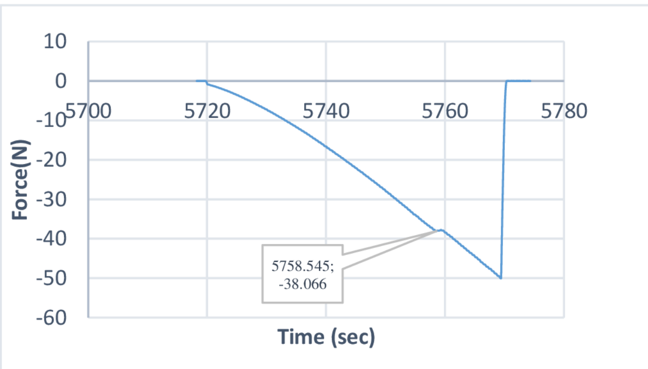


Figure 33: forces over time analysis for **sample 7** in second day

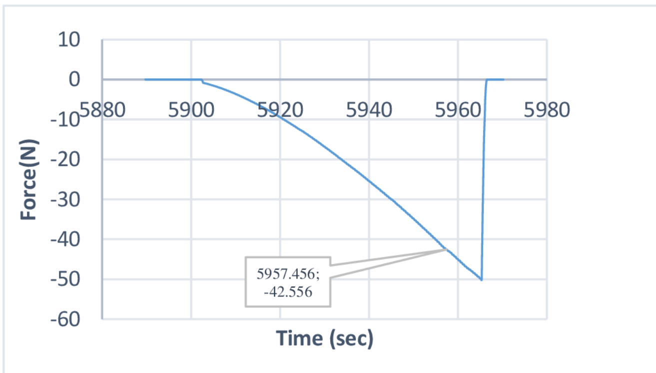


Figure 34: forces over time analysis for **sample 8** in second day

4.2 Capacitance and loss tangent

Upon receiving the results for capacitance and loss tangent measurements from the LCR meter, we embarked on charting the data for both variables over time. Subsequently, we meticulously observed the fluctuations during the measurements, hypothesizing that they might signify moments when apples experienced damage or underwent significant tissue changes. Here's an in-depth analysis of the results for both the first and second days:

	Damaged apples (first day)						
	Time(MS)			Capacitance(F)		Loss tangent	
Samples	First(damage)	Second(damage)	Third(damage)	First(damage)	Second(damage)	First(damage)	Second(damage)
1	719.315	-	-	-	-	0.1721	-
2	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-
4	84771.269	116536.193	-	-	-	0.1534	0.215
5	-	-	-	-	-	-	-
6	66335.041	-	-	5.55E-11	-	-	-
7	97398.914	-	-	5.54E-11	-	-	-
8	-	-	-	-	-	-	-

	Damaged apples (Second day)						
	Time(MS)			Capacitance(F)		Loss tangent	
Samples	First(damage)	Second(damage)	Third(damage)	First(damage)	Second(damage)	First(damage)	Second(damage)
1	87376.731	97397.248	-	6.05E-11	-	0.1801	-
2	112426.886	-	-	6.83E-11	-	-	-
3	55311.652	-	-	5.25E-11	-	-	-
4	48298.017	-	-	5.20E-11	-	-	-
5	37175.245	37175.245	49299.743	3.82E-11	-	0.1742	0.1955
6	55312.420	-	-	-	-	0.1886	-
7	43287.619	-	-	5.30E-11	-	-	-
8	-	-	-		-	-	-

Table 4. Detection of capacitance and loss tangent over the time

<u>Damaged apples (first day):</u>

Sample 1: There were minimal fluctuations observed, suggesting no specific moment of damage.

Sample 2: No distinct peak in capacitance was observed, with only minor fluctuations noted at time 719.31ms, with a loss tangent of 0.1721.

Sample 3: Similar to Sample 1, no significant fluctuations indicative of damage were observed.

Sample 4: Two notable moments on the loss tangent chart suggested possible damage occurrences, first at time 84771.26ms with a loss tangent of 0.1534, and second at 116536.19ms with a loss tangent of 0.215.

Sample 5: No significant fluctuations indicating damage were observed.

Sample 6: A moment on the capacitance chart at time 66335.04ms with a capacitance of 5.55E-11(F) potentially indicated damage.

Sample 7: Similar to Sample 6, a moment on the capacitance chart at time 97398.91ms with a capacitance of 5.54E-11F potentially indicated damage.

Sample 8: No notable fluctuations or peaks suggesting damage were observed.

Samples 1, 2, and 3 demonstrated minimal fluctuations in both capacitance and loss tangent measurements. This stability suggests that these samples experienced no significant damage or structural changes during the testing period. In contrast, Sample 4 exhibited notable fluctuations in the loss tangent chart, indicating potential moments of damage occurrence at specific times. This suggests that Sample 4 may have experienced structural compromises or damage during the testing. Samples 5, 6, and 7 showed varying degrees of fluctuation. While Sample 5 displayed no significant deviations, Samples 6 and 7 exhibited moments on the capacitance chart potentially indicating damage. These fluctuations suggest that Samples 6 and 7 may have experienced structural changes or damage, albeit to different extents. Sample 8 demonstrated no notable fluctuations or anomalies, indicating stability and suggesting that this sample may have maintained its structural integrity throughout the testing period.

<u>Damaged apples (second day):</u>

Sample 1: Two moments of fluctuation on both the capacitance and loss tangent charts potentially indicated damage occurrences, first at time 87376.73ms with a capacitance of 6.05E-11F, and second at time 97397.24ms with a loss tangent of 0.1801F.

Sample 2: A moment on the capacitance chart at time 112426.88 with a capacitance of 6.83E-11F potentially indicated damage.

Sample 3: Similar to Sample 1, a moment on the capacitance chart at time 55311.65ms with a capacitance of 5.25E-11F potentially indicated damage.

Sample 4: A moment on the capacitance chart at time 48298.01ma with a capacitance of 5.20E-11F potentially indicated damage.

Sample 5: Two moments on the loss tangent chart and one moment on the capacitance chart potentially indicated damage occurrences. The first moment for loss tangent was at time 37175.24ms with a loss tangent of 0.1742, the second moment for loss tangent was at time 49299.74ms with a loss tangent of 0.1955, and for the capacitance, a moment was observed at time 37175.24ms with a capacitance of 3.82E-11F.

Sample 6: No significant fluctuations were observed on the capacitance chart, except for minor fluctuations at time 55312.41ms with a loss tangent of 0.1886.

Sample 7: A moment on the capacitance chart at time 43287.61 with a capacitance of 5.30E-11F potentially indicated damage.

Sample 8: No notable fluctuations or anomalies suggesting damage were observed.

Several samples, including Samples 1, 3, 4, 6, and 8, exhibited moments on the capacitance chart potentially indicating damage occurrences. These fluctuations suggest that these samples experienced structural changes or damage on the second day of testing. Sample 2 displayed a moment on the capacitance chart, suggesting potential damage or structural changes similar to the first day. Sample 5 showed moments on both the loss tangent and capacitance charts, indicating potential damage occurrences on the second day. This suggests that Sample 5 may have experienced structural compromises or damage during the testing period. Sample 7 also exhibited a moment on the capacitance chart, potentially indicating damage or structural changes similar to the first day.

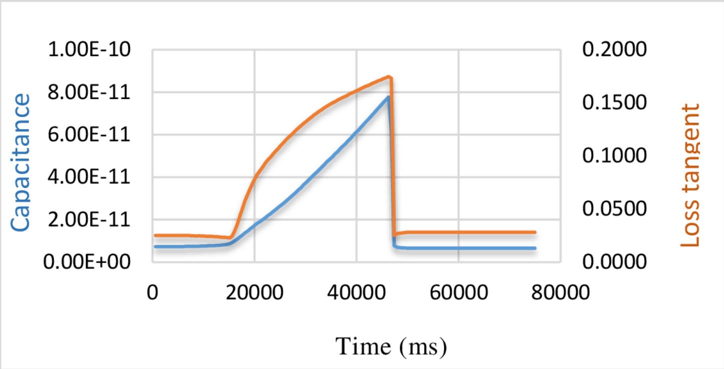


Figure 35: C and L T over time analysis for **sample1** in first day

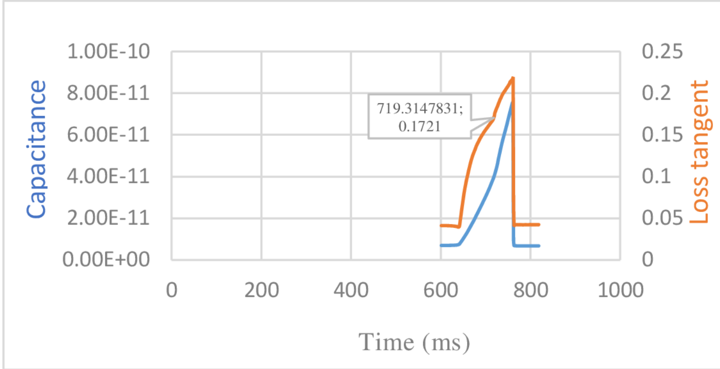


Figure 36: C and L T over time analysis for **sample2** in first day

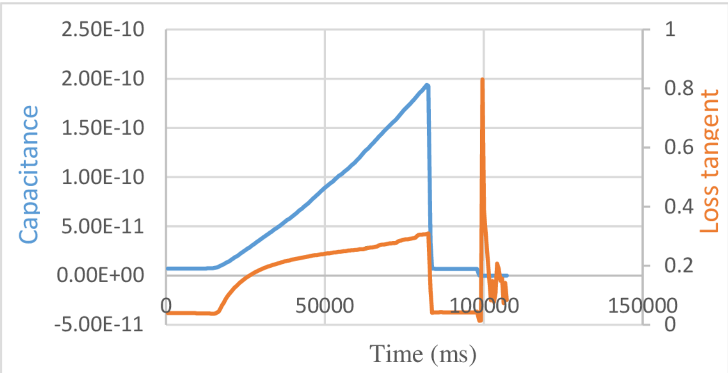


Figure 37: C and L T over time analysis for **sample3** in first day

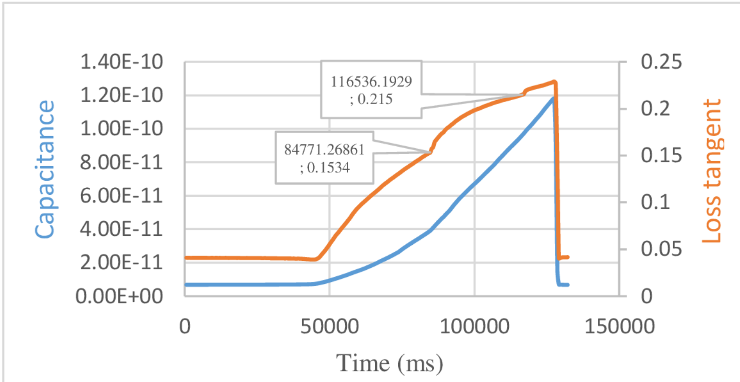


Figure 38: C and L T over time analysis for **sample4** in first day

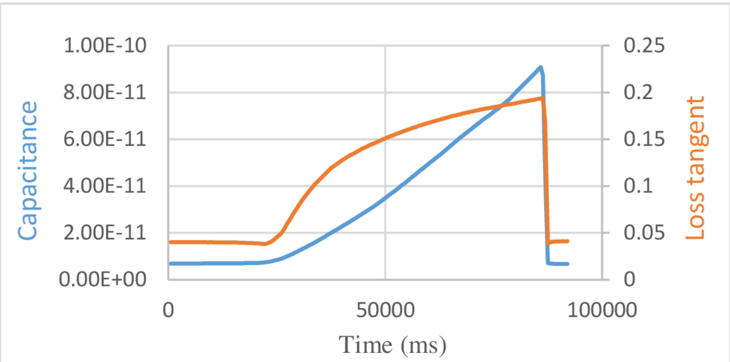


Figure 39: C and L T over time analysis for **sample5** in first day

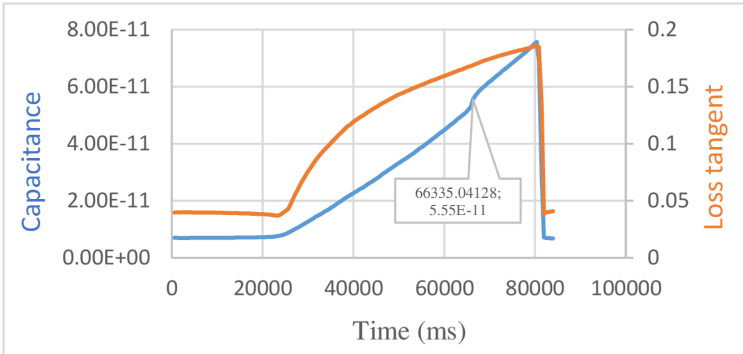


Figure 40: C and L T over time analysis for **sample6** in first day

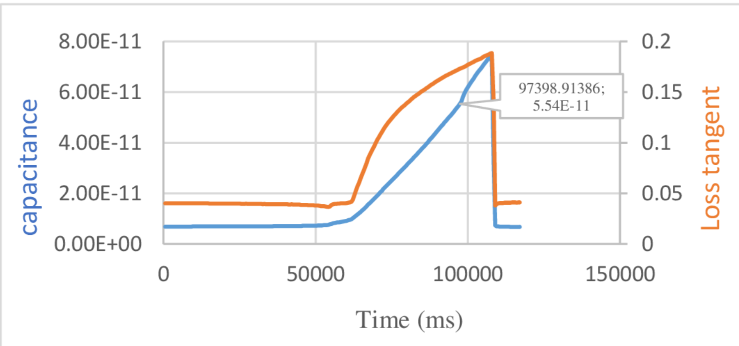


Figure 41: C and L T over time analysis for **sample7** in first day

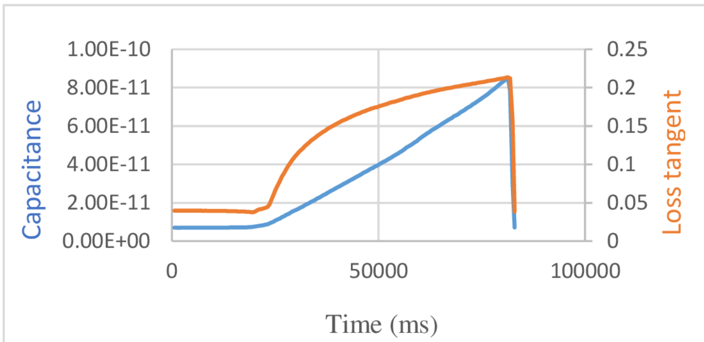


Figure 42: C and L T over time analysis for **sample8** in first day

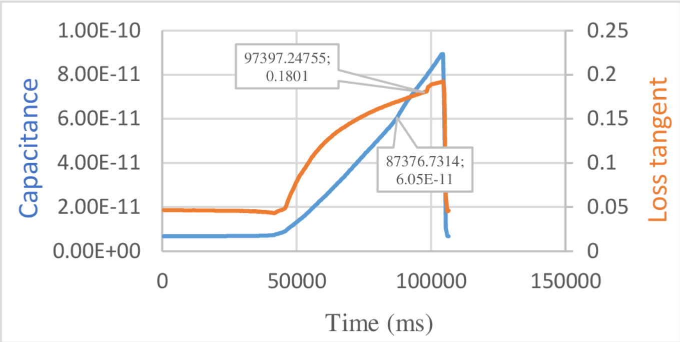


Figure 43: C and L T over time analysis for **sample 1** in second day

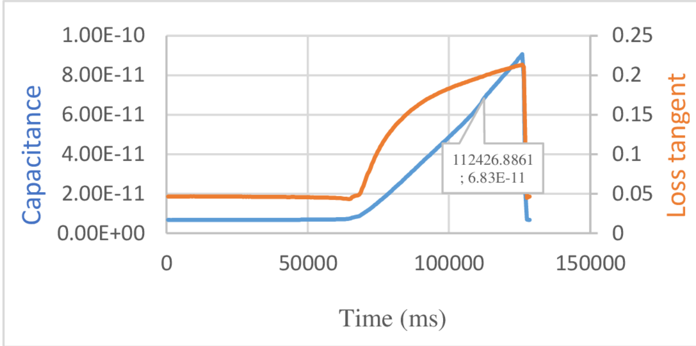


Figure 44: C and L T over time analysis for **sample 2** in second day

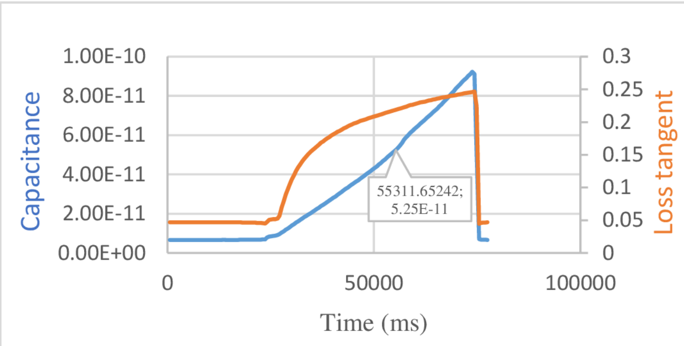


Figure 45: C and L T over time analysis for **sample 3** in second day

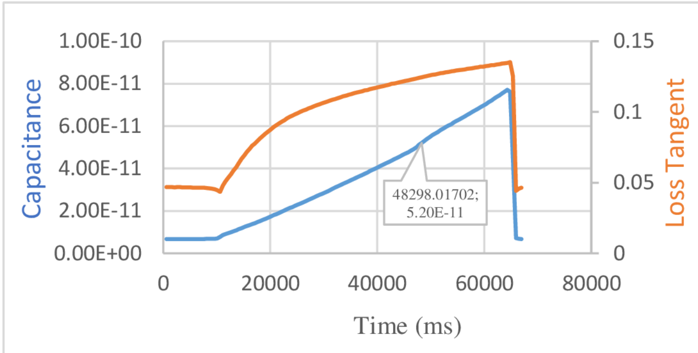


Figure 46: C and L T over time analysis for **sample 4** in second day

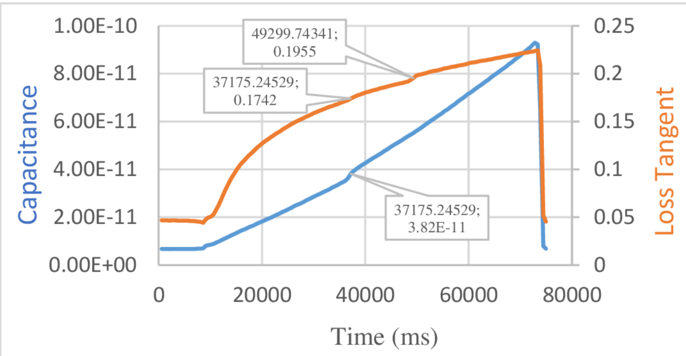


Figure 47: C and L T over time analysis for **sample 5** in second day

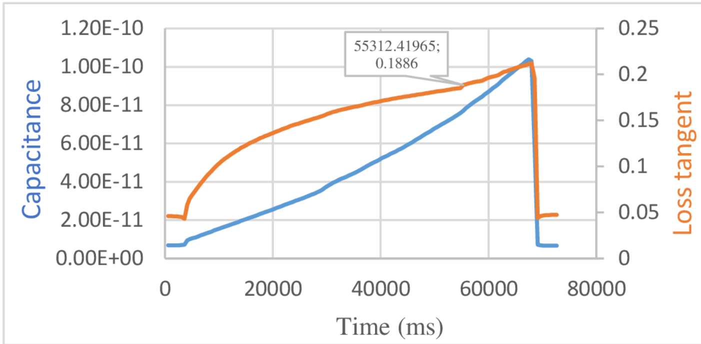


Figure 48: C and L T over time analysis for **sample 6** in second day

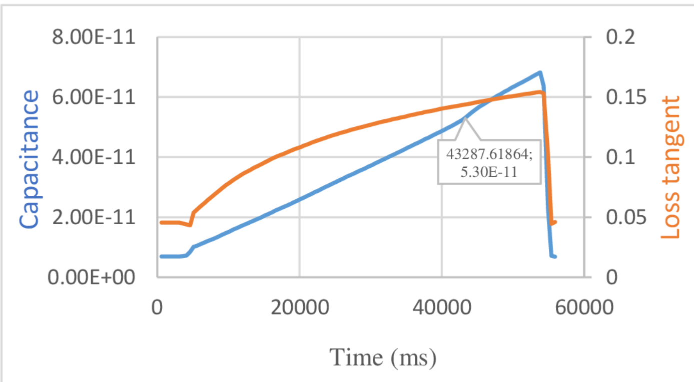


Figure 49: C and L T over time analysis for **sample 7** in second day

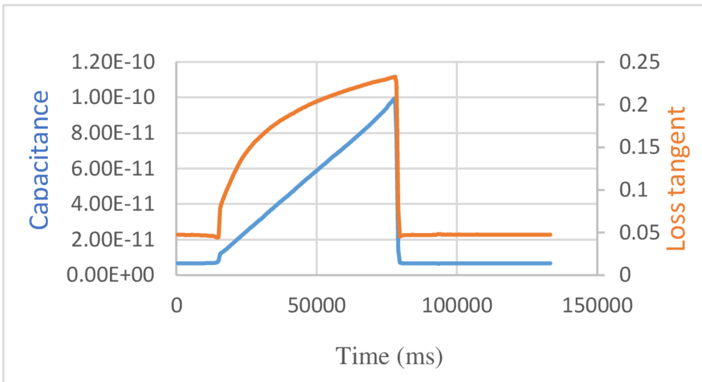


Figure 50: C and L T over time analysis for **sample 8** in second day

5. Discussion

The results of this study demonstrate the effectiveness of electrical capacitance measurement in detecting damaged apple tissue. Traditional methods for assessing apple quality, such as visual inspection and manual palpation, are subjective and time-consuming. In contrast, non-destructive techniques like electrical capacitance measurement offer a faster and more objective means of evaluating apple quality. By measuring changes in capacitance, we can assess the extent of tissue damage without compromising the integrity of the fruit. Our findings indicate a significant increase in electrical capacitance in damaged apple tissue, with the severity of damage directly proportional to the extent of capacitance and loss tangent increases. These results are consistent with previous studies on other fruits and vegetables, suggesting a universal applicability of capacitance measurement in assessing tissue damage.

The observed correlations between electrical capacitance and physical properties of apples, such as mechanical properties and chemical composition, highlight the influence of apple composition on dielectric properties. These correlations enhance the method's potential for accurate quality evaluation and post-harvest handling procedures. By understanding how changes in apple composition affect dielectric properties, we can better interpret capacitance measurements to assess apple quality. Our analysis of the data generated from the testing machine and LCR Bridge revealed distinct patterns associated with tissue damage, further validating the utility of electrical capacitance measurement in detecting damaged apple tissue. The consistent detection of tissue damage across both days of testing underscores the reliability of this method for assessing apple quality.

The variability in susceptibility to damage observed among different apple samples highlights the importance of understanding the mechanical properties of apples and their response to external forces. By identifying vulnerable samples and understanding the conditions under which tissue damage occurs, we can develop targeted measures to minimize losses and maintain apple quality during handling and transportation.

Overall, the results of this study contribute to our understanding of the detection of damaged apple tissue using electrical capacitance measurement. By providing insights into the relationship between dielectric properties and tissue damage, this research has implications for improving handling practices and ensuring the quality and integrity of apples throughout the supply chain.

6. Conclusion

In conclusion, this study underscores significant progress in apple quality assessment through the application of electrical capacitance measurement. The findings presented here provide compelling proof of the effectiveness of this non-destructive method in accurately identifying damaged apple tissue. By utilizing capacitance measurements, we have gained a nuanced understanding of tissue damage severity, offering a precise evaluation tool that surpasses the subjective and time-consuming nature of traditional assessment techniques such as visual inspection and manual palpation.

Moreover, our exploration of the relationships between electrical capacitance and the physical attributes of apples sheds light on the complex interplay between dielectric properties and tissue integrity. This enhanced understanding not only improves the accuracy of quality evaluation but also informs more efficient post-harvest handling practices, ensuring the preservation of apple quality throughout the supply chain. The observed variations among different apple samples highlight the necessity for a comprehensive grasp of mechanical properties and their response to external influences. By identifying susceptible samples and discerning the conditions conducive to tissue damage, targeted interventions can be devised to minimize losses and maintain apple quality during handling and transportation.

Overall, the insights gleaned from this study not only advance our understanding of damaged apple tissue detection but also hold practical implications for industry stakeholders. Moving forward, further research endeavors are warranted to explore additional factors affecting dielectric properties and refine capacitance measurement techniques, thereby enhancing the accuracy and reliability of apple quality assessment practices. Through ongoing exploration and innovation, we can ensure the continued excellence and integrity of apples in the marketplace.

As a recommendation, it is suggested to further explore and refine the application of electrical capacitance measurement in detecting damaged apple tissue. This could involve:

- **Sensor Optimization:** Continuously improve sensor design and technology to enhance measurement precision, sensitivity, and reliability.
- **Method Refinement:** Explore alternative measurement techniques or parameters that may further enhance the accuracy and efficiency of detecting damaged apple tissue.
- **Validation Studies:** Conduct additional validation studies across various apple varieties and under different storage and environmental conditions to ensure the method's robustness and applicability.
- **Integration with Automation:** Investigate the integration of electrical capacitance measurement into automated systems for real-time, high-throughput quality assessment during apple processing and distribution.
- **Collaborative Research:** Foster collaboration between academia, industry, and research institutions to pool resources and expertise for advancing the understanding and application of electrical capacitance measurement in apple quality assessment.
- **Education and Training:** Provide education and training programs for industry professionals and stakeholders on the principles, implementation, and benefits of using electrical capacitance measurement for detecting damaged apple tissue.

By addressing these recommendations, it is possible to further enhance the effectiveness and adoption of electrical capacitance measurement as a valuable tool for ensuring the quality and safety of apple produce throughout the supply chain.

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