Cleaner quality control system using bioimpedance methods: A review for fruits and vegetables

El Khaled D, Novas N, Gázquez JA, García RM, Manzano-Agugliaro, F*

Dpt. Engineering, University of Almería, 04120 Almería (Spain)

*Corresponding author. Tel.:+34 950015396; Fax: +34950015491.

E-mails: dalia.elkhaled@gmail.com; nnovas@ual.es; jgazquez@ual.es; rgarciasalvador@ual.es; fmanzano@ual.es

Abstract

Due to the very rapid development of technology as well as the increased demand of quality food, vegetables and fruits are more under spotlights for enhancing their healthy characteristics. With the involvement of new mathematical methods and updated variety of scientific investigations in food science, the need for better characterization of agricultural products arises. This review covers the bioimpedance method used for electrical characterization of fruits and vegetables, known as the bioimpedance spectroscopy. This electrical advantageous method offers an ecological agricultural production. By evaluating the quality factors of horticultural products, bioimpedance targets a double sustainable plan: an environmental friendly food control and an improved consumer's health care at once. An objective interpretation of the quality factors importance in the horticultural sector is presented along with a wide definition of bioimpedance spectroscopy. Moreover, the paper highlights techniques used for the bioimpedance properties measurements since their initiations. The collective data is tabulated for the destructive, non-destructive bioimpedance where clear objectives and focused conclusions of each measurement method are displayed. This paper summarizes the various findings and conclusions of these experiments seeking better oriented investigation in the future and encouraging further quality food applications in areas where data is still ambiguous. Non destructive bioimpedance techniques open new perspectives for cleaner quality control system in industrial applications for fruit and vegetables quality determination.

Keywords: Fruits, vegetables, bioimpedance, quality, clean control.

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Table of acronyms

Nomenclature	Definition
AC	Alternating Current
C1	Plasma membrane capacitance
C2	Tonoplast capacitance
C_{ef}	Effective capacitance
EIS	Electrical Impedance Spectroscopy
FFT	Fast Fourier Transform
I(t)	Current time function
ISR	Impedance square root
j	Imaginary unit
LCR	Inductance Capacitance Resistance analyzer
MUT	Material Under Test
R	Resistance
r	Reflection coefficient
R1	Cell wall resistance
R2	Cytoplasmic resistance
R3	Plasma membrane vacuole resistance
R_{ef}	Effective resistance
SSC	Soluble Solid Content
TA	Titratable Acidity
$U(j\omega)$	Voltage frequency
U(t)	Voltage time function
U_0	Maximum voltage
U_{inc}	Incident voltage
X1	Time factor
X2	Shape of the fruit factor
X3	Size and weight of the fruit
X4	Contact area of the probe electrodes
X5	Temperature of the fruit
X6	Random Variation factors
Z	Impedance
Z_0	Impedance of the transmission line
Z_{ef}	Effective impedance
Z_i	Impedance imaginary part
Z_r	Impedance real part
β	β dispersion
θ	Angular phase
ω	Angular frequency

1. Introduction

Nowadays the trend is a healthier diet, so decreasing the intake of meat and dairy, and increasing fish (Sánchez-Muros et al., 2014) and seasonal fruit and vegetable products, are needed (López et al., 2015). Due to the very rapid development of technology as well as the increased demand of quality food, vegetables and fruits are more under spotlights for enhancing their healthy characteristics. Engineering practices should be revised continuously to address methodological innovations (Halbe et al., 2015) to reach quality standards production at technical levels. Quality is a term that is frequently used as a multilayered expression that can be usually neutrally or positively occupied (Butz et al., 2005). The origin of the term "Quality" is the Latin word "Qualitas" pointing to the nature or property attribute of the object. Because quality exists only in the minds of the consumer, it may also be defined as the result of all interactions of this consumer (or observer) with a product and its circumstances, the market and its circumstances, and the social situation of the consumer himself. Site measurement of the weight of fruits on the harvester may enhance their market value and present a significant advance in precision agriculture (Qarallah et al., 2008). Thus, quality literally reflects the "acceptability" when speaking in the minds of the consumers. In the agricultural field, optical impression is an essential criterion for a product to be judged as "fresh", and this implies necessarily that special expectations about its internal components are created (Chilar et al., 1987).

Quality of food can be determined through four main factors, as by Bourne classification (Bourne, 2002). First of all, the appearance that involves the shape (Clement et al., 2013), size, colour and brightness (Clement et al., 2012). Second, comes the flavour which includes the smell and the taste. The texture of the product comes third by considering the physical stimulus that born through the part of the body contact with food; this phenomenon is known as the "sense of touch". Last but not least the amount of macronutrients (carbohydrates, lipids and proteins) and micronutrients (minerals, vitamins and fibers) which are combined and referred to as the nutrition factor. Apart from some other characteristics, the freshness of vegetables is determined considerably by the water content and the concentration of valuable constituents whereby these items often change rapidly during postharvest decay (Butz et al., 2005).

Seeking an efficient treatment and straightforward marketing, for the producers of agricultural products, the concept of quality involves the cultivation of specific factors such as resistances and potential of yield, as well as uniformity of the harvest products when it comes to size, shape and color. The set of processes occurring from the stage of growth to the development of the fruit, known as maturity, is highly interesting for the producers since it reflects the point of maximum quality (Watada et al., 1984). A major indicator of the maturity in fruits is the color, except for the fruits that change color after harvest, this factor becomes less deciding (López, 2003). From the marketing side, merchant are also interested in freshness and durability, whereas the processing industry has to contemplate the suitability for processing and preservation. Finally, the consumer should buy the produce in the consciousness to receive tasty commodities with nutritionally valuable and health-promoting contents. The consumer decision to purchase the fruit is essentially directed by the appearance of the product that is considered as primary attribute evaluating the first visual contact, and it is followed by texture and flavour (Mitcham et al., 1996).

From electrical perspective, impedance spectrometry is a simple low-cost technique that has a lot of potential to characterize fruits non-destructively in vivo, at the site of harvest and storage. By studying the passive electrical properties of the fruit or vegetable under measure, their impedance can be determined, using a multifrequency impedance analyzer by observing the electrical response of their tissue to the passage of the external power (Ortiz Meléndez, 2014).

In order to increase consciousness of quality in the food and health sector, it is strongly needed to enhance the research activities regarding a defined quality control and its preservation during marketing; but above all, it is essential to explore the possibilities of evaluating quality parameters of agricultural products and of integrating this into control processes. Applying bioimpedance spectroscopy on fruits and vegetables seeking better quality control constitutes an integration management system of high relevance with the journal scope. Such non-destructive studies aiming to avoid and reduce deficiencies in the agricultural production don't hold positive effects only on public health but have great economical impact on the consumption control as whole. Linking environmental impact directly with kind of economic performance reflects the sustainability of an eco-efficient system (Müller et al., 2014). Thus, such a qualified yield based on electrical engineering advances contributes to a cleaner environment and forms a life cycle assessment with healthier performance.

This being said, this paper is the outcome of an intensive review on bioimpedance measurements effected over several horticultural products detecting changes in various quality parameters listed above. Bioimpedance, being an electrical non-destructive characterization tool, contributes as an essential management system in enhancing the quality of fruits and vegetables.

2. State-of the-art Bioimpedance measurements of fruits and vegetables

2.1. Academic literature review method

In the review presented, the experiments considered for each fruit and vegetable are all peer-reviewed papers from international journals and conference proceedings. The review is organized to highlight the value of quality food products to what it brings at the consumers health level. Defining the concept of quality drives automatically to enlighten the concept of electrical characterization and particularly impedance spectroscopy. The review covers all main definitions, mechanisms and measurements techniques of impedance.

2.1.1. General aspects of the cases studied

It can be assumed that mainstream research of bioimpedance applied on fruits and vegetables began in around 1995. The review has covered all different experiments applied on every possible kind of fruit or vegetable since then by specifying the objective of the study, its technique and conclusions. The challenge was to filter only non-destructive studies that are essential for the cleaner system into assessment. Most of the stated experiments tackle more than one quality factor into study. The comparison of methods is not often applied to fruits production (Cerutti et al., 2014); it can be found for measurements methods and environment of study (temperature, frequency, storage time...).

2.2. Electrical characteristics of vegetables and fruits

The mechanisms of interaction between food and electromagnetic energy and microwave frequencies were the main reason behind all studies looking for electrical properties food data. The electrical properties that seek to find the amount of energy distribution within the product has been largely under scope. In 1992, Scudder states that the electrical properties and geometry of the product determine the heating effects of the electro thermal technology. In fact, non-uniform thermal properties change with time, temperature and location as a food product is heated or cooled which increases the demand for more accurate thermal property data. To predict electrothermal heating patterns, various physical and mathematical models are available and can be used to estimate time-temperature histories in food processes (Mudgett, 1986); a highly relevant issue for bioimpedance studies.

The material´s transmission properties may be defined in terms of a complex propagation factor that involves attenuation and a phase shift. The major electrothermal food characteristics can be measured through their different dielectric properties such as the transmission properties, the impedance and the conductivity. These properties determine the amount of energy coupled by a food product and therefore the product microwave heating process that may involve either conductive or radiative energy transfer. Any matter can be characterized electrically either by active electrical properties like current and voltage sources or by the passive electrical properties (Cole, 1968).

The impedance is the characterization of how the object impedes current flow excited by an outer electric field, and more specifically bioimpedance denotes the passive electrical properties of biological material. Electrical impedance measurements serve to detect the rapid changes associated with the positive response of the plant which can be seasonal changes associated with climate (Privé & Zhang, 1996) or physiological functions, or membrane damages; freezing injury (Zhang & Willison, 1992). On the opposite, when it comes to remove fruits from low temperature storage, they undergo a series of physiological changes such as ripening, senescence and cell dysfunction (Brady, 1987). Therefore, the changes occurring might present a unique biological system to explain the interaction between physiological condition and electrical properties of plant tissues (Harker & Forbes, 1997). Its measurement is limited to field strength where the current is linear with respect to the voltage applied, which is unlike the high electric field used in electrical treatment (Krassen et al., 2007).

Thus, the bioimpedance measurement is interesting to discuss because it consists of both resistance and reactance and it constitutes the most common electrical parameter correlating with numerous quality factors of agricultural products. Moreover, the complex character and simple measurements of impedance that consist of measuring the electrical current intensity through the tissue, makes of it a valuable quality food measurement application (Żywica et al., 2005).

Electrical Impedance Spectroscopy (EIS) measures the dielectric properties of a medium as a function of frequency. It is based on the interaction of an external electric field with the electric dipole moment of materials. EIS has been used extensively to characterize properties of solid materials (Takashima & Schwan, 1965; Prabakar & Rao, 2007).

When it comes to fruits and vegetables, their cells are surrounded by an insulating membrane, where the cytosol and the extracellular fluids are electrolytes. Despite the high permittivity of water, electrolytes behave like ohmic resistors up to hundreds of MHz. Membranes form capacitive elements due to their high resistance, where the typical time constant for charging cell membranes is of the order of a microsecond. Thus, cells influence the impedance in a frequency range up to several MHz.

The models based on circuit diagrams have been developed that allow complex impedance relationships to be resolved into resistances of the cell wall, cytoplasm, and vacuole, as well as the capacitances of the plasma membrane and tonoplast (Zhang & Willison, 1991). The EIS is considered competitive in comparison with other new microscopic techniques, since it permits detection of early changes both in physiological and structural states (Vozáry et al., 2012).

Moreover, there are two reasons for the bioimpedance measurements to be considered as a good approach for agricultural products quality assessment. First of all, the electrical impedance measurement is simple with the advanced mathematical modeling. Second, the electrical impedance is very sensitive to the permeability of cell membranes; therefore it is a great choice for the assessment of changes due to high voltage application. In addition to this, electric characterization of food products attracted much interest for quality checking or determination of fat content (Nelson, 1973a).

Electrical impedance may provide a method of simultaneously examining changes occurring in fruit tissue during ripening, since it can be used to detect changes in the resistance of intracellular and extracellular compartments. It was also stated that electrical current is unable to cross the plant plasma membrane at low frequency, and is confined to an extracellular pathway, whereas the current will travel via the symplast at high frequencies (Stout, 1988).

For measurements description, the impedance Z is measured by applying a small alternating current (AC) with a known small frequency to the system and determining the amplitude and phase shift of the electric potential (Ortiz Meléndez, 2014). Due to physical structure of the material under measure, or the chemical processes within the tissue, or a combination of both parameters, the impedance may vary as the frequency of the voltage applied is changing (Schröder et al., 2004). As a mathematical equation, the impedance is presented to be the ratio of the voltage time function U(t) and current time function I(t), eq. (1)

$$Z = \frac{U(jw)}{I(jw)} = \frac{U_0 \sin(\omega t)}{I_0 \sin(\omega t + \theta)} \qquad (1)$$

Where ω is the angular frequency and is equal to 2πf, θ is the angular phase that is the phase difference between voltage and current (Pänke et al., 2008), U_0 and I_0 are the maximum voltage and current respectively. The impedance can also be presented in the Cartesian coordinates as a complex number of two components, a real and an imaginary, eq. (2)

$$Z(\omega) = Zr(\omega) + jZi(\omega) \qquad (2)$$

With Z_r being the real part of the impedance, eq. (3), and Z_i being the imaginary part, eq. (4).

$$Zr(\omega) = Z\cos(\theta) \qquad (3)$$

$$Zi(\omega) = Z\sin(\theta) \qquad (4)$$

Thus the angular phase can be calculated as the inverse tangent of their ratio, eq. (5).

$$\theta = \tan^{-1}(Zi/Zr) \qquad (5)$$

Graphically the real part of the impedance is presented on the X axis, the imaginary part on the Y axis and an angle θ is formed (Fig. 1). And a vector Z_ω represents the relationship of the impedance with its both imaginary and real part, eq. (6).

$$Z(\omega) = \sqrt{Zr^2 + Zi^2} \qquad (6)$$

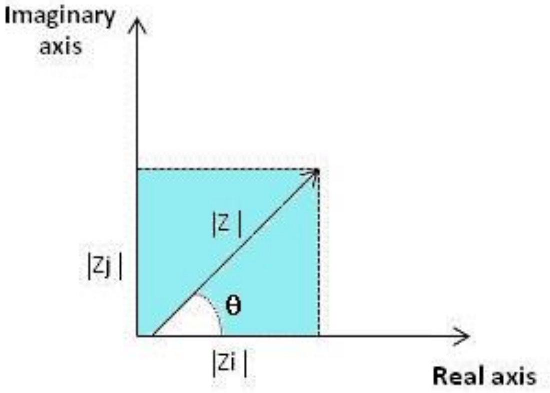

Fig. 1 - Vectorial diagram measuring the relation between the resistance and the reactance.

It is important to mention here that a circuit being formed serially from a capacitor and a resistor is at the same time capacitive reactance and resistive and therefore will have an angular frequency value of 45º. When the circuit is purely resistive the value of θ is 0, and it will move up to 90º in a pure capacitive circuit (Lietdtke, 1997).

3. Bioimpedance measurement

From the harvest side to reach the cool storage, the characterization of fruits has been an important issue in the automatic sorting of fruits. These characterization techniques can be divided between non-destructive and destructive techniques. It has been known that automatic sorting of fruit today, accompanied with the help of robotic arms follow preferably non-destructive fruits techniques in contrast with what used to happen earlier. This review focuses on the newly non-destructive techniques executed for the clean management system. Whether in-vivo or at the site of storage and harvest, impedance spectrometry has a lot of potential to be considered as a simple and low cost technique. In the aim of executing effective characterization of fruits, impedance spectroscopy has been very successful at very high frequency range (up to 6.25 MHz) as indicated by the large number of existing jobs (Harker & Dunlop, 1994; Harker & Maindonald, 1994; Inaba et al., 1995; Bauchot et al., 2000).

3.1. Measurement Principles

Measurement of impedance in food processing applies either direct or indirect techniques. For the direct measurements, the electric properties of the Material Under Test are assessed (MUT) with a variety of methods and setup where the frequency is the most distinct parameter. Particularly, at some low-level practical applications, the conductivity at a single frequency is sufficient. The β dispersion is used for a greater spectrum of more advanced interpretation. β dispersion is yielded by the polarization of membranes depending on the size of the cell and the surrounding electrolytes. It is shown in structured food but absent in unstructured food (Pliquett, 2010). The microwave spectroscopy is distinct from the radio-frequency measurements because the process responsible for dispersion in this region, such as the water relaxation, is very different from membrane relaxation or Debye relaxation of large molecules (Gabriel et al., 1996a; Gabriel et al., 1996b). However with indirect measurement, the characteristics of MUT are correlated with secondary quantities, such as the medium conductivity that are affected by the metabolites of living cells. Fig. 2 elaborates a good illustration of the bioimpedance measurements techniques.

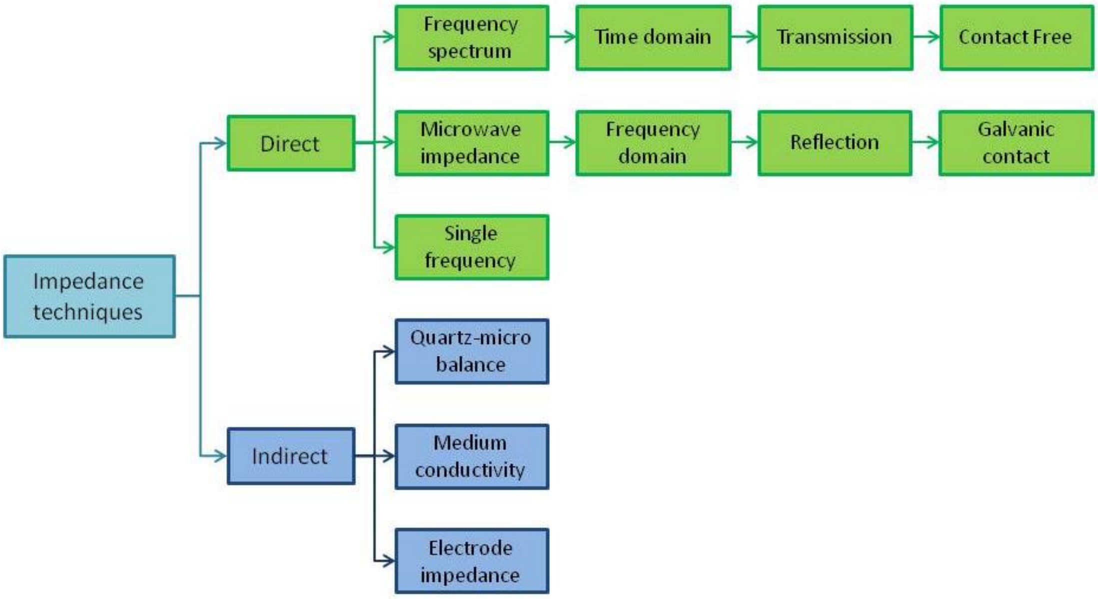

Fig. 2 - Bioimpedance measurement techniques.

3.2. Frequency and Time domain

Frequency is an independent parameter. The frequency sweep method is a technique that can be employed in frequency domain. It is applied with phase sensitive complex values for current and voltage measurement at each discrete frequency. For this method selective amplifiers like lock-in can be useful because only one frequency is processed at a time, which will enhance the signal to noise ratio and increases the sensitivity of the apparatus (Schwan, 1963). This method should take into account that time requirement becomes an essential limitation at low frequency. The application of a broad bandwidth signal and the measurement as a function of time is another approach to assess the spectrum in a wide range (Pliquett et al., 2000; Feldman et al., 2003).

Fourier transforms serves for periodic signals, Laplacian transformation is necessary for transient signals. However because most applications use repeating signals Fast Fourier transform (FFT) is the best choice method. Both generation and interpretation of the waveform are simple to be read and judged visually. The most popular waveform interpretation for fast impedance measurement is the rectangular waveform, where the noise of the system determines the lower limit of the bandwidth and the resolution of the analog-digital converter (ADC) (Pliquett, 2010). The binary signal is the maximum length sequence (pseudo random noise) that is generated digitally and requires only simple hardware (Sachs, 2005; Sachs et al., 2007). The sampling rate, the resolution of the ADC and the noise level of the amplifier are the most important quality parameters. By transforming the voltage U(t) and current I(t) to the frequency domain, the spectrum is obtained and passive electrical behavior is calculated, eq. (7). F(U(t)) and F(I(t)) are the Fourier transform of the voltage and time function respectively.

$$Z(jw) = \frac{F(U(t))}{F(I(t))} \qquad (7)$$

All measurements can be applied whether in time domain or frequency domain independently of the frequency range. The time and frequency domain measurement lead to same results and this can be proved with the measurement of a potato in both time domain (frequency range of 500 Hz – 100 KHz) and frequency domain (frequency range of 100 Hz – 10 MHz). For that a stainless steel electrode was inserted once and a low capacitive switch was used to toggle between both measuring systems. It is important here to mention that because the non-linearity characteristic of the current/voltage, the Fourier transform cannot be applied (Pliquett, 2010).

3.3. Transmission and Reflection

Although both transmission and reflection measurements contribute eventually to similar results, transmission measurements are simpler in the low frequency region. The reflectometry set up is considered easier for problems associated with electrode configuration and electrode system matching at higher frequency. Moreover, galvanic coupled systems are the best choice for low frequency systems to avoid electrode problems. Transmission mode is used at the low frequency region to characterize the material by the energy transmitted though, it such as the total current through the object or the voltage dropping across the electrodes. At high frequencies, the reflection mode that consists of characterizing the material by its reflected energy is more practical. The transmission and reflection illustration of the Material Under Test (MUT) is shown below in Fig. 3 (Pliquett, 2010).

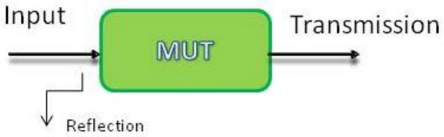

Fig. 3 - Transmission and Reflection of the Material Under Test.

A common arrangement is the termination of a transmission line by the material under test or directing an antenna to the material under test (Bone, 1988; Cole 1977; Cole et al., 1980). The reflection coefficient r depends on the characteristic impedance of the transmission line Z_0, eq. (8).

$$r(jw) = \frac{U_{ref}(jw)}{U_{inc}(jw)} = \frac{Z(jw) - Z_0}{Z(jw) + Z_0} \qquad (8)$$

Where U_{ref} is the voltage reflected and U_{inc} is the incident voltage. No reflection occurs for the case of matching objects; however for short circuits or open line all the energy is reflected. Moreover, reflection measurement is preferably used at high frequency above 100 MHz. For low frequency applications, next to the electrode systems, reflection systems are applied through antennas with a contactless measurement (Sachs, 2005).

3.4. Measurement Setup

Although a variety of equipment was available in the market for impedance measurements in the last decades, network analyzers, constructed for other purposes, were the most commercially utilized. This reason goes to the fact that other electrochemistry equipments were limited by the capability for large electrode systems and by frequency range network analyzers. Moreover, most of the work was executed with matching head stages (front-end) (Pliquett, 2010). The data analysis of the impedance starts with two difficult yet very important stages. At first stage with a physical model elucidation of the system under investigation, which involves a physical understanding of the system in terms of equations or equivalent circuits. At the second stage, the estimation of the model parameters is necessary, which involves a wise arsenal of mathematical methods to extract the parameters of the models (Sanchez et al., 2013).

The experimental results confirm that extracting the impedance parameters of the single and double dispersion, Cole impedance models can be done indirectly. Indeed this could be realized by using the excited step response of a nonlinear least squares fitting method. This will reduce the required circuitry needed for extraction of the impedance parameters (Freeborn et al., 2013). The monitoring of the voltage across the electrodes after applying current is the most spread method for impedance measurement. Bridges are another common method, however today self balancing bridges such as the Agilent Network Analyzer, giving the impedance value directly are more practical than the manual ones used earlier. Independent of the frequency range, higher voltage measurement is applied for a better signal to noise ratio (higher than 10 to 300 mV). Such approaches are basic and more robust yet simple equipment is needed for practical application. Fig. 4 resumes the different measurement instruments that will be discussed later for each product by chronological order.

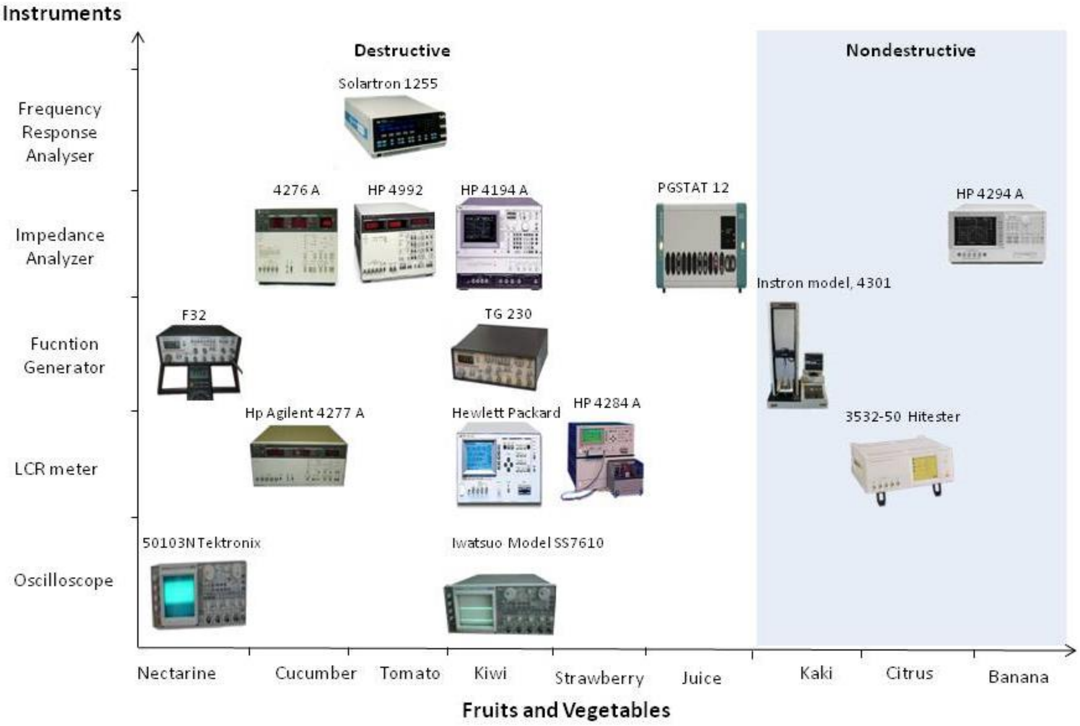

Fig. 4 - Bioimpedance measurement instruments.

4. Bioimpedance applications data

In the goal of elaborating a cleaner production control, the review focuses on the newly non-destructive techniques applied on a variety of fruits and vegetables along with their proper description. Old destructive experiments will be resumed in the analysis section later for purposes of comparison with the newly applied non-destructive techniques.

4.1. Apple

An impedance measurement test was applied to “Anna” apples in order to observe the conservation of the organoleptic properties by date and relate them to the conservation degree as well (Alzate et al., 2009). The experiments were performed over a frequency range from 2 KHz to 1.6 MHz, at room temperature with ten fruit samples for 16 days. During 16 days, bioimpedance measurements on each of the 10 samples suggest that the maturation of the apple “Anna” type is slow because the variation of the curves is not significantly resistive, when compared with each other. Because the water loss and electrolyte passage is low with time, it can be noticed that organoleptic properties such as taste, colour, aroma and texture are retained. It is noted that the extracellular resistance values are larger than the intracellular ones and this is due to the age fact. Actually, the cell wall presents a polymer component formed from sugar molecules (glucose component), which gives the cell walls high rigid opposition to the passage of electric current. Moreover the characteristic frequency for the first 7 apples have different population cell values than the last three, which might be due to the dehydration or loss of electrolytes of the Anna apple with consecutive days. Vozáry and Benko in 2010 conducted another experiment to obtain the apples impedance spectra with and without shells using two, 10 mm diameter, Ag/AgCl electrodes separated by 2 cm and obtained a model equation arranging three resistors in series (Vozáry et al., 2010).The results of the experiments concluded that the strength of the apples with peel is greater than the peeled ones.

In 2013, the apples properties during aging were monitored using EIS to provide information about the physical properties of apple. The first technique was based on a single measurement at a low frequency range of 100 Hz. The second technique on Argand Plot shows complex numbers as points. The results propose that the changes observed in EIS can be attributed to the changes in the relative moisture content of the apples (Yovcheva et al., 2013).

In 2013, another experiment was conducted to observe 14 bio-impedance parameters (freshness, moisture content, acid content, righteousness...) under nine frequencies of total 424 “Fuji” apple fruit, with different freshness grading from 1 to 5, and different weight losses varying from 0.5% to 10% to 15%. The Sparse principal component analysis linear classifier (SPCA-LDC) model was used to compute the obtained data. The results of classification accuracy reached maximum stability when the ratio of training sample was 9:1. The correct proportion rate reached a high level of stability with 90% of the sample data for training and 10% for the test sample. The average rate of classification accuracy reached 89.90% within 50 test repeats (Cai et al., 2013).

4.2. Avocado

In 2013, a study evaluated the corrosion inhibition of inedible avocado extract on the corrosion of carbon steel in molar hydrochloric acid, using electrochemical impedance spectroscopy. Results show that the charge transfer resistance of the corrosion process is increased simultaneously after the addition of the inedible avocado extract in the corrosive solution, and the double layer capacitance is decreased (Belkhaouda et al., 2013). Other dielectric properties measurement experiments on avocado executed by Cornoel et al. and Nelson et al. were cited by El Khaled et al. (El Khaled et al., 2015).

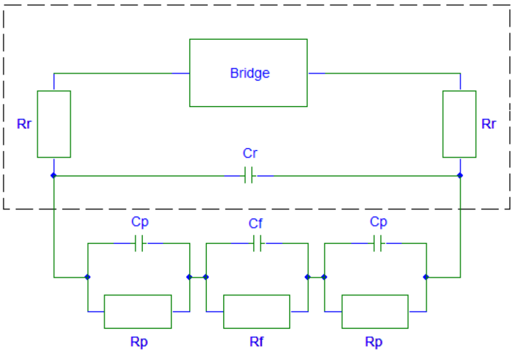

Fig. 5 - Equivalent circuit diagram of the avocado electrode system.

4.3. Banana

In order to assess the freshness of fruits, bananas have been under a non-destructive evaluation to study the changes of electrical impedance during ripening. The banana fruit was attached to Ag/AgCl electrodes, where a small current was injected and measurements are effected using 4294A impedance analyzer in a frequency ranging from 50 Hz to 1 MHz. Results of EIS show a significant variation of the phase angle, real and imaginary parts with the different states of banana ripening. Both imaginary and real parts increase with ripeness which is shown by the shift in Nyquist plots (Chowdhury et al., 2015).

4.4. Cucumber

In 2013, electrochemical impedance spectroscopy was used to control the successive modifications steps for building an immunosensor seeking the selection of Prunus necrotic ringspot virus in cucumber leaves. The electrochemical impedance technique was capable of discriminating between samples of extracts from healthy plants and consisting of leaf extracts from infected plants diluted 10000 times, with extract from healthy plants (Jarocka et al., 2013).

4.5. Garut Citrus

In 2012, a non-destructive electrical impedance measurement was used to investigate the acidity of the Garut citrus fruit. Measurements that were conducted at various pH levels and frequencies show significant response of the electrical parameters to the acidity leading to a change in the electrical properties. When the pH increases, the resistance per weight, reactance per weight, inductance per weight, inductance per weight, and impedance per weight of the citrus fruit declined. Only the capacitance per weight decreases. Using multiple regression equations, it was estimated that the correlations between pH and electrical parameters are highly linear at 1 MHz (Juansah et al., 2012).

4.6. Kaki and Persimmon

In 2012, an investigation was executed in order to study the effects of temperature on electrical parameters for “Huoshi” persimmon fruit, over a frequency range from 100 Hz to 3.98 MHz, using the inductance, capacitance and resistance analyzer (LCR) meter and parallel plate electrode. When frequency increases, results show that the fruit impedance, inductance and low frequency conductance (f<15.8 KHz) varied exponentially. When temperature rises from 10°C to 40 °C, the fruit impedance varies from 28% at 3.98 MHz to 38% at 1 KHz, the inductance varies from 30% at 3.98 MHz to 38% at 1 KHz. While the capacitance increased from 43% at 3.98 MHz to 56% at 1 KHz, and the conductance has an increasing trend. For the protection of electrical parameter values at different temperatures, the study comes up with some linear correlation equations between temperature and electrical parameters. Moreover, the frequency properties of the fruit electrical parameters were attributed to the homogeneity of the fruit structure, the penetrating capacity variance of the electric fields to the flesh and the variation of dominant electric loss factors at different frequency ranges. Also, the ionic conduction accounted for the temperature behaviour of electrical parameters (Wang et al., 2012).

4.7. Kiwi

In 2012, a study investigated the change of electrical properties and physiological parameters with the extension of storage time of the “Qinmei” Kiwi fruit. The parameters under test were the complex impedance, the parallel equivalent capacitance and the impedance angle, next to other 12 physiological parameters of fruits such as firmness. The results prove that the impedance drops significantly with the storage while the equivalent capacitance increases. As for the firmness, and the total acid of the fruit, they increase in contrary of the total soluble sugar that decreases with storage time extension. Moreover, a positive correlation was concluded between the reduction of starch and cellulose with the fruit firmness. The study stated that impedance can quantify 8 physiological parameters, such as firmness and impedance angle at a frequency of 0.1 KHz. On the other hand, the equivalent capacitance can quantify six physiological parameters in the frequency range of 1 MHz to 1.58 MHz (Tang et al., 2012).

4.8. Lettuce

Ortiz Meléndez (2014) executed bioimpedance measurements over 30 lettuce plants, treated with different nutrient solution based on the Steiner modified solution (Steiner, 1984) in order to know the level of the nitrates in the lettuce leaves. The measurements were done at a frequency range of 1 KHz to 100 KHz, with a constant current of 50 μA and two insulinic stainless steel electrodes, 1.5 cm distant, placed in the stem of young lettuce leaves. The results of the experiments concluded that a difference in nutrition between treatments led to phenotypic differences in size and color. In other means the more the nitrogen constitution, the larger the size is and the more intense green is. The impedance versus the frequency curves for the different concentration of nitrate treatments show that there is a inverse effect of the total nitrogen factor of the nitrate, which leads to a conclusion that the higher the concentration of total nitrogen, the higher the impedance value. These results support the hypothesis that bioimpedance can be a tool to monitor the concentration of nitrogen (total nitrogen and nitrates) in lettuce plants, and suggest the use of this non-destructive method to estimate the effects of other ions in the tissue plants, which will make necessary corrections to ensure greater crop yields.

4.9. Mango

A non-destructive impedance spectroscopic technique has been applied on mangoes to characterize raw and ripe fruits, in 20011. For this reason effective capacitance vs. Frequency and effective resistance vs. Frequency were determined through equivalent circuits. For equivalent circuits, effective values should be taken since the values of the resistance and capacitance will not be pure (Hague & Foord, 1971), thus the effective impedance Z_{ef} of any fruit represented by its electrical equivalent circuit can be measured. Normally, a parallel combination of an effective capacitance C_{ef} and effective resistance R_{ef} is chosen, eq. (9) (Rehman et al., 2011).

$$\frac{1}{Z_{ef}} = \frac{1}{R_{ef}} + jWC_{ef} \qquad (9)$$

The effective capacitance and resistance are values dependant on the fruit structure. Since the impedance obtained at the skin, pulp or seed level of the fruit are different, the effective resistance and capacitance will also be different and can be measured using a LCR meter. These values may vary according to several factors that can be assessed systematically or statistically determined. Thus the fruit impedance can be presented as a function of several variables, eq. (10).

$$Z_{ef} = f(x_1, x_2, x_3, \dots, x_n) \qquad (10)$$

$x_1, x_2, x_3,$ **and** x_n refer to the different experimental variables (table 1).

Table 1. Assessment factors.

Variable	Factor
X1	Time function (the fruit is unripe, ripped or over ripped)
X2	Shape of the fruit
X3	Size and weight of the fruit
X4	Contact area of the probe electrodes
X5	Temperature of the fruit
X6	Random variation of contact resistance and temperature around the controlled temperature

During ripening, mangos change colour from dark green to bright yellow color, which will change the values of the impedance measurements. A signal proportional to the impedance of the ripe fruit will be generated for a robot pluck actuation (Edan, 1995). Lower resistance and higher capacitance are provided by a bigger cross section at the contrast of lower cross sections electrodes, which will result in higher resistance and low capacitance. One drawback is that the setup design accommodates only fruits of 7.2 cm width and 8.5 cm height. Measurement were done using 5 mm diameter electrodes, with the help of a digital mass measuring system installed at the bottom of the device and temperature sensor based AD590 (a 2 terminal integrated circuit temperature transducer).

Moreover, exhaust fans are used for uniform temperature inside the container. The results of the effective resistances and capacitances measured at one Volt for a frequency range 1-200 KHz for 7 day (a duration in which unripe mangos become ripe) show that the influence of random effects decrease with the increase in frequency. Moreover, they serve to conclude that fruits have the highest effective resistance and capacitance at 1 KHz. Resistance value varying from (28.8 ± 8) KΩ to (8.3 ± 0.1) KΩ at 1 KHz and 200 KHz respectively, deduce an appreciable ratio of 6.8 existing between the effective resistances of ripe and raw fruits at 1 KHz, and the ratio is reduced to 4.1 at

200 KHz. For the effective capacitance versus frequency function, effective capacitance varies from (0.725 ± 0.021) nF at 1 KHz to (0.115 ± 0.003) nF at 200 KHz, which deduces a ratio of raw and ripe fruit of 3.3 at 1 KHz. These results prove that the effective resistance decreasing and reaching a lowest value is a very important characteristic utilized in establishing a relationship between the effective resistance, capacitance at one side and the fruit condition.

4.10. Nectarine

An experiment driven by Ling and his co-workers in 2014 determines the dielectric properties of nectarine between 10 MHz and 1.8 GHz using an impedance analyzer. Results show that the dielectric constant varies generally between 60°C bad 75°C taking into account a change of 8 to 10% due to temperature effect. On the other hand loss factor was decreasing linearly with frequency on the log scale but increased about 108% with temperature going from 20°C to 60°C and scored 1.66 at 20°C (Ling et al., 2014). Another system implemented recently obtains conductivity of a number of biological test samples among which are nectarines suggests potential studies on bioimpedance to yield rapid and sensitive results on the long term (O´Toole et al., 2015).

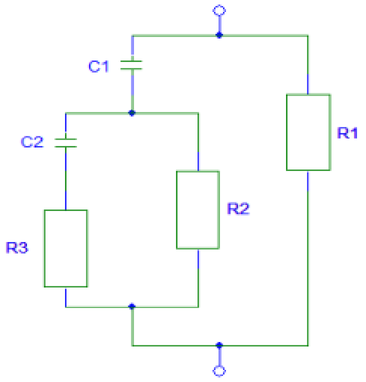

Fig. 6 - Circuit diagram to model current flow in nectarine fruit includes cell wall resistor (R1), a cytoplasmic resistance (R2), a plasma membrane capacitance (C1), its vacuole resistor (R3) and a tonoplast capacitance (C2).

4.11. Pear

A non-destructive electrical parameters measurement was executed on the "Red Bartleett" pear fruits, in 2009, at a frequency ranging from 100 Hz to 5 MHz, using parallel plate copper electrodes. The quality attributes under scope were the firmness and the soluble solids content. The results show that the impedance and inductance of the fruit were decreasing exponentially with the frequency increase, and decreasing also with fruit ripening. No regular change was noticeable for the capacitance and the conductance. Within 100 Hz to 1 MHz, the correlation coefficient of the fruit impedance increased from 0.45 to 0.84 with the inductance, from 0.45 to 0.83 with the capacitance, and from 0.37 to 0.73 with the fruit firmness. No significant change was noticeable above 1 MHz. Thus 1 MHz was considered to be the optimum test frequency, and the electrical indices considered for fruit ripening were the impedance, capacitance and inductance (Wang et al., 2009).

4.12. Strawberry

A non-destructive bioelectric impedance measurement was performed for strawberries types: “Sweet charile”, “festival”and “camino real” (González-Araiza, 2014). The designed device is inexpensive, easy to use, ensures the contact between the surface of the fruit and the electrodes. To keep a perpendicular contact between the symmetry axes of both of the electrodes and the sample, to adapt to different samples sizes and to handle repeatability in measurements with a coefficient of 0.85.

The results show significant relation of the colour variables with the maturity criteria established and a decrease in the destructive strength with the degree of maturity. The results of the intracellular resistance measurement show that the factor size does not significantly affect its variability. Moreover, the more mature the strawberry is, implies a lower intracellular resistance (ion concentration increase in the vacuoles results affects the strength of the vacuoles, which is related to the intracellular resistance). However, the maturity has an opposite effect on the extracellular resistance, because the fruits with higher maturity level classification showed higher values of extracellular resistance than those of lower maturity (reduction in the concentration of free ions).

4.13. Tomato

The monitoring the root growth of tomato was investigated through EIS, using two unpolarisable Ag and Ag/Cl electrodes measuring system, in 2005. The experiment model that used a nine parameters, which value were estimated by Complex Non Linear Least Squares Curve Fitting, was considered to be a new contribution to the understanding to root electrical properties in the non-destructive diagnosis at that time. Results show that both electrical capacitance and resistance components characterize root growth. Via changes in their electrical properties, obvious relationships between the root dry weight and length increment were demonstrated through the new yet invasive method (Ozier-Lafontaine & Bajazet, 2005).

In 2006, impedance measurement was used to study the effect of cucumber mosaic virus red bean isolate on electrical resistance of tomato leaves. The results show that the resistance of tomato leaves was smaller than that in sound plant leaves. With the increase of disease severity, the impedance in leaf tissues decreases, which was detected within 4 days after the inoculation. This proves that impedance measurement is a rapid and clever method for simple plant disease diagnosis (Huirong et al., 2006).

In order to observe the plant stress caused by the lack of mineral nutrients in the tomato growth medium, a study has applied the EIS as non-destructive, economical and reliable measurement method. Two sets of hydroponically-grown tomato plants “Lycopersicon esculentum Mill” and “Maliniak” were fed alternately with flow of necessary nutrients and with distilled water. The most sensitive frequency was determined by measuring the impedance spectra at a frequency ranging from 100 Hz to 50 KHz. Variability of mineral nutrition with plants was indicated through the proposition of a nutrition index tested later for its correlation with the experimental data. The study shows a monotonic function between the nutrition index and the stress caused by lack of mineral nutrients in the growing medium (Tomkiewics & Piskier, 2012).

Once more, the electrochemical impedance spectroscopy was used in 2014, at a frequency range from 100 mHz to 100 KHz, using Ag/AgCl electrodes to study the herb “paraquat” in tomatoes. The Nyquist plots were modelled with an equivalent circuit by identifying the charge transfer resistance as the relevant concentration dependent parameter. Results show that the methodology have some good repeatability and impedimetric response to paraquat in the range from 1.0 * 10^{-14} to 8.0 * 10^{-4} mol/L (Farahi et al., 2014).

5. Results and Discussions

As mentioned earlier, for analysis purposes, Table 2 presents, in chronological order, different vegetables and fruits on which destructive bioimpedance measurement were applied, with their appropriate authors, objective of the study and their principal conclusions.

With destructive methods, the following products strawberry, Kiwi, kaki and nectarine were measured for the same frequency range going from 50 Hz to 1 MHz. While the avocado and pear were measured under a frequency ranging 214 Hz to 20 KHz, the tomato from 50 Hz to 10 MHz, the cucumber was measured for a frequency range going from 500 Hz to 1 MHz, the apple from 1 Hz to 1 MHz and the juice from 0.5 Hz to 1 MHz. At the other hand, non-destructive measurements were applied on the apple for a frequency ranging from 30 Hz to 1.6 MHz, the mango fruit from 1 KHz to 200 KHz, the citrus from 100 Hz to 1 MHz, the lettuce from 1 KHz to 100 KHz, the Kiwi from 1 MHz to 1.58 MHz, the tomato from 100 mHz to 100 KHz, the persimmon from 100 Hz to 3.98 MHz and the pear from 100 Hz to 5 MHz.

The range of frequency chosen for measurement depends highly on the type of fruit under test and its physical composition. Water content and sugar levels are major factors affecting the bioimpedance measurements. For instance, impedance behaviour for sugar is different from acidic or vegetables mediums rich in minerals. Their correlation with quality parameters are highly affected by the frequency range of measurements as well. Analysis proves that some correlations appear at specific frequencies, while some other changes are not noticeable at different frequencies. Thus, it comes out that food composition itself directs to the appropriate frequency measurement range and affects impedance behaviour.

Table 2. Destructive bioimpedance data.

Product	Objective	Principal Conclusions
Apple (Jackson & Harker, 2000)	Investigate the impedance characteristics of individual tissues on the whole fruit during ripening and on the outer and inner perircap as well.	The fruit weight did not affect the initial measurement and that the variations of the temperatures with the resistance occur at 50 Hz. A high correlation exists between ΔR and the degree of damage of both varieties. Further methodology development will be able to produce faster and more convenient volume and weight estimations of the damage immediately after impact.
Apple (Li et al., 2005)	Relate impedance parameters with apple quality.	Impedance decreases with increasing frequency from 1 Hz to 1 MHz. At high frequencies, impedance of rot and good apples were similar, but not at low frequencies.

Apple (Fang et al.,2007)	Explore the connection between impedance and fruit taste.	The soluble solid content (SSC) correlates linearly with impedance for low acidity. Titratable Acidity (TA) has linear relationship with the impedance square root (ISR) for high acid variety. Both TA and SSC contribute to this linear relationship for medium acid variety.
Avocado (Montoya et al., 1994)	Measure the electrical conductivity of avocado under different conditions of temperature and different atmospheric conditions during storage.	Measurements of electrical conductivity of avocado are simple and fast to determine the fruit quality. The fast increase in the conductivity is due to the occurrence of physiological disorders that are chilling injury (See Fig 5).
Cucumber (Inaba et al., 1995)	Analyze the tissue impedance changes due to the application of current simultaneously with the induction of ethylene biosynthesis.	The increase in the extracellular space resistance and partially on the capacitance of the plasma membrane is significantly reduced by the ethylene production inhibition.
Kaki and Persimmon (Harker & Forbes, 1997)	Measure the electrical impedance to provide relevant information about the physiology of fruit maturity.	The temporary reduction in the concentrations of free ions in the tissue or the transient increase in insulating compounds have resulted in the rapid and transient increase in R at 20°C during the first 21 days.
Kiwi (Bauchot, et al., 2000)	Detect possible information on the size and weight of a bruise that can be provided by EIS performed with electrodes placed on opposite sides of the bruise.	Only small changes were identified in the impedance of the fruit during maturation. The differences in the firmness and volume of extracellular fluid and the differences in ion content and cell sugar explain the resistance difference at 50 Hz and 1 MHz of the pericarp center tissues. However, during maturation, no major tissue impedance changes are noticeable.
Lime and Orange Juice (Sundararajan et al., 2008)	Pasteurize the juices to enhance their longevity	The pulsed juices present a 5 log reduced amount of lactic bacterial acid (at 1250 V/cm) compared with the unpulsed juices.
Nectarine (Harker & Maindonald, 1994)	Characterize the nectarine tissue blocks impedance and differentiate the electrodes effect.	For low frequency measurements, changes in the extracellular medium are related to the resistance R, while at high frequencies R is associated mainly with the vacuole remains constant. A decrease in R occurs in the cytoplasm during maturation (See Fig. 7).
Nectarine (Harker & Dunlop, 1994)	Measure electrical impedance of ripe and unripe nectarine at alternating frequencies.	Tissue resistance is greater at low frequencies (50-100 Hz). The resistance of the whole fruit is lower than that of an excised block of tissue.
Pear (Montoya et al., 1994)	Determine the existence of a correlation between electrical properties changes and metabolic fruit development.	The frequency of the electrical conductivity in the fruit mesocarp is electrolytic. The pear is a fruit high in water content and organic acids of low molecular weight (weak electrolytes), but its conductivity is lower than the avocado that is less rich in water and acid and high organic molecular weights.
Strawberry (Harker et al., 2000)	Examine the effect of CO2 on the characteristics of the cell and tissues and its influence on the firmness of the “Bird” strawberry both in harvest and storage periods.	At 50 Hz, the resistance R of the apoplast was lower for stored strawberries subjected to treatments with CO2 than the ones that were untreated but no significant resistance changes were noticeable at 1 MHz, which implies an increase of electrolytes within the extracellular solution.
Tomato (Benavente et al., 1998)	Measure electrical impedance to investigate the physiology of fruit maturity.	The angular frequency for different samples in the study such as the cutin and cuticule of mature and immature fruits has different dielectric behavior for each membrane.

Fig. 7 classifies the different vegetables and fruit species according to their destructive or non-destructive sequence of study in frequency range. It is clear that all of the products except for the tomato and pear have been under destructive study first. The reason for this goes for two major factors. First of all, most of the bioimpedance experiments seeking the quality improvement of fruits and vegetables started at lower frequencies. It is very logical for a new growing field of study to start an experiment at low frequency ranges then to move higher according to the results obtained. The second factor goes for the technology. Early measurements were necessarily destructive meanwhile new techniques have facilitated the conduction of non-destructive experiments.

Although logical, one cannot conclude that lower frequency ranges are less harmful than higher ones; because for the same frequency corresponds both destructive and non-destructive applications. Moreover, avocado for example has been only destructively measured since the only existing experiment goes for 1994 and no recent studies were elaborated. In contrary, lettuce and mango are recently explored which explains the presence of only non-destructive data. In fact, the frequency chosen depends highly on the technique; with the availability of new instruments, higher frequency is allowed in non-destructive experiments. The case of tomato is special since it was under scope severally. Recent studies dating to 2005, 2006 and 2012 (Ozier-Lafontaine & Bajazet, Huirong et al., and Tomkiewics & Piskier respectively) started at a frequency of only 1 Hz, while the destructive study of Benavente et al., in 1998 goes from 50 Hz up to 10 MHz. For the pear, the destructive range applied by Montoya et al. was narrow enough that is has been covered and extended by the non-destructive study of Wang et al. as well. The experiments come out with a definitive result regarding the validity of elaborating the cleaner system of control based on bioimopedance spectroscopy. The challenge of such a system lies in the fact that high sensitivity of instruments is required for non destructive impedance measurements whereas demand on the agricultural field scale requires fast high throughput sensors of rugged design.

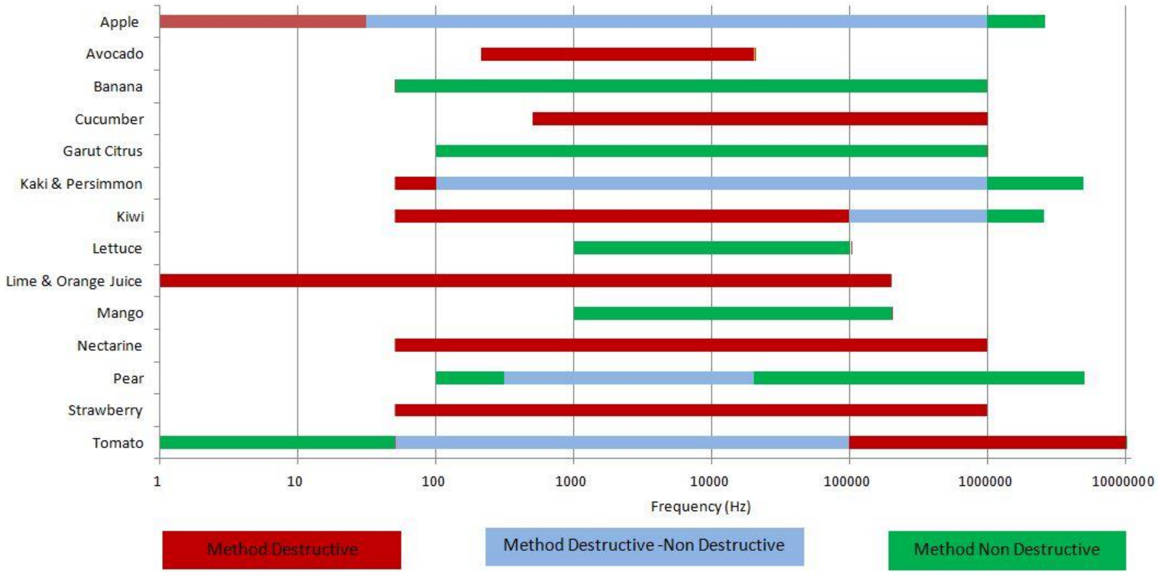

Fig. 7 – Destructive and non-destructive sequence of measurement with frequency.

The bioimpedance turns out as a good electrical measurement for consideration in ripening fruits. For the case of the kiwi for example, significant changes in the strength occurred, but only small changes in the impedance could be observed. This is not the case of other fruits such as nectarine, Kaki and tomato that undergo considerable impedance reductions during ripening (Bauchot et al., 2000). In the case of Nectarine, a decrease in the resistance was due to the increase in the concentration of mobile ions at low frequencies; which has leaded to this extracellular change. Same for the Kaki, a correlation between the capacitance and the tonoplast area membrane was recorded.

Fig. 8 is a graphical chronological presentation of the experiments executed on the various products from year 1994 up to today. The nectarine and avocado were the first fruits to be quality assessed for their electrical impedance measurements. Some products such as apple and tomato were heavily under scope in several experiments up to 2013; whereas some others like mango, citrus and lettuce appeared only once in 2011, 2012 and 2014 respectively.

Bioimpedance technique was used widely for different objectives such as determining the fruit tissue characteristics, the effect of the electrodes (Harker & Maindonald, 1994), measuring the conductivity under various atmospheric conditions and temperature variations during storage and determining the correlation existing between the electrical properties changes and the metabolic fruit development (Montoya et al., 1994). Also detecting the electrical impedance difference in ripe and unripe fruits (Harker & Dunlop, 1994), analyzing the tissue impedance changes due to the application of current simultaneously with the induction of ethylene biosynthesis (Akitsugu, 1995), measuring the fruit physiology variation under the bioimpedance spectroscopy measurements (Harker & Forbes, 1997) and revealing information about the fruit physiology maturity (Benavente et al., 1998). Others objectives were determining the characteristics of fruits during ripening for both external and internal tissues (Jackson & Harker, 2000), detecting the weight and size of a bruise (Bauchot et al., 2000), analyzing the effect of CO_2 on the firmness and ripening of a fruit during harvest and storage period (Harker et al., 2000), relating impedance parameters with fruit quality (Li et al., 2005) and exploring the connection between impedance and fruit taste (Fang et al., 2007). All these measurements were conducted using destructive impedance methods. However with the development of new instruments, many of these criterias are now accessible for measurements through non-destructive measurements at appropriate acquisition rates; which have a positive effect economically on the number of samples used for the experiment. Non-destructive methods do not have negative or dangerous aspects on the fruit itself, thus the same sample can be used once more for the repetition of the experiment which will be more economically encouraging for a cleaner production system. Therefore, the improvement of real time bioimpedance spectra analysis is highly essential.

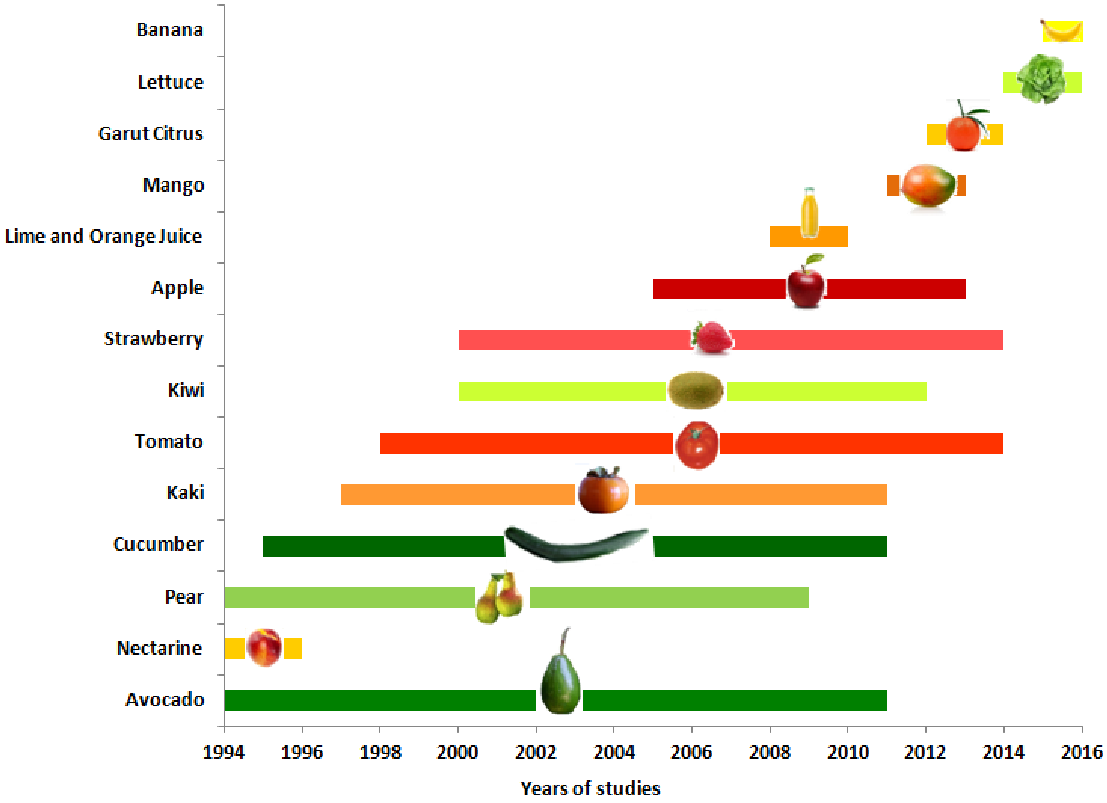

Fig. 8 - Period of study for the fruits and vegetables.

In this context, all the recent bioimpedance spectroscopy measurement conducted followed non-destructive techniques, although they were seeking similar or very approximate measurements such as monitoring root growth of a fruit (Ozier-Lafontaine & Bajazet, 2005), studying the effect of an isolate virus on electrical resistance of a fruit leaves (Huirong et al., 2006), relating the bioimpedance measurement with the conservation of a fruit (Alzate et al., 2009) and correlating the impedance parameters with the fruit firmness and soluble solid contents (Wang et al., 2009). Others as studying the differences in bioimpedance spectrum with or without shell (Vozary & Benko, 2010), observing the ripening process of a fruit (Rehman et al., 2011), studying the extraction of fruit pigments towards corrosion (El Gharras, 2011), studying the effects of temperature on fruit electrical parameters (Wang et al., 2012) and studying the plant stress caused by lack of mineral nutrients (Tomkiewics & Piskier, 2012), investigating the electrical and physiological fruit properties with storage time (Tang et al., 2012). Or investigating the acidity of the fruit using electrical properties (Juansah et al., 2012), monitoring the fruit properties during aging (Yovcheva et al,, 2013),

evaluating the corrosion inhibition of a fruit extract on the corrosion of carbon steel in molar hydrochloric acid (Belkhaouda, 2013) and observing the bioimpedance parameters with varying fruit freshness and weight (Cai et al,, 2013). Also controlling the steps for building an immunosensor to select necrotic viruses in fruits (Jarocka et al., 2013), estimating the total nitrogen and nitrates in a vegetable “Lettuce” (Ortiz Meléndez, 2014) and investigating the fruit firmness (González-Araiza, 2014).
Thus, like it was stated earlier, most of the industrial applications of bioimpedance measurements tend to use non-destructive techniques, and nowadays the destructive techniques are being limited to genetically used experiments.
To resume, knowledge of dielectric properties is essential to understand the interaction between the electromagnetic fields and the target stone fruits to design treatment beds in industrial applications. Sensing food quality through electrical properties reveals impressing results (El Khaled et al., 2015). Storage time, maturity, fruit peeling, temperature, frequency, ionic and acidic compositions are all indices that show a positive contribution of the electrical characterization of fruits and vegetables.

With the technological improvement, advanced technology and computerized data processing have facilitated the rapid evolvement of non-destructive methods. Economically, the modern facilities that have accompanied the non-destructive measurement had a great saving impact on the number of samples required compared with destructive techniques, where continuous experiments need more samples under test. In practice, destructive and non-destructive techniques may be following very close methods of measurements. However, more advanced measurements opened the door to a more focused exploration at higher frequency ranges, using recent technological instruments that avoid destroying or harming the samples. In addition, better electrode use, improved calibration and mathematical elaboration enhanced much the non-destructive measurement. This being said, further explorations of the fruits and vegetables that have already been under test seek higher frequency ranges measurements. At higher frequency ranges, the intention is to reach more precise correlations between quality factors under scope and food electrical impedance characteristics; for each quality factor corresponds appropriate conditions.

It is important to mention that not only mathematical formulation helped the advances realized in the fruits and vegetables characterization field, but also the development of better sensors and measurements instruments served to great achievements. In this context, Hmamou et al. (2012) used the electrochemical impedance spectroscopy in the prickly pear seed oil extract and got high inhibition efficiency at elevated temperature.

6. Conclusions

This review summarizes the potential of bioimpedance spectroscopy to detect electrical characteristics in fruit and vegetables which will enhance the quality production parameters. It offers a comprehensive overview of bioimpedance techniques focussed on electrical characteristics of vegetables and fruits. For the cleaner control elaboration, non-destructive techniques for different species are presented and the wide variety of equipment available in the market for impedance measurements in the last decades was shown and divided in these two categories. Each fruit and vegetable available in the literature was revised in order to highlight the new advances for bioimpedance spectroscopy.

The list of vegetables and fruits revised were: Apple, Avocado, Cucumber, Garut Citrus, Kaki and Persimmon, Kiwi, Lettuce, Lime and Orange Juice, Mango, Nectarine, Pear, Strawberry, and Tomato. In the last section, a resume table for destructive experiments was made to highlight the common and differences for the different vegetables and fruit species analyzed in their frequency range, showing the overlap between both. This review illustrates a timeline for the different publications related to the vegetables and fruits and builds up a path for cleaner control system integration. The correlations of impedance parameters with agricultural product quality factors leaded to some successful conclusions in some applications and failed in others. Because the most essential aspect of assessing the bioimpedance spectroscopy with agricultural product quality factors shows a great effectiveness, there is a huge need for further explorations in this field. Finally, this manuscript shows as main conclusion, that non destructive bioimpedance techniques open new perspectives for cleaner quality control system in industrial applications for fruit and vegetables quality determination.

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