Chapter

Dielectric Spectroscopy for the Non-Destructive Characterization of Biomaterials: Fundamentals, Techniques, and Experimentations

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Abstract

This chapter provides an overview of research on the dielectric properties of fresh food and their applications in assessing food quality and freshness. Non-destructive methods, including dielectric techniques such as dielectric spectroscopy (DS) and bioelectrical impedance spectroscopy (BIS), have gained importance in assessing food quality without damaging the products. The importance of external appearances, such as color, size, brightness, and hardness, in determining the freshness of fruits and vegetables is emphasized. Several dielectric techniques, such as impedance, capacitance, and electrical conductivity measurements, are studied to assess quality at distinct stages of the supply chain. These techniques can detect defects, diseases, and mechanical damage and facilitate storage quality control and processing quality evaluation. Accurate measurements and instrumentation advancements are crucial for effectively implementing these techniques. The study of dielectric properties offers promising prospects for evaluating food quality and ensuring freshness. Further research and technological advances in this field can enhance the monitoring and maintaining optimal conditions for fresh produce throughout the food supply chain, reducing food waste and improving consumer satisfaction.

Keywords: dielectric properties, dielectrics, non-destructive, bioelectrical impedance spectroscopy (BIS), Characterization of Biomaterials

1. Introduction

The rapid advancement of technology has broadened its field of application, improving the daily lives of users and their food. Currently, research is being done on systems that will enhance food production to meet the high demand, in addition to studying its quality and improvements in transport conditions [1]. The current trend is to achieve a healthy diet, to which seasonal fruit and vegetable products significantly contribute [2]. Fresh foods are essential in the human diet due to their high

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nutrients, vitamins, minerals, and fiber content. The quality of these foods can be evaluated in several ways, considering their external appearances, such as color, size, brightness, smell, and hardness, or internal such as taste, texture, water content, and nutritional content. The external appearance is considered an essential criterion to consider some fruit as "fresh" and implies creating expectations about its internal quality. Manufacturers seek a balance between the appearance and maturity of the fruit in the highest qualities, such as color and hardness for consumption, in addition to achieving maximum economic performance in its marketing, including freshness and durability. In the commercialization phase, durability is essential for its processing and commercialization until it arrives at homes in optimal conditions of internal and external quality.

Before marketing, the transfer of fruits and vegetables must be controlled from the orchard to the distribution warehouses and the shops for sale. Depending on the product and the distance, the product must be moved in refrigerated chambers, where temperature and humidity affect fruits and vegetables differently. If it is not moved at the proper temperature, it causes cold damage, not arriving in the right conditions optimal for shops. Therefore, cold damage is investigated, looking for combinations of products with a wide temperature range to be transported with others of a more demanding range but of more excellent economic value [1].

Horticultural engineering has evolved a lot, and higher quality products are increasingly sought, but at the same time more resistant to transport, production, and storage conditions. More research is being conducted on post-harvest treatment, where innovative technologies make it possible to extend the useful life of the products so that they arrive in the best conditions at the consumers' tables. Constant product quality monitoring is essential at every stage of the supply chain, and it is crucial to utilize portable tools in industrial and field environments [3].

The tendency to consume high-quality fresh products has motivated the producers and marketers of these products to encourage the study of quality detection methods, optical, acoustic, and mechanical systems have been developed to assess quality based on sensory perceptions such as sight, smell, and touch [4]. Quality parameters such as nutritional value, health, and safety are less tangible for consumers because they require measurements. The results of these measurements are shown to consumers on their labels and are a claim for the most demanding consumers or who seek high-quality products in a healthy diet.

In the last decade, non-destructive methods are advancing evaluating food quality since they can be assessed without destroying the examined product. Within non-destructive methods, the main application is those based on images [5], thermal imaging [6], and spectroscopy [7]. However, many systems are based on the simulation of smell, such as the electronic nose or taste, the electronic tongue [8], and sound as acoustic systems [9].

Among other methods of assessing quality, one can consider the measurement of dielectric properties, which refer to the ability of materials to store and transmit electrical energy in an electrical field [10]. The technique known as dielectric spectroscopy (DS) refers to the interaction between a material and an externally applied electric field. In the case of fruits and vegetables, non-destructive methods such as bioelectrical impedance spectroscopy (BIS) are utilized for quality control purposes [11]. Measurement of dielectric properties offers helpful insights into the quality and freshness of food at different stages of the food chain, as well as the presence of defects or diseases [12], storage quality control, and processing quality evaluation [13]. The measurement of these properties can be done using different dielectric techniques, such as DS (which measures the dielectric response of materials at varying frequencies), electrical impedance (a method used to measure the electrical resistance of materials), capacitance (a technique that measures the electrical energy storage capacity of materials) and electrical conductivity (a technique that assesses the ability of materials to conduct electrical current).

DS determines the dielectric properties utilizing a multifrequency impedance analyzer, which observes the electrical response when current passes through the tissue for certain measurement conditions. The approach entails the assessment of the dielectric constant and dielectric loss, which indicate the material's ability to store and discharge electrical energy. Electric permittivity encompasses the interaction between electromagnetic waves and substances, as well as the determination of charge density when subjected to an external electric field [14]. The first documentation of dielectric properties for grains was reported by Nelson in 1965. Permittivity depends on the dielectric constant and a loss factor [15], explained in the next section for varied materials ranging from solids to liquids and gases.

At present, the dielectric characteristics of many foods are known, being one of the factors that affect the measure of moisture content. Also, certain mineral substances and organic acids have the potential to undergo dissociation, producing elevated electrolytic conductivity in food.

This review presents an overview of the current research on fresh food's dielectric properties. It delves into the various dielectric techniques employed to measure these properties and explores their applications in evaluating food quality and freshness.

2. Techniques

2.1 Theory

For decades, many industrial applications have succeeded in taking advantage of the potential discovery of radio frequency to establish empirical correlations between the physical properties in materials and the dielectric properties and develop techniques for the rapid and non-destructive study of physical properties. Measurement, modeling, and applications of the dielectric properties is a unique scientific journey in dielectrics that reveals as many challenges as rewards [16].

By dielectric properties of materials are designated the electric characteristics determining the interaction of materials with electric fields. In this concern, a particular approach defines the interaction of the electric field component of the electromagnetic waves when it comes to food materials, agricultural products, and other dielectric materials.

Being dependent on the composition of material, frequency, and temperature, dielectric properties have been opted as bases for developing sensors. These rapid and nondestructive methods can be valid for assessing the physical properties of materials [17].

In discussing the applications of dielectric properties, some simplified definitions are helpful. Primarily, the propagation of electromagnetic energy in free space at the velocity of light (c) is the fundamental characteristic of all forms of electromagnetic energy. The electromagnetic parts of a material have a markable influence on the speed of propagation (V) of electromagnetic energy in that material, and this velocity (V) is given by Eq. (1), such as the magnetic permeability is given by μ and the electric permittivity by ε .

$$V = \frac{1}{\sqrt{\mu\varepsilon}} \quad (1)$$

The same equation defined in free space becomes as follows in Eq. (2), where μ_0 is the vacuum permeability y of free space, and ε_0 is vacuum permittivity.

$$V = \frac{1}{\sqrt{\mu_0\varepsilon_0}} \quad (2)$$

To interpret the molecular mechanism, the interaction of electromagnetic waves with any material is studied by Maxwell's equation [18]. The relative complex permittivity (ε^*) is represented in Eq. (3), where ε' and ε'' are commonly called the dielectric constant and loss factor, respectively, and j = $\sqrt{}-1$.

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \quad (3)$$

Relatively to free space, the relative complex permittivity $\left(\varepsilon_r^*\right)$ will be presented as follows in Eq. (4).

$$\varepsilon_r^* = \frac{\varepsilon_a}{\varepsilon_0} = \varepsilon'_r - j\varepsilon''_r \quad (4)$$

Where ε_0 is 8854×10^{-12} F/m, and ε'_r, and ε''_r are the relative dielectric constant and loss factor respectively; hence, this latter the two quantities of interest that are the real part of the complex permittivity ε referred to as the dielectric constant and the complex part given by (ε referred to as loss factor).

As a material classified as "dielectric", this reflects its ability to store energy under the application of an external electric field. When subjected to an electric field, the real part, ε', describes the ability of a material to store energy and influences the electric field distribution and the phase of waves traveling through the material; its value is related to chemical structure and intermolecular interaction [19].

The amount of energy lost or dissipated by the material under an external electric field or in any polarization mechanism generating heat is measured by the loss factor, which is the imaginary part of the permittivity [20]. Nevertheless, this loss factor is always proportional to the amount of conversion of thermal energy in food [21].

The loss factor is always positive and has smaller values than the dielectric constants. The values of dielectric constants are usually higher than the loss factor that, is commonly limited and positive and is returned to the energy dissipation such that a material is lossless when this loss factor is null [22].

Relaxation time (τ) measures the mobility of the molecules (dipoles) in a material. It is the time required for a displaced system aligned in an electric field to return to 1/e of its random equilibrium value. It is also called the time needed for dipoles to become oriented in an electric field.

The alternating electric field is slow enough for the dipoles to keep pace with the field variations at frequencies below the relaxation frequency. Since the polarization can fully develop, the loss factor, $\varepsilon r''$, is directly proportional to the frequency. As the frequency increases, $\varepsilon r''$ continues to increase, but $\varepsilon r'$ decreases due to the phase lag between the dipole alignment and the electric field. Above the relaxation frequency, both $\varepsilon r''$ and $\varepsilon r'$ decrease as the electric field is too fast to affect the dipole rotation, causing the orientation polarization to disappear.

Figure 1 shows the dielectric properties of distilled water at 25°C [23]. Many liquids and solids have been experimented with through the various models of Debye. Thermal agitation is the most significant in liquids where thermal agitation is maximal, thus producing more considerable losses at higher frequencies [24].

It is crucial to obtain the optimum frequency range at which the material under test will have appropriate dielectric properties to develop a proper heating process based on electromagnetic energy [25]. The interaction between the material and high-frequency electromagnetic energy is crucial for defining the desired properties. Consequently, it is essential to carefully select food and meals to facilitate MW propagation [26–28].

2.2 Measurement systems

Building measurement systems rely on providing equipment for the abovementioned properties. Through the past years, worldwide experiments have witnessed a variety of technologies implemented for that purpose. The built systems differ according to the material under test and the properties such as resonant frequency and quality factor from another perspective. Knowing the physical dimensions of the material and measuring the transmission and/or reflection can characterize the permittivity and permeability. At low frequencies, impedance analyzers and LCR were considerably used by simulating the material with an AC source and monitoring the capacitance and dissipation factors [27]. The impedance data analysis starts with two complex yet critical steps. The first stage involves investigating the physical circuit and estimating the necessary equations. The mathematical methods are evaluated at a second stage, allowing the model parameters to be extracted [29].

Depending on the material's nature, the fixture's choice was made so that the sample holder would fit the solid, liquid, powder, or gaseous nature of the tested material, along with appropriate software modeling the interaction of the fixture with the said material. The impedance measurement method is commonly applied by

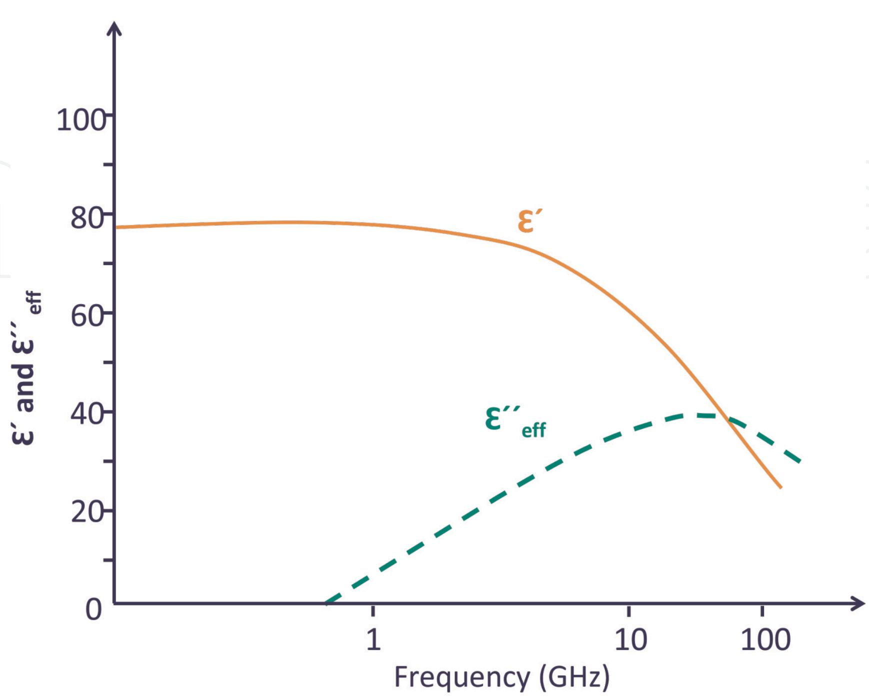


Figure 1.
The frequency-dependent dielectric characteristics of water.

applying a current across electrodes and observing the voltage. Another widespread practice for many applications is the self-balancing bridges developed by Agilent. Such bridges under a higher voltage can give a better signal-to-noise ratio higher than 10–300 mV. Such applications are robust, simple, and more practical than the old manual bridges. With advances in experiments comes the urge for more complex systems to give accurate results and cover more material. This led to a fast improvement in techniques. Moreover, high microwave frequencies applied during experiments were to produce radiation loss, especially considering the expensive design of a microwave network analyzer. Throughout the past decades, a variety of equipment has been accessible in the market for impedance measurements. However, network analyzers emerged as the most widely employed option due to their capacity to handle large electrode systems and cover a wide frequency range. Notably, vector network analyzers like PNS, PNA-L, ENA, and ENA-L are capable of sweeping high-frequency stimulus responses, ranging from 300 kHz to 110 GHz or even 324 GHz. Impedance and scalar network analyzers [30] are known for their cost-effectiveness compared to Vector Network Analyzers (VNAs). However, their usage is restricted to the frequency range associated with the α and β dispersions.

The experimental setup involves utilizing the open-ended probe technique, which includes a coaxial probe and dedicated software, to conduct a range of experiments using the network analyzer. Keysight Technologies came out with spectrum and network analyzers with high measurement integrity.

The S11 reflection parameter determines the surface of contact between the probe and the tested material using the VNA that is meant to be a probe with specialized software. The phase shift corresponding to the change in the magnitude ratio is called S11. The illustrations of reflection and transmission probes are highlighted in **Figure 2**. Some exemplary models are incorporated into the supplied software to collect the real and imaginary parts of the dielectric permittivity.

For less expensive solutions, the 85070E probe is replaced with another subminiature version (SMA) coaxial connector that can perform correctly at some good frequency ranges [32].

Conversely, coaxial transmission lines or waveguides are employed to evaluate the S21 parameter, which represents the ratio between the transmitted signal through the material under test and the incident signal. The magnetic permeability and dielectric permittivity analysis determine the S21 parameter [33].

In the reflective operating mode, the VNA produces a sinusoidal signal spanning a wide frequency range from 20 kHz to 8 GHz. The incident and reflected signal separation happen at this point [34]. From the reflected signal of the probe, dielectric properties obtained are chargeable to derive the phase and the amplitude. Theoretical models are also used to derive the frequency spectra for permittivity factors $\varepsilon'(f)$ and $\varepsilon''(f)$. Moreover, some elements should be counted as a distribution parameter system for modeling purposes, especially since the real part of $\varepsilon^*(f)$ requires applying high frequencies [35].

2.3 Measuring techniques

The test fixture was selected depending on the nature of the material to be experimented with. Some significant features behind the considered elected option are the frequency range, the required accuracy level, the measurement volume, and the experiments' budget [31]. Consequent to the dielectric material under test, the

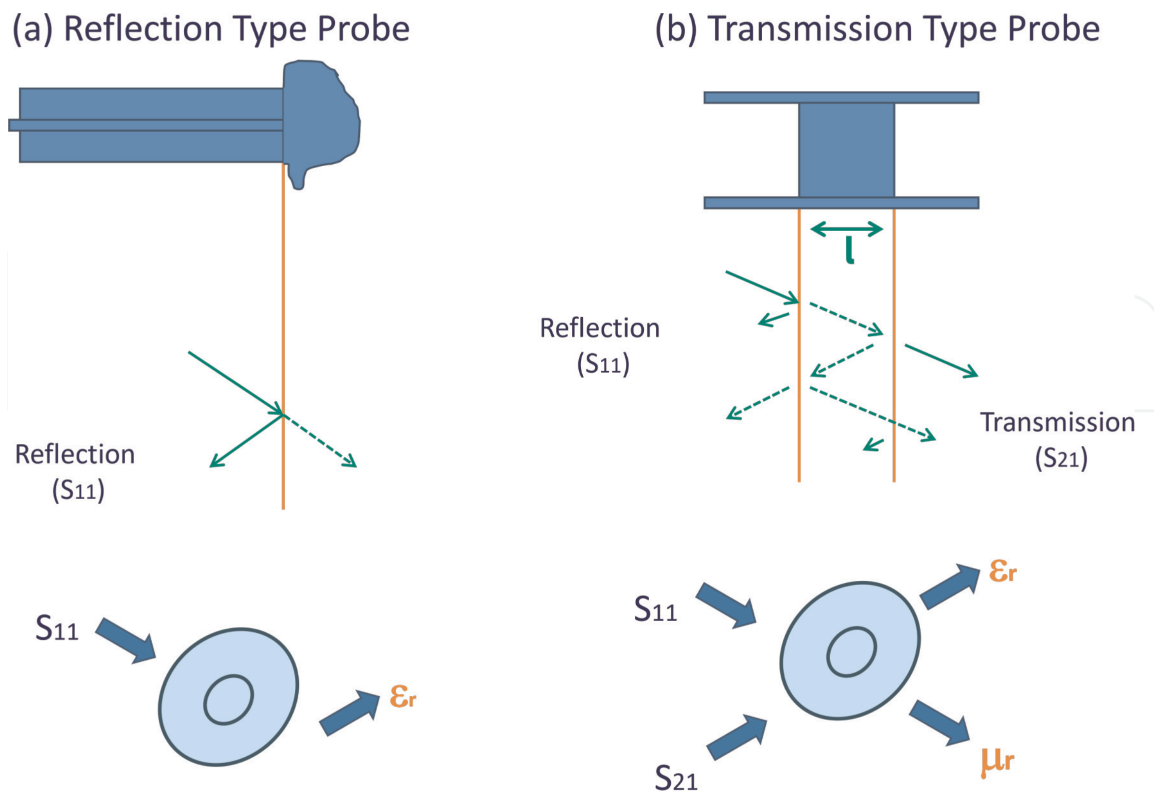


Figure 2.
Reflection and transmission types of probes [31].

design of the sample holder, the measurement system, and the technique was designated.

Figure 3 illustrates the main methodologies employed in the agricultural and food industry in relation to frequency.

The coaxial probe method is a simple and convenient method for liquids and semi-powders where the material is measured by emerging the probe into the liquid and such a system consists of the probe, the network analyzer, the software that is included in the 85070E probe kit. No external computer is needed for the PNA generations. At the same time, it is not the case for other analyzers that rely on the 82357A USB (universal serial bus) to GPIB (General Purpose Interface Bus) interface. A common technique is the Agilent 85070E open coaxial probe, which has been used immensely in biological materials, liquids, and other mixtures, where the permittivity can be derived at a frequency ranging from 0.2 to 50 GHz [31]. The vector network analyzer accompanying such experiments is the popular Agilent 87070 [31]. This system is premeditated to be highly priced but was extensively used in the industry, being one of the most commercial measurement systems adapted for solids and liquids.

Most of the food industry experiments in the last decade were executed using the 85070E Dielectric Probe Kit, including probe and software. The complete system used in process analytic technologies is based on a network analyzer measuring the dielectric parameters of the material (dielectric constant, loss factor, loss tangent, and Cole-Cole). It is connected to the Vector network analyzer Agilent N9912A.

Currently, a commercially available THz-TDS system (TeraView TPS 4000) is employed, which incorporates a pair of GaAs photoconductive antennas (emitter and receiver). This system utilizes a femtosecond laser module to generate laser pulses that are divided into two separate beams (pump and probe) using a beam splitter [30].

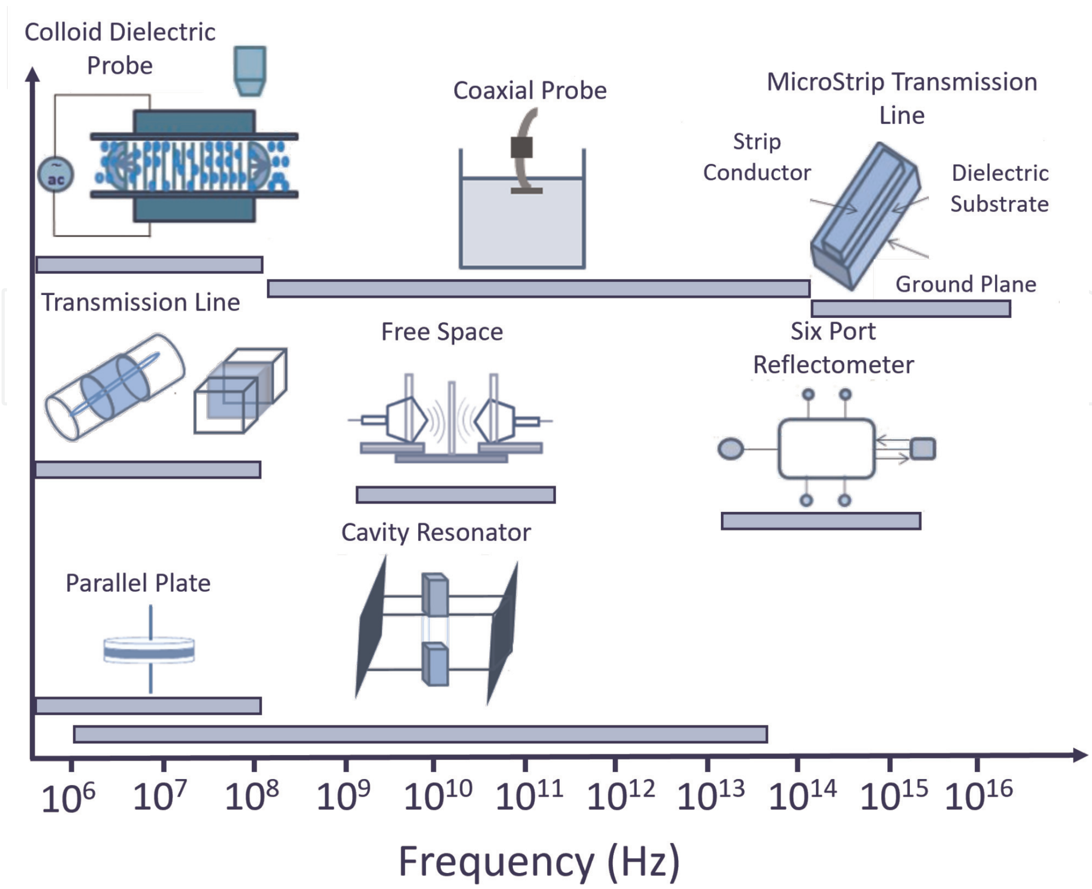


Figure 3.
Methods for characterizing dielectric properties in the agri-food sector across different frequency ranges [31].

The transmission line technique is primarily employed for machinable solids that can be inserted into the transmission line. This broadband method is limited in frequency coverage only by the size of the sample holder.

A technique that requires no contact is the free space approach. This method relies on antennas to focus microwave energy through a slab of the material under elevated temperature, mainly used at millimeter wave frequency.

Within a specific frequency range, the cavity perturbation technique has been widely employed for liquid samples at both low and high temperatures. The resonant cavities at a specified frequency are influenced by the material sample, allowing for the calculation of permittivity. Notable options include Keysight's 85072A 10 GHz split-cylinder resonator and split-post dielectric resonators [27].

The fundamental inexpensive technique widely applied is the parallel plate capacitor method, where the material is placed between the electrodes forming a capacitor. An impedance analyzer or even an LCR meter can be adopted for a typical system. Another method relies on inductance measurement to derive the permeability where the material under test is wrapped with a wire, and inductance is evaluated with respect to the ends of the wire. For this technique, the Keysight 16454A magnetic material test fixture is available. When a toroidal core is put in, this probe does not flux and thus is considered ideal for single-turn inductors. Reflection-based measurements offer a versatile approach to investigate solids and liquids over a broad frequency spectrum. Alternatively, by employing the Fourier transform of the sensor's reflectogram resulting from the applied forcing pulse, the frequency spectrum of the complex dielectric permittivity can be obtained. To construct a dielectric permittivity sensor, two or three stainless steel rods can be strategically positioned within the material under examination, forming a segment of a parallel waveguide.

Graphical representation depicted in **Figure 4** illustrates the system's measurement suite, classified according to the material type being tested and the frequency range employed for measurements.

Some genuine dielectric properties experiments were recently witnessed at the Institute of Agrophysics in Lublin. A web server was used to store data concerning the soil moisture, temperature, and salinity of the soil. Such an implementation has some advantages in lowering power consumption in the long term [36].

While extensive scientific research on dielectric properties explores the testing of various objects, achieving accurate characterization across a wide frequency range through dielectric spectroscopy remains challenging. Therefore, improving dielectric measurements and developing advanced sensors can expand the field's investigation scope. Additionally, designing equipment for radiofrequency and MW dielectric heating applications holds significant importance [37].

3. Applications

Although it has extended to medicine and material engineering, the main field of research for dielectric characterization has been the horticultural field. The number of applications of these techniques is extensive, and they are usually classified according to the technique used, appearing in two large divisions, dielectric characterization studies and BIS measurement studies [38].

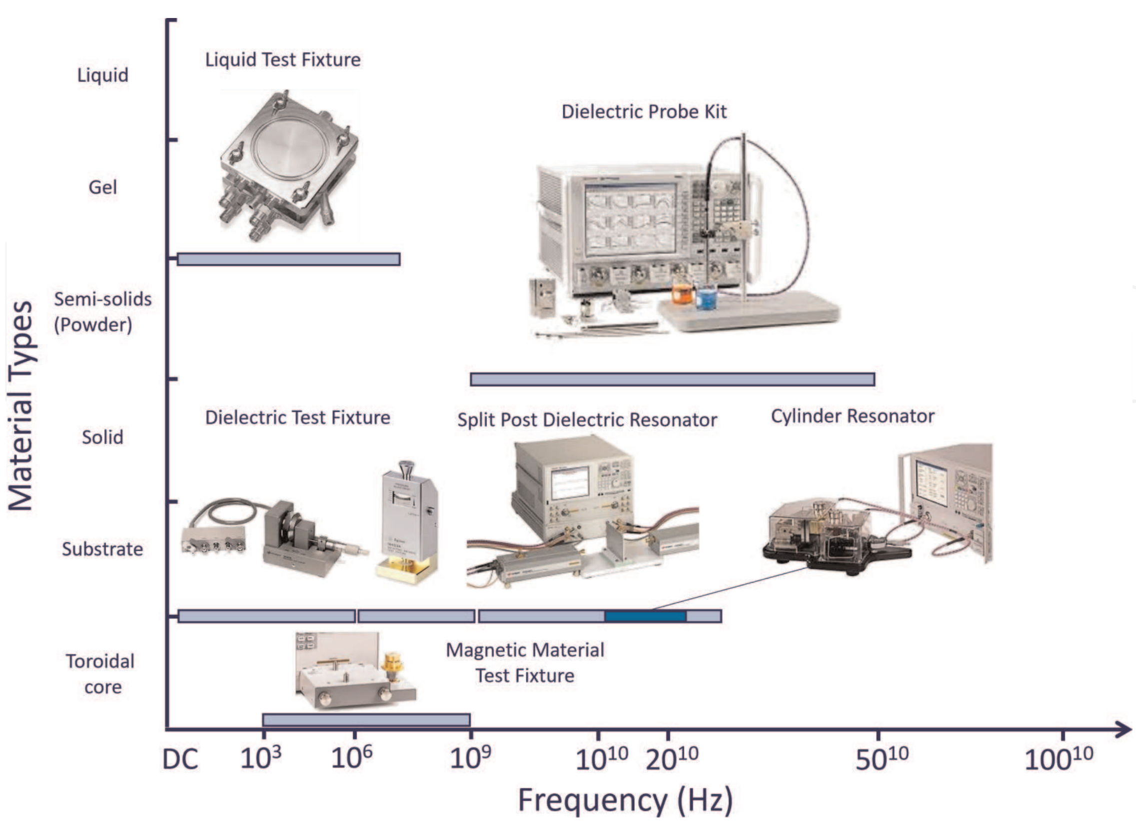


Figure 4.
Measurement apparatus used for the measurement of materials [12].

The quality factors of fruits and vegetables that are notably worth highlighting are moisture content, maturity defects, and imperfections. All these factors help harvest, classify, and package the products, improving their uniformity and quality [39]. Conducting this type of measurement using simple and innocuous techniques has been a subject of constant development in recent years, with dielectric characterization being a handy tool in food engineering and technology. Initially, the quality studies contemplated the properties of fruit and vegetables [40]. Subsequently, they have spread to other tissues of animal origin, such as meat [41] or fish [42].

The dielectric properties correlate with the quality parameters of the objects, as well as with their physical characteristics and chemical properties [12]. Quality parameters encompass firmness, pH, soluble solids, moisture content, and electrical conductivity. It is essential to ascertain the ideal frequency range that yields the desired dielectric properties, the depth of penetration reached in a particular food, and its variability with frequency or temperature to characterize varied materials.

Table 1 summarizes the main advances established in studies and applications of dielectric characterization in recent years.

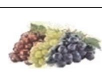
Electrical impedance spectroscopy is a method employed to evaluate the electrical characteristics of substances through the application of alternating electrical signals at various frequencies, followed by the measurement of the resulting response signals. This technique is safe, non-invasive, fast, portable, low cost, and easy to use, thereby holding significant potential for monitoring quality processes within the food industry [107].

The structure and composition of the materials determine the dielectric properties, while the frequency and temperature are related to the maturity of the agricultural product. Furthermore, ionic components exert notable repercussions on dielectric properties. Density is one more crucial element affecting the interaction between the electromagnetic field and the mass involved. The storage time of agricultural products also plays a vital role in their dielectric properties, as maturation processes occurring during storage can affect them.

The focal point of this investigation involves examining the interrelationships between the dielectric properties and additional chemical and physical attributes of the analyzed substance. The utilization of rapid and non-destructive quality assessment techniques for agricultural products is of utmost importance when evaluating dielectric spectroscopy methodologies in the field of agrophysics [9]. These techniques offer a clean and non-destructive approach that is imperative for effective management systems. They can provide a means to simultaneously examine changes in fruit tissue during ripening and intracellular and extracellular behaviors. Impedance spectroscopy has succeeded in a very high-frequency range, reaching up to 6.25 MHz.

Among the main BIS applications, it is worth highlighting the determination of freshness in fruits of different kinds, such as apples [108] and bananas [109]. As well as the measure of aging [110] or the ripening of apples [111], mangos [112], citrus [113] and pears [114], and other fruits. This technique can also build an immunosensor that looks for virus selection in products [115] and discriminates between healthy and infected samples [116]. Determining acidity in citrus using dielectric impedance has been particularly interesting in recent years as it is a non-destructive method [117]. The effects of temperature on kakis [118], nectarines [119], and their content of soluble solids [120] have been established.

BIS can monitor the concentration of elements such as nitrogen in plants [121]. Therefore, it is considered a non-destructive technique for estimating the impacts of

Food	Research	Reference
 Apples	Relationship with quality during ripening on the tree	[40, 43]
	Maturation and shelf life	[44]
	Identification of the varieties	[45]
	Bruised product quality	[46]
	Quality parameters	[9, 46]
	Maturity parameters	[47]
	Determination of soluble solids content	[48]
	Quality factors during 10 weeks of storage	[43]
	Decreases with temperature and frequency	[48]
 Apple juice	Temperature dependence similar to water	[4]
 Apple peel	The dielectric constant decreases with temperature	[40]
 Carrots	Variation with frequency, enormous values at low frequencies	[49]
	Inflection points and critical edge frequency at 100 MHz	[50]
	Internal structure and physiological state of tissues	[51]
 Peas	Changes in the salt content and sample thickness	[52]
 Eggplants	Increase with increasing storage period	[52]
	Energy storage capacity and energy loss vary depending on ambient temperature	[53]
 Avocados	Temperature dependence disappears at a frequency of 100 MHz	[54]
	It decreases with increasing temperature	[55]
 Coconut water	The energy storage capacity reduces with frequency and is minimum around 2 GHz	[53]
 Coconut oil	Use as electrical insulating material	[56]
 Grapes	Loss factor increases with storage time	[12]
 Grape juice/ wine	Variation of dielectric properties with time of change of state	[57]
	Relationships with the variety or the area of the collection can influence the outcome	[58]
	Control of wine fermentation	[59]
	Dependence on humidity and temperature	[60]
	Relaxation frequencies according to the molecular structure of the varieties	[61]
	Determination of adulteration	[62]

Food	Research	Reference
	Dielectric constant and loss factor are higher in grape juice than in wine at 200 MHz	[58]
	Dielectric constant decreases with frequency	[57]
 Guavas	The depth of penetration showed a decrease as the frequency and temperature increased	[63]
	Dielectric constant decreased with temperature for frequencies above 1000 MHz	[64]
 Mangos	Physicochemical transformations occurred in the ripening process	[65]
	Sugar content, lowest value on the day of peak maturity	[66]
	Ripening characteristics	[67]
	Relationship with loss factor, critical frequency, pH, and moisture content during preharvest	[68]
	Relationship with fructose and pH in the 2.5–12.5 GHz range	[69]
	Dielectric constant and the loss factor decrease as humidity decreases at low frequencies	[70]
	Sound product properties (0.5–20 GHz)	[71]
 Melon	Linear relationship with the content of soluble solids	[72]
	Classification of varieties	[73]
	Quality parameters	[74]
 Watermelon	Detection of maturity of 10 MHz–1.8 GHz and quality parameters	[75]
	Decreased permeability with humidity	[47]
	Determination of sugar content	[76]
 Tomatoes	Maturity	[77]
	The values exhibit a downward trend as the frequency increases. Additionally, at elevated temperatures, there is a decrease in the dielectric constant and an increase in the dielectric loss	[78]
	Determination of varieties	[79]
	The depth of penetration exhibits a reduction as the frequency and loss factor increase	[80]
 Potatoes	Quality evaluation	[47]
	Dielectric properties decrease with frequency	[81]
 Pears	Determination of firmness	[82]
	Qualitative characteristics.	[83]
	Higher values for higher bruise levels and lower moisture contents	[84]
 Peaches	Values decrease with increasing frequency and temperature	[85]
	Non-linear relationship with soluble solids, moisture content, and pH	[86]
 Oranges	Evaluate penetration depth of microwaves and design applicators for pasteurization processes	[87]
 Cane sugar	Variation with sugar concentration and temperature	[88]

Food	Research	Reference
 Honey	Honey adulteration	[89]
 Nuts	Moisture content	[90]
	Values increase with temperature	[91]
 Legumes	Increase with temperature and moisture concentration, decrease with frequency	[92]
	There is an inverse linear correlation observed between the loss factor and the frequency	[93]
	Depth of penetration decreases with increasing frequency	[94]
 Milk	Decreases with increasing frequency and varies with storage	[95]
	Measurement of sugar content and relationship with fat content	[96]
	Variation of properties with frequency	[97]
 Vinegar	Dielectric constant decreases as frequency increases	[98]
 Animal products	Relationship with temperature and humidity	[99]
	Identification of sex and age of the species	[100]
	Determination of metabolic state	[41]
 Eggs	Quality parameters	[42]
	Composition	[101]
	Quality classification	[102]
	Freshness	[103]
	Decreased with frequency, less in the bud	[104]
 Liquids	Measurement of alcohol content	[105]
 Oils	Composition, adulteration and quality	[106]

Table 1.
Dielectric characterization applications and studies in recent years (1949–2023).

other ions on plant tissue, achieving higher crop yields. Additionally, BIS enables monitoring of plant conditions, including early developmental stages, and facilitates quality control of the final products.

Impedance measurement has recently been employed to investigate the isolated effect of viruses [122]. The findings reveal that the resistance of the leaves of the infected plant is lower than that of the leaves of the healthy plants. Therefore, the impedance measurement is a fast and intelligent method to diagnose the existence of diseases in plants [123], the relaxation processes [10], or the diffusion and interaction of biomolecules with water [124].

BIS is an intriguing method to assess the condition or composition of human organs and different types of biological tissues in vivo [125]. Given the significance of food disinfection for public health and safety, numerous related applications exist. An example of this is the development of an innovative methodology for the real-time detection of the amount of disinfectant in a sample by determining the characteristic frequencies and the dielectric permittivity spectra within a specific frequency range. This method establishes a correlation between the characteristic frequencies and disinfectant concentration with acceptable precision [126].

Among postharvest applications, radiofrequency (RF) and microwave (MW) heating affects the dielectric properties of materials. Permittivity and moisture content are closely correlated in food with high water content. It is essential to find the dielectric properties of partially frozen materials to assess the heating rates and uniformity during microwave (MW) thawing [51]. Water in the microwaved material can increase heating efficiency, as water is a strong microwave absorber that converts microwave energy into heat. However, when the moisture content is too high, there can be a negative effect on heating efficiency, as the water can absorb so much energy that thermal overload occurs in the material, leading to degradation or even carbonization. Therefore, the relationship between moisture content and microwave heating efficiency is intricate and influenced by many factors, such as the composition and structure of the material, the frequency and intensity of microwaves, and the duration of heating. These properties are essential to detect processing conditions or food quality [127].

Dielectric heating has shown its applicability for fruit drying, often achieving quickly and providing higher quality dried products with low energy consumption [128]. Through RF and dielectric heating applied in the drying of agricultural products, it improves thermal efficiency, the quality of the final product and reduces drying time compared to conventional drying. Using RF and dielectric heating, food can be protected from insects inside the nuts [129]. The dielectric heating methodology can be used to reduce the necessary times of heat treatment that entail the control of pests present in food after harvest [130].

The pasteurization and sterilization of fruit juice concentrate are processes where the proper choice of frequency is essential to obtain a uniform pasteurization [131].

In this context, considering the significance of the characterization process of fruits and vegetables from harvest to cold storage, along with the accelerated technological advancements and the availability of mathematical methods, as well as the numerous research studies conducted worldwide, there is a significant demand to review the existing electrical characterization methods in the horticultural field.

4. Conclusions

The robust association between the dielectric response and the chemical and physical composition of agro-physical materials enables the identification of specific properties and quality indicators related to them. One of the primary applications of DS and BIS is the assessment of fruit ripeness and quality. As fresh produce ripens, its dielectric properties change, utilized as indicators of ripeness and quality. The detection of dielectric properties of fresh fruit can also be used to detect disease and mechanical damage. These techniques can also be used to determine the quality of the products during storage, and therefore their control prevents loss of quality and freshness. In addition, they can be used to evaluate product quality during processing to meet quality and freshness standards since techniques such as pasteurization or freezing affect their dielectric properties.

The development of particular and advanced techniques and instrumentation improves the capabilities of these non-destructive characterization techniques, as they are valuable for environmental and economic scientific evaluation within the food industry. Accuracy is indispensable in the measurement of dielectric and bioelectrical impedance spectroscopy since some essential characteristics must be maintained during the execution of the measurement. Factors such as the probe's altitude, the material's manufacture, and the quality and size of the beaker used must be considered in the experimentation and measurement. In addition, the amount of liquid under the test in which the probe is fused, the agreement with the amount of water under which the calibration has been performed, and an essential parameter such as the constant depth of the measurement must be considered. Advancements in understanding the dielectric characteristics of materials have led to further progress in the sensing field, enabling the monitoring of fresh produce's properties. The objective is to maintain the optimal conditions of fresh produce from production and harvesting to consumption.

Despite the antiquity of applying these non-destructive techniques, they are still experimental techniques under development, with a solid technological impact and providing numerous novelties. The traditional field of research has been the fruit and vegetable sector, although nowadays, the study has been extended to different areas, thus establishing new challenges and future perspectives.

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References

[1] Novas N et al. Development of a smartphone application for assessment of chilling injuries in zucchini. Biosystems Engineering. 2019;**181**:114-127

[2] Xu Y, Li C, Wang J. How does agricultural global value chain affect ecological footprint? The moderating role of environmental regulation. Sustainable Development. 2023; (February):1-12

[3] Palumbo M et al. Emerging postharvest technologies to enhance the shelf-life of fruit and vegetables: An overview. Food. 2022;**11**(23):1-29

[4] Al Faruq A et al. New understandings of how dielectric properties of fruits and vegetables are affected by heat-induced dehydration: A review. Drying Technology. 2019;**37**(14):1780-1792. DOI: 10.1080/07373937.2018.1538157

[5] Mahanti NK et al. Emerging non-destructive imaging techniques for fruit damage detection: Image processing and analysis. Trends in Food Science and Technology. 2022;**120**(October 2021): 418-438. DOI: 10.1016/j.tifs.2021.12.021

[6] Guo B et al. Bruise detection and classification of strawberries based on thermal images. Food and Bioprocess Technology. 2022;**15**(5):1133-1141. DOI: 10.1007/s11947-022-02804-5

[7] Cavaco M et al. Nondestructive assessment of citrus fruit quality and ripening by visible–near infrared reflectance spectroscopy. In: Muhammad Sarwar Khan M, Ahmad Khan I, editor. Citrus—Research, Development and Biotechnology. Chapter 13. UK: IntechOpen; 2021. pp. 1-30

[8] Zhu D et al. Collaborative analysis on difference of apple fruits flavour using electronic nose and electronic tongue. Scientia Horticulturae (Amsterdam). 2020;**260**(August 2019):108879. DOI: 10.1016/j.scienta.2019.108879

[9] Ali MM, Hashim N. Non-destructive methods for detection of food quality [Internet]. In: Future Foods: Global Trends, Opportunities, and Sustainability Challenges. Amsterdam, Netherlands: Elsevier Inc.; 2021. pp. 645-667. DOI: 10.1016/B978-0-323-91001-9.00003-7

[10] Li Y et al. Radio-frequency dielectric relaxation behavior of selected vegetable tissues: Spectra analysis with logarithmic derivative method and simulation with double-shell model. Journal of Food Engineering. 2020;**277**(September 2019): 109914. DOI: 10.1016/j.jfoodeng.2020.109914

[11] El Khaled D et al. Cleaner quality control system using bioimpedance methods: A review for fruits and vegetables. Journal of Cleaner Production. 2017. DOI: 10.1016/j.jclepro.2015.10.096

[12] El Khaled D et al. Fruit and vegetable quality assessment via dielectric sensing. Sensors (Switzerland). 2015;**15**(7):15363-15397

[13] Kongshuang Z, Yuan L. A review of the application of dielectric spectroscopy in food field. Food Science. 2019;**40**(19): 0-1

[14] You KY, Sim MS, Abdullah SN. Emerging microwave technologies for agricultural and food processing. Precision Agriculture Technologies for Food Security and Sustainability. Chapter 5. Hershey, Pennsylvania, USA: IGI Global; 2020. pp. 94-148

[15] Nelson SO et al. Assessment of microwave permittivity for sensing peach maturity. Transactions of ASAE. 1995;**38**(2):579-585

[16] Tan DQ. The search for enhanced dielectric strength of polymer-based dielectrics: A focused review on polymer nanocomposites. Journal of Applied Polymer Science. 2020;**137**(33):1-32

[17] Marzec A et al. Structural, optical and electrical properties of nanocrystalline TiO_2, SnO_2 and their composites obtained by the sol-gel method. Journal of the European Ceramic Society. 2016;**36**(12):2981-2989

[18] Anatolii S et al. Model of combined solid plasma material for the protection of radio-electronic means of optical and radio radiation. International Journal of Advanced Trends in Computer Science and Engineering. 2019;**8**(4): 1241-1247

[19] González M, Pozuelo J, Baselga J. Electromagnetic shielding materials in GHz range. Chemical Record. 2018;**18** (7):1000-1009

[20] Szychta L et al. The dielectric properties of worker bee homogenate in a high fre-quency electric field. Energies. 2022;**15**(24): 9342

[21] Ravi Kumar K, Krishna Chaitanya NVV, Sendhil KN. Solar thermal energy technologies and its applications for process heat-ing and power generation—A review. Journal of Cleaner Production. 2021;**282**:125296

[22] Zhao B et al. Achieving wideband microwave absorption properties in PVDF nanocomposite foams with an ultra-low MWCNT content by introducing a microcellular structure. Journal of Materials Chemistry C. 2019;**8** (1):58-70

[23] Munawar T et al. Multi metal oxide NiO-CdO-ZnO nanocomposite–synthesis, structural, optical, electrical properties and enhanced sunlight driven photocatalytic activity. Ceramics International. 2020;**46**(2):2421-2437. DOI: 10.1016/j.ceramint.2019.09.236

[24] El Khaled D et al. Microwave dielectric heating: Applications on metals processing. Renewable and Sustainable Energy Reviews. 2018;**82**(November 2017):2880-2892. DOI: 10.1016/j.rser.2017.10.043

[25] Prateek TVK, Gupta RK. Recent Progress on ferroelectric polymer-based nanocomposites for high energy density capacitors: Synthesis, dielectric properties, and future aspects. Chemical Reviews. 2016;**116**(7):4260-4317

[26] Meng Z, Wu Z, Gray J. Microwave sensor technologies for food evaluation and analysis: Methods, challenges and solutions. Transactions of the Institute of Measurement and Control. 2018;**40**(12): 3433-3448

[27] Keysight. 2023. pp. 1–6. Available from: https://www.keysight.com/us/en/home.html

[28] Ahmed OF, Thaher RH, Ahmed SR. Design and fabrication of UWB microstrip Antenna on different substrates for wireless Communication system. In: 2022 - International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA). Vol. 3(7). Ankara, Turkey. 2022. pp. 7-10

[29] Dunster JL et al. Mathematical techniques for understanding platelet regulation and the development of new pharmacological approaches. Methods in Molecular Biology. 2018;**1812**:255-279

[30] Landinger TF, Schwarzberger G, Jossen A. A novel method for high

frequency battery impedance measurements. In: 2019 IEEE International Symposium on Electromagnetic Compatibility, Signal & Power Integrity (EMC+SIPI), New Orleans, LA, USA. 2019. pp. 106-110

[31] El Khaled D et al. Dielectric spectroscopy in biomaterials: Agrophysics. Materials (Basel). 2016;**9**(5):310

[32] Skierucha W, Walczak R, Wilczek A. Comparison of open-ended coax and TDR sensors for the measurement of soil dielectric permittivity in microwave frequencies. International Agrophysics. 2004;**18**(4):355-362

[33] Oliveira JGD, Junior JGD, Pinto ENMG, Neto VPS, D'Assunção AG. A new planar microwave sensor for building materials complex permittivity characterization. Sensors (Switzerland). 2020;**20**(21):1-15

[34] He H et al. Topological negative refraction of surface acoustic waves in a Weyl phononic crystal. Nature. 2018; **560**(7716):61-64. DOI: 10.1038/s41586-018-0367-9

[35] Kopetz H. Real-time systems: Design principles for distributed embedded applications. In: Real-Time Systems Series. Vol. 34. New York, NY: Springer; 1997. 142 p

[36] Park C et al. A dielectric mixing model accounting for soil organic matter. Vadose Zone Journal. 2019;**18**(1):190036

[37] Macana RJ, Baik OD. Disinfestation of insect pests in stored agricultural materials using microwave and radio frequency heating: A review. Food Review International. 2018;**34**(5):483-510

[38] Qu S et al. Dielectric and magnetic loss behavior of Nanooxides. In: Spectroscopic Methods for Nanomaterials Characterization. Netherlands: Elsevier Science; 2017. pp. 301-319

[39] Ragni L et al. Quality evaluation of shell eggs during storage using a dielectric technique. Transactions of the ASABE. 2007;**50**(4):1331-1340

[40] Guo W et al. Maturity effects on dielectric properties of apples from 10 to 4500 MHz. LWT—Food Science and Technology. 2011;**44**(1):224-230. DOI: 10.1016/j.lwt.2010.05.032

[41] Traffano-Schiffo MV et al. New methodology to analyze the dielectric properties in radiofrequency and microwave ranges in chicken meat during postmortem time. Journal of Food Engineering. 2021;**292**(September 2020):110350. DOI: 10.1016/j.jfoodeng.2020.110350

[42] He J, Li F, Jiao Y. Prediction of salmon (*Salmo salar*) quality during refrigeration storage based on dielectric properties. International Journal of Agricultural and Biological Engineering. 2021;**14**(4):262-269

[43] De Vasconcelos D, Andrade Pina VA. Postharvest quality parameters evolution in 'Golden delicious', 'Gala' and 'Starking' apple. KnE Engineering. 2020;**5**(6):51-62

[44] Kafarski M et al. Evaluation of apple maturity with two types of dielectric probes. Sensors (Switzerland). 2018;**18**(1):121

[45] Shang L, Guo W, Nelson SO. Apple variety identification based on dielectric spectra and chemometric methods. Food Analytical Methods. 2015;**8**(4):1042-1052

[46] Bian HX et al. Quality predictions for bruised apples based on dielectric

properties. Journal of Food Processing & Preservation. 2019;**43**(8):1-10

[47] Ikediala JN et al. Dielectric properties of apple cultivars and codling moth larvae. Transactions of the American Society of Agricultural Engineers. 2000;**43**(5):1175-1184

[48] Solyom K et al. Effect of temperature and moisture contents on dielectric properties at 2.45 GHz of fruit and vegetable processing by-products. RSC Advances. 2020;**10**(28):16783-16790

[49] Schwan HP. Electrical properties of tissue and cell suspensions: Mechanisms and models. In: Proceedings of 16th Annual International Conference of the IEEE Engi-neering in Medicine and Biology Society, Baltimore, MD, USA, 1994. pp. A70-A71

[50] Shaw TM, Galvin JA. High-frequency-heating characteristics of vegetable tissues determined from electrical-conductivity measurements. Proceedings of the IRE. 1949;**37**(1):83-86

[51] Zhang C et al. In-situ dielectric analysis on the responses of vegetable cells to freezing treatment. International Journal of Refrigeration. 2020;**118**:384-391. DOI: 10.1016/j.ijrefrig.2020.06.029

[52] Jain D et al. Effect of changes in salt content and food thickness on electromagnetic heating of rice, mashed potatoes and peas in 915 MHz single mode microwave cavity. Food Research International. 2019;**119**(January 2018): 584-595. DOI: 10.1016/j.foodres.2018.10.036

[53] Kundu A, Gupta B. Broadband dielectric properties measurement of some vegetables and fruits using open ended coaxial probe technique. Int Conf Control Instrumentation, Energy Commun CIEC. 1980;**2014**(2014): 480-484

[54] Nelson SO. Frequency and Temperature permittivities of fresh fruits and vegetables from 0.01 to 1.8 GHz. Trans Agric Res Serv. 2018;**46**(2): 567–574

[55] Coronel P et al. Dielectric properties of pumpable food materials at 915 MHz. International Journal of Food Properties. 2008;**11**(3):508-518

[56] Pambudi NA, Yusuf AM, Sarifudin A. The use of single-phase immersion cooling by using two types of dielectric fluid for data Center energy savings. Energy Eng J Assoc Energy Eng. 2022; **119**(1):275-286

[57] García A et al. Dielectric characteristics of grape juice and wine. Biosystems Engineering. 2004;**88**(3): 343-349

[58] García A et al. Dielectric properties of grape juice at 0.2 and 3 GHz. Journal of Food Engineering. 2001;**48**(3):203-211

[59] Zheng S, Fang Q, Cosic I. An investigation on dielectric properties of major constituents of grape must using electrochemical impedance spectroscopy. European Food Research and Technology. 2009;**229**(6):887-897

[60] Sólyom K et al. Dielectric properties of grape marc: Effect of temperature, moisture content and sample preparation method. Journal of Food Engineering. 2013;**119**(1):33-39

[61] Vijay R, Jain R, Sharma KS. Dielectric spectroscopy of grape juice at microwave frequencies. International Agrophysics. 2015;**29**(2):239-246

[62] Naderi-Boldaji M et al. Potential of two dielectric spectroscopy techniques

and chemometric analyses for detection of adulteration in grape syrup. Journal of the International Measurement Confederation. 2018;**127**(March):518-524. DOI: 10.1016/j.measurement.2018.06.015

[63] Kataria TK et al. Dielectric properties of guava, mamey sapote, prickly pears, and nopal in the microwave range. International Journal of Food Properties. 2017;**20**(12):2944-2953. DOI: 10.1080/10942912.2016.1261154

[64] González-Monroy AD et al. Dielectric properties of beverages (tamarind and green) relevant to microwave-assisted pasteurization. Journal of Food Science. 2018;**83**(9):2317-2323

[65] Silva PF et al. Characterization of the dielectric properties of the Tommy Atkins mango. Journal of Microwaves, Optoelectronics and Electromagnetic Applications. 2020;**19**(1):86-93

[66] Lima CMC et al. Electromagnetic characterization of the tommy atkins mango in the maturation period. 2019 SBMO/IEEE MTT-S Int Microw Optoelectron Conf IMOC 2019. 2019;**2019**(3):2019-2021

[67] Yahaya NZ et al. Microwave dielectric properties for detection of "Harumanis" mangoes ripeness. Journal of Physics Conference Series. 2018;**1083**(1):012020

[68] Suhaime N et al. Microwave technique for moisture content and pH determination during pre-harvest of mango cv. Chok anan. Sains Malaysiana. 2018;**47**(7):1571-1578

[69] Krairiksh M, Mearnchu A, Phongcharoenpanich C. Nondestructive measurement for mango inspection. In: IEEE International Symposium on Communications and Information Technology. 2004;**2004**(2):646-649

[70] Cheng EM et al. Microwave reflection based dielectric spectroscopy for moisture content in Melele mango fruit (*Mangifera indica* L.). Journal of Telecommunication, Electronic and Computer Engineering. 2018;**10**(1–14):1-6

[71] Shivamurthy HT, Matacena I, Spirito M. Dielectric measurements of mangoes from 0.5GHz to 20GHz using a custom open-ended coaxial probe. In: 2017 47th European Microwave Confer-ence (EuMC), Nuremberg, Germany. Vol. 2017. 2017. pp. 958-961

[72] Liu D et al. Non-destructive sugar content assessment of multiple cultivars of melons by dielectric properties. Journal of the Science of Food and Agriculture. 2021;**101**(10):4308-4314

[73] Zhuanwei W et al. Non-destructive testing of melon varieties based on dielectric spectrum technology. Journal of Agricultural Engineering. 2017;**33**(9):290-295

[74] Nelson SO, Trabelsi S. Examination of dielectric spectroscopy data for correlations with melon quality. Am Soc Agric Biol Eng Annu Int Meet 2011, ASABE 2011. 2011;**6**(July 2018):5123-5128

[75] Nelson SO, et al. Dielectric spectroscopy studies on honeydew melons. 2007 ASABE Annu Int Meet Tech Pap. 2007;7 BOOK(07).

[76] Isa MM et al. Sugar content in watermelon juice based on dielectric properties at 10.45GHz. In: 2009 IEEE Student Confer-ence on Research and Development (SCOReD), Serdang, Malaysia. 2009. pp. 529-532

[77] Li J et al. Maturity assessment of tomato fruit based on electrical impedance spectroscopy. International Journal of Agricultural and Biological Engineering. 2019;**12**(4):154-161

[78] Lurwan MM et al. Dielectric properties of fresh Roma and Cherry tomato samples at different frequencies and temperatures. Journal of Science Education and Technology. 2021;**9**(4): 2021

[79] Türker U, Talebpour B, Yegül U. Determination of the relationship between apparent soil electrical conductivity with pomological properties and yield in different apple varieties. Zemdirbyste. 2011;**98**(3):307-314

[80] Abea A et al. Combined effect of tempera-ture and oil and salt contents on the varia-tion of dielectric properties of a tomato-based homogenate. Food. 2021; **10**(12):3124

[81] Luo GY et al. Optimization of the microwave drying process for potato chips based on the measurement of dielectric properties. Drying Technology. 2019;**37**(11):1329-1339. DOI: 10.1080/07373937.2018.1500482

[82] Zhang H et al. Non-destructive detection of the fruit firmness of Korla fragrant pear based on electrical properties. International Journal of Agricultural and Biological Engineering. 2022;**15**(6):216-221

[83] Mahmoodi MJ, Azadbakht M. Investigating the effects of qualitative properties on pears dielectric coefficient. Journal of Agricultural Machinery. 2021; **11**(1):71-81. Available from: https://jame.um.ac.ir/article_34585.html?lang=en

[84] Azadbakht M et al. Relationship of pears' dielectric properties and rates of pears' bruise. Agricultural Engineering International: CIGR Journal. 2020;**22**(1): 169-179

[85] Lombardo R, Rubino T, Cammalleri M. Dielectric characterization of fruit nectars at low RF frequencies. International Journal of Food Properties. 2015;**18**(10):2312-2326

[86] Zhang G et al. A comprehensive peach fruit quality evaluation method for grading and consumption. Applied Sciences. 2020;**10**:1348

[87] Franco AP, Tadini CC, Wilhelms Gut JA. Predicting the dielectric behavior of orange and other citrus fruit juices at 915 and 2450 MHz. International Journal of Food Properties. 2017;**20**(2):1468-1488

[88] Sumranbumrung R et al. Characterization model of dielectric properties of cane sugar solution over 0.5–14 GHz. IEEE Transactions on Instrumentation and Measurement. 2021;**70**:8003908

[89] Liu W, rt al. Quantitative determination of acacia honey adulteration by terahertz-frequency dielectric properties as an alternative technique. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy. 2022;**274**:121106

[90] Solar M, Solar A. Non-destructive determination of moisture content in hazelnut (*Corylus avellana* L.). Computers and Electronics in Agriculture. 2016;**121**:320-330

[91] Ling B et al. Dielectric properties of pistachio kernels as influenced by frequency, temperature, moisture and salt content. Food and Bioprocess Technology. 2015;**8**(2):420-430

[92] Oke AB, Baik OD. Role of moisture content, temperature, and frequency on

dielectric behaviour of red lentil and Kabuli chickpea in relation to radio frequency heating. Applied Food Research. 2022;**2**(1):100046

[93] Taheri S et al. Dielectric properties of chickpea, red and green lentil in the microwave frequency range as a function of temperature and moisture content. The Journal of Microwave Power and Electromagnetic Energy. 2018;**52**(3):198-214

[94] Cover JH. Bps 2021. In: Horabik J, editor. 20th International Workshop for Young Scien-tists. Lublin, Poland: BioPhys Spring; 2021. pp. 1-74

[95] Szerement J et al. The effect of storage time on dielectric properties of pasteurized milks and yoghurt. In: 2018 12th Int Conf Electromagn Wave Interact with Water Moist Subst ISEMA 2018. 2018. pp. 3-5

[96] Zhu X, Guo W, Liang Z. Determination of the fat content in cow's milk based on dielectric properties. Food and Bioprocess Technology. 2015;**8**(7): 1485-1494

[97] Nunes AC, Bohigas X, Tejada J. Dielectric study of milk for frequencies between 1 and 20 GHz. Journal of Food Engineering. 2006;**76**(2):250-255

[98] Tanaka F et al. Analysis of dielectric properties of rice vinegar and sake. Transactions of ASAE. 2002;**45**(3):733-740

[99] Sun J et al. Evaluation of fish freshness using impedance spectroscopy based on the characteristic parameter of orthogonal direction difference. Journal of the Science of Food and Agriculture. 2020;**100**(11):4124-4131

[100] Gómez-Salazar JA et al. Dielectric properties of fresh rabbit meat in the microwave range. Journal of Food Science. 2021;**86**(3):952-959

[101] Cong H et al. Dielectric properties of sea cucumbers (*Stichopus japonicus*) and model foods at 915 MHz. Journal of Food Engineering. 2012;**109**(3):635-639

[102] Li CH et al. Nondestructive detection of the gel state of preserved eggs based on dielectric impedance. Food. 2021;**10**(2):1-13

[103] Jun S et al. Non-destructive detection of egg freshness based on dielectric properties and yolk index regression model. Journal of Agricultural Engineering. 2016;**32**(21):290-295

[104] Guo W et al. Storage effects on dielectric properties of eggs from 10 to 1800 MHz. Journal of Food Science. 2007;**72**(5):E335-E340

[105] Kataria TK et al. Dielectric properties of tequila in the microwave frequency range (0.5–20 GHz) using coaxial probe. International Journal of Food Properties. 2017;**20**(1):S377-S384

[106] Salim A, Lim S. Review of recent metamaterial microfluidic sensors. Sensors (Switzerland). 2018;**18**(1):232

[107] Bauchot AD, Harker FR, Arnold WM. The use of electrical impedance spectroscopy to assess the physiological condition of kiwifruit. Postharvest Biology and Technology. 2000;**18** (1):9-18

[108] Nesheva DD et al. Effect of the sublayer thickness and furnace annealing on the crystallographic structure and grain size of nanocrystalline ZnxCd1-xSe thin films. Bulgarian Chemical Communications. 2013;**45**(B):11-17

[109] Ibba P et al. Bio-impedance and circuit parameters: An analysis for

tracking fruit ripening. Postharvest Biology and Technology. 2020;**159** (September 2019):110978

[110] Watanabe T et al. Electrical impedance estimation for apple fruit tissues during storage using Cole–Cole plots. Journal of Food Engineering. 2018; **221**:29-34

[111] Chowdhury A et al. Studying the electrical impedance variations in banana ripening using electrical impedance spectroscopy (EIS). In: Proceedings of the 2015 Third International Conference on Computer, Communication, Control and Information Technology (C3IT), Hooghly, India. 2015. pp. 21-24

[112] Figueiredo Neto A et al. Determination of mango ripening degree by electrical impedance spectroscopy. Computers and Electronics in Agriculture. 2017;**143**(May):222-226

[113] Gupta AK et al. Emerging approaches to determine maturity of citrus fruit. Critical Reviews in Food Science and Nutrition. 2022;**62**(19): 5245-5266

[114] Zhu X, Guo W, Wu X. Frequency- and temperature-dependent dielectric properties of fruit juices associated with pasteurization by dielectric heating. Journal of Food Engineering. 2012;**109** (2):258-266

[115] Ambrico M et al. Highly sensitive and practical detection of plant viruses via electrical impedance of droplets on textured silicon-based devices. Sensors (Switzerland). 2016;**16**(11)

[116] Khan MZH et al. Ultrasensitive detection of pathogenic viruses with electrochemical biosensor: State of the art. Biosensors & Bioelectronics. 2020; **166**(July):112431

[117] Chowdhury A et al. Electrical impedance spectroscopic study of mandarin orange during ripening. Journal of Food Measurement and Characterization. 2017;**11**(4):1654-1664

[118] Arnal L, Del Rio MA. Quality of persimmon fruit cv. Rojo brillante during storage at different temperatures. Spanish Journal of Agricultural Research. 2004;**2**(2):243

[119] O'Toole MD et al. Non-contact multi-frequency magnetic induction spectroscopy system for industrial-scale bio-impedance measurement. Measurement Science and Technology. 2015;**26**(3)

[120] Shen J et al. Prediction model of soluble solid content in Lingwu Changzao jujube based on dielectric Spectrum. J Agric Eng Trans. 2016;**32**(2): 369-375

[121] Zeleňáková L et al. Determination of nitrates in lettuce (*Lactuca Sativa* var. *Capitata*) from various producers by ion-selective electrode. Journal of Hygienic Engineering and Design. 2022; **40**:19-26

[122] Khaled AY et al. Early detection of diseases in plant tissue using spectroscopy–applications and limitations. Applied Spectroscopy Reviews. 2018;**53**(1):36-64

[123] Bukhamsin AH. Impedimetric plant biosensor based on minimally invasive and flexible microneedle electrodes. In: 2020 IEEE 33rd International Conference on Micro Electro Mechanical Systems (MEMS), Vancouver, BC, Canada. 2020. pp. 307-310

[124] Zhang J, Matsuura H, Shirakashi R. A method for measuring dielectric relaxation of water by NIR spectroscopy: Applicability and application to

measurement of water diffusion coefficient. Journal of Food Process Engineering;**2023**(November 2022)

[125] Kanoun O. Advanced systems for biomedical applications. Serie Smart Sensors, Measurement and Instrumentation. Springer International Publishing. 2021;**39**:1-286

[126] Liu J et al. Real-time sensing of disinfectant by a novel dielectric methodology. Sensors and Actuators A: Physical. 2023;**357**(March):114350

[127] Meda V, Orsat V, Raghavan V. Microwave heating and the dielectric properties of foods. In: The Microwave Processing of Foods: Second Edition. United Kingdom: Woodhead Publishing; 2017. pp. 23-43

[128] Bogale Teseme W, Weldemichael Weldeselassie H. Review on the study of dielectric properties of food materials. American Journal of Engineering and Technology Management. 2020;**5**(5):76

[129] Ayad E, Roshdy O, Afifi H. Effect of microwave energy on some stored product mites. Egyptian Academic Journal of Biological Sciences, B. Zoology. 2022;**14**(2):145-151

[130] Soto-Reyes N, Rojas-Laguna E, Sosa-Morales M. Modelación del calentamiento dieléctrico (microondas y radiofrecuencia) en sistemas alimenticios modelo. Temas Sel Ing Aliment. 2012;**6**(2):19-31

[131] Nguyen TP, Songsermpong S. Microwave processing technology for food safety and quality: A review. Agriculture and Natural Resources. 2022;**56**(1):57-72