Transformation and agro-industry

Revision article

Electrical impedance spectroscopy applied to quality control in the food industry

Espectroscopia de impedancia eléctrica aplicada al control de la calidad en la industria alimentaria

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Abstract

Electrical impedance spectroscopy (EIS) is a technique used to analyze the electrical properties of diverse materials, including the biological, inducing, and measuring alternating electrical signals at different frequencies. Impedance measurements are employed to establish ripeness in fruits, identify adulterations in meat and dairy products, determine physicochemical properties in all types of food matrices, and even to quantify microorganisms present in food and on work surfaces. This technique is safe, non-invasive, fast, portable, inexpensive and easy to use, which makes it a method with great potential to be used in the food industry to monitor and control quality processes. This systematic review compiles scientific information published between the years 2012 and 2018 that describes the use of EIS applied to food quality control. Searches were made through the databases ScienceDirect and Springer as well as using the search engine Google Scholar, through the strategy: Spectroscopy electrical impedance AND Foods. After using a series of filters and a manual search, 52 articles and four theses related to the topic were found. The systematic review showed that most of the studies focus on the quality assessment of meat and fishery products, as well as on the characterization of the changes generated during the thermal processes and fruit ripening.

Keywords: agroindustry, animal tissues, food control, plant tissues, processed foods

Resumen

La espectroscopia de impedancia eléctrica (EIE) es una técnica que permite analizar las propiedades eléctricas de materiales, incluso biológicos, al inducir señales eléctricas alternas a diferentes frecuencias y medir las señales de respuesta. Se ha utilizado para determinar la madurez en frutos, identificar adulteraciones en productos cárnicos y lácteos, determinar propiedades físico-químicas en todo tipo de matrices alimentarias, incluso para cuantificar microorganismos presentes en alimentos y en superficies de trabajo. Esta técnica es segura, no invasiva, rápida, portátil, de bajo costo y fácil de usar, lo que la convierte en un método con un gran potencial para ser usado en la industria de alimentos, con el fin de monitorear y controlar los procesos de calidad. La presente revisión sistemática recopila información científica publicada entre el 2012 y el 2018, que describe el uso de EIE implementada en el control de calidad de alimentos. Se realizó una búsqueda en las bases de datos ScienceDirect y Springer, así como a través del buscador Google Académico mediante la estrategia *Spectroscopy electrical impedance AND Foods*. Con base en una serie de filtros y una búsqueda manual, se encontraron 52 artículos y cuatro tesis relacionadas con la temática. Asimismo, se encontró que la mayoría de los estudios se centran en la evaluación de calidad de productos cárnicos y pesqueros, así como en la caracterización de los cambios generados durante los procesos térmicos y maduración de frutas.

Palabras clave: agroindustria, alimentos procesados, control de alimentos, tejidos animales, tejidos vegetales

Introduction

Analytical methods to guarantee physicochemical, microbiological, and sensory quality are required by the food industry (Jiménez & León, 2009). Traditional analytical techniques, such as gravimetric, volumetric and colorimetric determinations have little specificity and provide low sensitivity for the determination of traces, whereas other methods, such as chromatography have the ability to detect up to parts per trillion, but they are expensive and involve a previous preparation of the sample, which implies more processing time (Jiménez & León, 2009).

In addition, in most cases classical analyses techniques are expensive and require highly trained personnel, as well as prolonged processing time to obtain the results and, moreover, are destructive, leaving the study piece unusable. Therefore, numerous research studies have focused on the search for non-destructive and rapid methods to develop food product monitoring systems. Some of the techniques used are magnetic resonance imaging, application of electronic sensory systems (tongues and noses), near-infrared spectroscopy, spectral nephelometry and time domain reflectometry (Masot, 2010). These methods are characterized by having a high precision (Blanco-Díaz, Del Río-Celestino, Martínez-Valdivieso, & Font, 2014), although they require expensive instrumentation (Grossi, Di Lecce, Toschi, & Riccò, 2014).

Electrical impedance spectroscopy (EIS) is an excellent option compared to traditional analysis methods, since it allows real-time field measurements, as well as being easy to move and use. In the area of medicine, it has been used to monitor cell cultures, establish changes in organ volume and body composition, and classify and monitor tissues (Aristizábal-Botero, 2010). In the food area, it is used to characterize vegetables, fruits and meat tissues in cell cultures as well as fermentation processes, to measure the biomass concentration, and to correlate physicochemical properties of thermally treated foods (Pérez, 2014).

Thus, the EIS is a promising detection technology with multiple advantages, such as its speed, economy, easy implementation, as well as being non-destructive and environmentally friendly (El Khaled, Castellano, Gazquez, García-Salvador, & Manzano-Agugliaro, 2017), and with a potential to replace traditional methods, saving time, costs and staff training. On the other hand, it has problems in data processing and interpretation, so it is necessary to automate its processing (Pliquett, 2010). Besides, several factors intrinsic to the material inside the cell can affect the response of the spectrum (Jorge et al., 2018), so the electrode materials and measurement procedures must be standardized.

The EIS allows analyzing the electrical properties of materials and systems by inducing alternating electrical signals at different frequencies and measuring the response signals (Fernández-Segovia et al., 2012). In this way, the frequency spectra of the impedance, conductivity, and permittivity of the samples are obtained and adjusted, using mathematical models that allow calculating the parameters that characterize the tissues. In addition to the Hayden model, one of the most widely used mathematical models is Cole-Cole together with its graphic representations using the Nyquist and Bode diagrams (Aristizábal-Botero, 2010).

The Nyquist diagram is very common in the evaluation of solid impedance data. It shows the curve of the imaginary component Z "against the real component of the same Z." It also allows evaluating the impedance data for the entire frequency range. The representation is a circular arc, as can be seen in figure 3.1.3., of the thesis carried out by Farfán (2011).

The Bode diagram represents the module and phase as a function of frequency; the logarithm of the impedance (Log $|Z|$) and the offset (θ) are plotted against the logarithm of the frequency (Log ω), as shown in figure 3.1.4., found in Farfan (2011).

Hayden's model considers intracellular and extracellular resistance, as well as resistance and capacitance or the cell membrane. It is assumed that the membrane resistance can be ignored because the impedance value is much larger than the values of other parameters, as shown in figure 3.a, of the research published by Ando, Mizutani, and Wakatsuki (2014).

Impedance is the opposition that biological materials manifest to the passage of an alternating electric current, which breaks down into two modules: resistance (the real part) and phase (the imaginary part). The first is established by the passage of the current through the intracellular and extracellular electrolytic solutions, while the second depends on the dielectric properties of the tissues or by the temporary accumulation of charges on the cell membranes (Aristizábal-Botero, 2010).

The cell is the basic unit of living matter (Rodríguez, Uriarta, Palazuelos, & Pérez, 2012) and its main element is the cell membrane, whose structure is composed of a lipid bilayer in which the proteins that facilitate channel formation for an ionic exchange with the outside, are found (Salazar-Muñoz, 2004). Due to their high resistance and surface charge, cell membranes behave as a non-conductive material and can be represented as the two plates of an electric capacitor; consequently, when a constant electric field is applied, electrically charged ions move and deposit on both sides of the membrane (Salazar-Muñoz, 2004).

For this reason, cells and tissues (both plant and animal) can be modeled as electrical circuits, considering the resistive and capacitive properties of intracellular, extracellular and cell membrane fluids (Aristizábal-Botero, 2010).

One of the most used electrical circuits, i.e., Fricke's model, consists of a resistor to simulate the behavior of the extracellular environment (Re), another for the intracellular medium (Ri), and a capacitance (amount of energy stored) for the membrane (Ci), as shown in figure 10 of the thesis elaborated by Masot (2010).

By inducing alternating electrical signals at different frequencies to a biological tissue, generally at low-frequency apoplasmic resistance (of the cell wall), it functions as a resistance parallel to the resistance of the membrane, while at high frequency, the resistance of the membrane is short-circuited so that it can be ignored (Ando, Mizutani, & Wakatsuki, 2014). Therefore, impedance as a function of frequency can easily indicate changes in cell membrane integrity and solute leak in the apoplasm, through the effects on capacitance and resistance at high and low frequencies (Caravia, Collins, & Tyerman, 2015; During, Becari, Lima, & Peres, 2016).

The experimental setup was straightforward. An impedance analyzer and a computer were used to control the analyzer during the measurement process; with the results obtained and the calculation of the models, a control and data acquisition software and electrodes were used to measure the electrical properties. There are references of impedance analyzers that operate at different frequency ranges: 0.01 Hz-1 MHz, 100 Hz-1 MHz (Scandurra, Tripodi, & Verzera, 2013), 100 Hz-5 MHz (Das et al., 2017) and the maximum is at 110 MHz (Guermazi, Kanoun, & Derbel, 2014). Some of the most used softwares are the following: the EIS Spectrum Analyzer developed by Bondarenko and Ragoisha in 2005; Software Bode 100 created by Caravia et al. (2015), and Zview developed by Villa-García, Pedroza-Islas, Martín-Martínez and Aguilar-Frutis (2013). These softwares allow extracting the resistance and capacitance values of the system. Then, the impedance response can be modeled with the Hayden Model, modified model, and equivalent circuit.

Generally, the data obtained in the analyzes are represented in graphs that show the change in impedance as the frequency increases. In potato tissue during drying, there are temporary changes in the impedance spectra, which markedly declines when the frequency increases between 10^4 and 10^6 Hz. This phenomenon in which the impedance decreases as the frequency increases is called *dispersion* (Ando et al., 2014).

During testing, it is not necessary to carry out special conditioning on the samples before analyzing.

However, it is essential to ensure that the samples remain static during measurements. For this, supports and electrodes are designed in such a way that they adapt to the type of food or system (solid and liquid) and the morphology.

In the case of milk analysis, two SAE 316 stainless steel rods have been used, spaced 10 mm from each other and submerged to a depth of 20 mm (Durante et al., 2016). In broths of microbiological cultures, two stainless steel electrodes of 10 cm in length with a diameter of 0.9 mm and a separation between them of 1 cm have been used (Villa-García et al., 2013). In honey analysis, gold electrodes subject to a hinged metal arm have been used, which allows the desired angles to be adjusted, as well as the distance and depth of the electrodes (Scandurra et al., 2013); further, platinum electrodes have also been used (Das et al., 2017). In the electrical characterization of oil, a pair of stainless-steel electrodes have been used, with 6 mm in diameter and 12 mm of space between them, and submerged in a water/oil emulsion (Yu et al., 2015).

Interdigital capacitive sensors (ID) have been developed, which are more sophisticated to explore the presence of phthalate esters in fluid media, and which have multiple detection gold electrodes, manufactured on a silicon substrate and coated with a thin polymer film of parylene C, to improve the capacitive sensing capabilities of the sensor and reduce the magnitude of faradic current flowing through the sensor (Zia et al., 2013).

In spherical solid foods such as berries, the most stable measurements have been obtained when placed with a small portion of skin (3 mm in diameter) on each side of the smaller diameter of the berry, between two disk electrodes (Ag/AgCl) of 8 mm in diameter attached to an acrylonitrile butadiene styrene plastic frame, with a suspended arm that adjusts with a micrometric screw. In this way, the electrodes can be placed carefully to touch the surface and accurately measure the distance between the electrodes (Caravia et al., 2015). For the analysis of mango ripening, two Ag/AgCl electrodes arranged on the opposite side of the fruit (equatorial zone of the samples) have been used (Figueiredo-Neto, Cárdenas-Olivier, Rabelo-Cordeiro, & Pequeno de Oliveira, 2017). In spinach leaves, 17 mm steel needle electrodes have been used, located along the central vein at points that are approximately 5 mm of distance (Watanabe, Ando, Orikasa, Shiina, & Kohyama, 2017).

In meat and fish products, electrodes with pointed ends have been designed to facilitate penetration into the muscle fibers. These are inserted 10 mm perpendicular to the fiber direction (Fernández-Segovia et al., 2012). Circular penetration probes have been used to increase reproducibility consisting of a central electrode and eight surrounding steel electrodes (Guermazi et al., 2014).

Materials and methods

The systematic review was carried out in the ScienceDirect and Springer databases using the search strategy: {(Spectroscopy electrical impedance) AND (Food)}. The following filters were applied: Years: 2012 to 2018; English language; Item Type: Review, Original. Finally, the Google Scholar search tool was used to obtain more documents that were not found in the previously mentioned databases. In this case, the following filters were used: Years: 2012 to 2018; Language: English and Spanish; Type of document: Articles and master and doctorate theses. Additionally, manual debugging was performed, discarding the repeated articles and those that did not have a direct relationship with the subject.

Results and discussion

The systematic review with the proposed search strategy managed to obtain a total of 80 documents (ScienceDirect: 49, Springer: 21 and Google Scholar:

10). Subsequently, the repeated documents were eliminated, and the analyses were focused only on the development of the electric model without considering the correlations with the physicochemical, sensory or microbiological properties in the food studied, obtaining finally 56 documents (52 articles and four doctoral theses).

The documents were grouped into seven categories that represent the fields of application of EIS in the most representative tasks of the food industry that include: (i) identification of fraud, (ii) detection of contaminants, (iii) establishment of physicochemical properties, (iv) establishment of maturity, (v) evaluation of the quality of meat products, (vi), characterization of heat treatments, and (vii) detection of microorganisms. Table 1 shows the synthesis of the articles found in each of the defined categories.

Table 1. Synthesis of the articles found

Application in the food industry	Year	Authors	Description
Identification of fraud	2012	Fernández-Segovia et al.	Detection of fraudulent sale of frozen-thawed salmon under the name of fresh
	2013	Scandurra et al.	Establishment of the floral origin of honey
	2013	Fuentes et al.	Detection of fraudulent sale of frozen-thawed sea bass under the name of fresh
	2013	Yang et al.	Establishment of the content of illegally injected water in pig muscles
	2016	Chen et al.	Detection of fraudulent sale of frozen-thawed chicken breast under the name of fresh
	2016	Durante et al.	Detection of milk adulteration
	2017	Das et al.	Development of a platform to detect honey adulteration

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(Continuation of table 1)

Application in the food industry	Year	Authors	Description
Detection of contaminants	2013	Zia et al.	Phthalate detection in water and juices
	2015	Farahi et al.	Pesticide detection in milk and tomato
	2015	Yu et al.	Detection of aflatoxins in olive oil
	2017	Boumya et al.	Determination of aldehydes in food
Establishment of physicochemical properties	2012	Jishu and Du Guangyuan	Changes in physiological parameters of kiwi during storage
	2012	Juansah, Budiastra, Dahlan and Seminar	Evaluation of the acidity of oranges
	2014	Grossi et al.	Fast and accurate method to establish the acidity of olive oil
	2015	Żywica and Banach	Prediction of total soluble solids (TSS) content in apple juice
	2016	Nakonieczna, Paszkowski, Wilczek, Szypłowska and Skierucha	Detection of artificial additives in liquid foods
	2017	El Khaled et al.	Systematic review on the application of EIS in the quality of fruits and vegetables
	2017	Lopes et al.	Wine characterization
	2017	Sharma et al.	Determination of moisture in tea leaves
	2018	Lopes, Machado, Ramalho and Silva	Ultra-pasteurized milk characterization
	2018	Watanabe, Ando, Orikasa, Kasai and Shiina	Changes during apple storage

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(Continuation of table 1)

Application in the food industry	Year	Authors	Description
Establishment of maturity	2013	Kuson and Terdwongworakul	Durian maturation evaluation
	2014	Juansah, Budiastra, Dahlan and Seminar	Orange ripening evaluation
	2014	González- Araiza	Procedure to measure the degree of ripeness of strawberry
	2015	Caravia et al.	Regression model that allows an accurate prediction of the degree of maturity in Shiraz
	2016	Nakawajana, Terdwongworakul and Teerachaichayut	A technique to evaluate the quality of export type mangosteen
	2017	Chowdhury, Singh, Bera, Ghoshal and Chakraborty	Orange mandarin ripening study
	2017	Figueiredo- Neto et al.	A technique applied in the identification of mango ripening
	2017	Chowdhury, Kanti Bera, Ghoscal and Chakraborty	Banana ripening study
Quality evaluation of meat products	2012	Vidaček et al.	Freshness evaluation of sea bass (*Dicentrarchus labrax*)
	2013	Kaltenecker, Szöllösi, Friedrich and Vozáry	Determination of salt content in ripened pork
	2013	Rizo et al.	Method to monitor the quality of smoked salmon
	2014	De Jesús et al.	Method to monitor ham quality
	2014	Pérez-Esteve et al.	Method to establish the freshness of the gilt-head sea bream (*Sparus aurata*) stored and from different sources
	2014	Guermazi et al.	Method to monitor the quality of beef and veal

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(Continuation of table 1)

Application in the food industry	Year	Authors	Description
Quality evaluation of meat products	2015	Nguyen and Nguyen	Quality assessment of pork meat during storage
	2016	Zavadlav et al.	Evaluation of the shelf life of refrigerated squid
	2017	Zhao et al.	Review of the advances in the application of EIS in the quality of meat and fish
	2018	Sun et al.	Evaluation of the freshness of carp (*Cyprinus carpio*)
Thermal process characterization	2014	Ando et al.	Method to evaluate the condition of the potato tissue subjected to a drying process.
	2014	Fuentes et al.	Micro-structural and texture changes in potatoes cooked in water
	2015	Kertész, Hlaváčová, Vozáry and Staroňová	Changes in the moisture content of dehydrated carrots
	2015	Imaizumi, Tanaka, Hamanaka, Sato and Uchino	To evaluate the degree of potato softening during heating
	2016	Ando et al.	Changes in the texture of dehydrated, frozen and rehydrated carrots
	2016	Bera, Bera, Kar and Mondal	Changes in cooked banana stem tissues
	2017	Ando, Hagiwara and Nabetani	Texture changes in cooked Japanese radish (*Raphanus sativus*)
	2017	Watanabe et al.	Establishment of optimal spinach scalding conditions

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Application in the food industry	Year	Authors	Description
Detection of microorganisms	2013	Villa-García et al.	Growth monitoring of *Lactobacillus acidophilus*
	2013	Dong, Zhao, Xu, Ma and Ai	Establishment of *Salmonella* in milk
	2014	Paredes, Becerro and Arana	Establishment of biofilms of *Staphylococcus epidermidis*
	2015	Liu, Settu, Tsai and Chen	Development of a sensor to establish bacterial contamination in dairy farms and processing plants
	2016	Wang, Palmer and Flint	A quick method to determine *Yersinia enterocolitica* biofilms
	2018	Tubia, Paredes, Pérez-Lorenzo and Arana	Method for *in situ* and real-time detection of wine yeast rot

Source: Elaborated by the authors

Identification of fraud

An adulterated food is one that has a complete or partial suppression of high value constituents; total to partial replacement with food components of lower quality or economic value, masking of defects and inferior quality or addition of substances not declared on the label to increase the weight or volume of the product (Hargin, 1996). This problem mainly affects consumers (loss of quality and dissatisfaction), but also the industry, as unfair competition is generated. For this reason, techniques are required to address the problem accurately and effectively (Hernández-Chávez et al., 2007).

To avoid unfair competition through false labeling, this method has been used to establish the legitimacy of the floral origin of honey (Scandurra et al., 2013) and adulteration of honeys with sucrose syrup (Das et al., 2017), as well as for the detection of fraudulent sale of fish and frozen-thawed chicken under the name of fresh chicken (Chen et al., 2016; Fernández-Segovia et al., 2012; Fuentes et al., 2013). EIS allows detecting changes in milk caused by mastitis, as well as the adulteration of this with water, hydrogen peroxide, sodium hydroxide and formaldehyde (Bertemes-Filho, Valicheski, Pereira, & Paterno, 2010; During et al., 2016).

In meat products, it has been used as a viable method to discriminate adulterated pig meat. This has been done since, in recent years, meat illegally injected with water has been repeatedly discovered in the Chinese market; this increase in moisture content allows microbes to multiply easily, which could affect human health and cause significant problems for the meat processing industry (Yang et al., 2013).

Detection of contaminants

Food can be a vehicle for the transport of toxic substances, which can be formed during processing, preparation, and storage. Foods such as dairy products and tomatoes can be contaminated by the use of pesticides that are used for tick control in cattle and weed control (Farahi et al., 2015); some aldehydes —that in trace quantities may contribute to the fresh aroma at higher concentrations— can be irritating and carcinogenic (Boumya et al., 2017); toxins produced by *Aspergillus flavus* and *Aspergillus parasiticus* have been implicated in the etiology of human hepatocellular carcinoma (Yu et al., 2015), and phthalate esters (DEHP) from the plastics industry are toxic for development and reproduction (Zia et al., 2013), so they represent a serious risk to human health. It is essential to establish a method with high selectivity and sensitivity to establish the levels of these substances in food, to ensure safety when consumed.

The analytical techniques used to measure phthalate concentrations in food products and beverages, such as gas chromatography and mass spectroscopy, require expensive equipment and long test time, which can pose a problem in industrial production. For its part, EIS allows the concentration of phthalates to be established using a novel sensor made of silicon and coated with a thin film of a polymer (Zia et al., 2013).

Furthermore, EIS has been used as a rapid technique capable of detecting the presence of aldehydes from water samples and orange juice, using 2,4-dinitrophenyl hydrazine (DNPH) as a derivatization reagent. The impedance measurements were studied in the frequency range of 100 mHz to 100 kHz. Nyquist diagrams were modeled with an equivalent Randle circuit. Results showed that the diameter of the Nyquist circle decreases with increasing concentration of aldehydes. This decrease is directly related to the concentration of DNPH and the formation of new product formed in the working electrode. Under optimized conditions, the derivatized aldehyde analysis has detection limits in the order of 0.01 μmol/L. Moreover, the analytical results show that under optimized working conditions, the present method can be widely applied to determine aldehydes in samples of drinking water, orange juice and apple vinegar (Boumya et al., 2017).

This method can be applied in the determination of ultra-trace amounts of paraquat (pesticide) in tomato and milk samples. The method proposed by Farahi et al. (2015) was able to detect 7.37 × 10-16 mol/L of paraquat with good sensitivity. It has also been used in the detection of aflatoxins in agricultural products and vegetable oils (Yu et al., 2015).

Establishment of physicochemical properties

Impedance spectra can be useful for establishing physicochemical tests or indices, which are essential for characterizing and classifying foods according to the quality standards requested by the health authorities. According to international regulations, the quality of olive oil is mainly defined by the acidity index and the peroxide index, two measurements that are carried out in a laboratory environment by manual titration. However, this type of method cannot be used in oil production sites. Therefore, Grossi et al. (2014) presented a new technique to measure the acidity of olive oil through EIS, allowing a quick and economical analysis with immediate results.

The most important parameter that affects the quality of tea leaves is moisture because it affects the physical and chemical aspects related to stability during harvesting, processing, storage, and transportation. Sharma, Bansod, and Thakur (2017) developed a moisture prediction model applying EIS. A correlation was made between moisture and five electrical properties; finally, higher accuracy was observed using a single electrical parameter compared to the humidity measurement. Therefore, the model that was developed may be applicable for the evolution of a better technology to measure valid and precise moisture content in tea leaves.

Wine is a beverage produced by the fermentation of grapes, whose quality depends on the grape variety, as well as its origin and processing. The EIS has been used to characterize different wine varieties, comparing the results with the standard chemical analysis. The results obtained by Lopes, Machado, and Ramalho (2017) show that the technique has a high potential in the wine industry, both to replace as well as to complement the traditional chemical method.

Additionally, it has been used to characterize ultra-pasteurized milk (whole, skim, semi-skimmed, fortified, and organic), correlating electrical measurements with chemical measurements such as calcium, sugar, fat, dry matter, and protein content, among others. The results revealed that impedance leads to assertive milk characterization (Lopes et al., 2018).

Several studies have been reported as a useful base for future research on the prediction of the content of total suspended solids in fruit juices and the detection of adulteration (Żywica & Banach, 2015), as well as for the non-destructive determination of the acidity of citrus fruits (Juansah et al., 2012). Nonetheless, it is also a useful technique to assess the integrity of cell tissues during storage and discriminate apple varieties (Watanabe et al., 2018), as well as to evaluate changes in the physiological parameters of kiwi during storage (Jishu & Du Guangyuan, 2012).

The impedance spectroscopy technique has the potential to become an effective method for the detection of artificial additives since it allows the content to be described in a relatively simple way when the compounds of interest are present in small quantities in chemically complex materials such as food (Nakonieczna et al., 2016).

Determination of maturity

The set of processes that occur from the growth to the development stage of the fruit known as maturity is crucial for producers since it reflects the maximum quality point (Watada, Herner, Kader, Romani, & Staby, 1984). Further, color is the most important external feature in establishing the maturation point and post-harvest life. Other parameters such as dry weight, soluble solids, titratable acidity, pH and hardness are also involved in maturation (Torres, Montes, Pérez, & Andrade, 2013).

The physicochemical properties of fruits are measured with equipment, specific processes, and trained personnel, which implies high analysis costs. However, it is possible to relate them to properties that are easy to measure and do not involve destructive analysis, such as color (Torres et al., 2013). Color can be measured simply with colorimeters in the CIE L*A*B* Color Space, but it has the disadvantage that the surface to be measured must be uniform and small, which makes the measurements not very representative in heterogeneous materials, such as most fruits (León, Domingo, Pedreschi, & León, 2006).

From the marketing point of view, the trader is interested in freshness and durability, while the processing industry must consider the suitability for processing and conservation. The consumer is interested in acquiring a product with good organoleptic and nutritional characteristics, and his/her purchase decision is based on the appearance that is evaluated at the first visual contact, followed by its texture and flavor (Mitcham, Cantwell, & Kader, 1996).

The EIS has a great potential to be used in the characterization of fruits and vegetables in a non-destructive way *in vivo* and at the harvest and storage site (Rehman, Izneid, Basem, Abdullah, & Arshad, 2011), allowing to evaluate the quality parameters of agricultural products and integrate them into control processes. In this way, it can contribute to the reduction of post-harvest losses during the production chain and ensure that a quality product reaches the consumer.

The EIS has been used to know if there is a relationship between the impedance variables with firmness and the degree of maturity of three strawberry varieties ('*Sweet Charlie*', '*Festival*' and '*Camino real*'). A significant relationship of the color variables with the established maturity criteria and a decrease in destructive strength with the degree of maturity was observed. Furthermore, the riper the strawberry was, the lower the intracellular resistance (increased ion concentration) and the higher the extracellular resistance (reduced free ion concentration) (González-Araiza, 2014).

Juansah et al. (2014) conducted an experiment to correlate the degree of maturity of *Garut* oranges with physicochemical properties such as firmness, total soluble solids, pH and hydrogen ion concentration. The electric model proposed described the internal conditions of citrus fruits without damaging the fruit.

The EIS has been used to study variations in electrical impedance during the ripening of mandarin orange. The results obtained by Chowdhury, Singh, Bera, Ghoshal, and Chakraborty (2017) revealed that the impedance increased, and the weight of the orange decreased with the increase in the ripening state. Therefore, the electrical properties of fruits are considered accepted indicators for the establishment of fruit quality.

Likewise, the EIS was used to identify the degree of ripening of mango, based on the dependence of the variation of the gross resistance with the ripening of the fruits, due to the variation in the liquid content of fruit fibers. The results revealed a strong correlation between mechanical tests and electrical parameters (Figueiredo-Neto et al., 2017).

In banana, the ripening process has been characterized in terms of the impedance variation. The test results showed that the complex impedance, as well as the real and the imaginary parts of the impedance, increased with the maturation process. Statistical analysis showed that the standard deviation of all impedance parameters of different banana samples obtained from the same group is very low compared to the corresponding mean values. Therefore, EIS studies conducted on a limited number of samples may be useful to characterize ripening in banana stacks. This technique could also be useful to analyze its physiological changes, taste and nutrient levels; moreover, it can also be used to help find the optimal maturation state (Chowdhury, Kanti Bera, Ghoshal, & Chakraborty, 2017).

It is necessary to have a reliable method to establish the degree of ripeness of the grapes to decide the appropriate harvest time, and in turn, to obtain good quality wines (Ojeda & Pire, 1997). If the fruits are not harvested at the ideal time, they lose their vitality, which could modify the resulting flavor present in the harvest and affect the quality of the wine.

Caravia et al. (2015) studied the EIS as a method to detect the loss of cellular vitality of Shiraz grapes, whose measurements were made in a frequency range between 100 Hz and 1 or 2 MHz. Fluorescein diacetate measurements were performed to determine the leakage of the intracellular material, as well as total suspended solids. The results indicated that, from the ripening or change in color up to the beginning of cell death, the impedance of the grape follows the accumulation of total suspended solids; then, the impedance decreases proportionally until its death. Finally, the authors concluded that changes in the cellular vitality of the grape could be determined objectively through EIS.

In agricultural products of an export type, it is essential to know the state of optimum maturation, which guarantees the quality of the food to the final consumers. Therefore, it is necessary to standardize the maturity indexes, since in most cases they are performed manually, so they are prone to error (Kuson & Terdwongworakul, 2013).

In the case of mangosteen, the translucency of the pulp is a particularly undesirable characteristic concerning quality. During selection, each fruit has its pericarp partially open to allow visual inspection of the fruit and verify the appearance of translucency; a fruit without visible translucency is closed and pasted with adhesive tape around the cutting line and frozen for export. The EIS allows discriminating normal mangosteen from translucent ones, offering a cheap and minimally destructive solution for inspection in small and medium enterprises (Nakawajana et al., 2016).

The inclusion of immature durian in export markets is a big problem, as it provides unacceptable quality. Besides, the non-destructive techniques they use to determine the degree of maturity are not practical, due to the large size of the fruit and the thickness of the peel. Therefore, indirect measurement with EIS of the dry matter content of the pulp based on the measurement of the stem and bark is a viable method for the evaluation of maturity. The impedance parameters could be used to classify and separate the immature fruits from the ripe ones with accuracy of not less than 83.3 % (Kuson & Terdwongworakul, 2013).

Evaluation of the meat product quality

The use of EIS to monitor and evaluate meat has been widely explored. Applications include monitoring the freshness of fresh meat and processed products during storage. Meat and fish are highly perishable foods due to their water content and abundant nutrients available on their surfaces, which makes them susceptible to deterioration by microbial development. Unpleasant flavors, discoloration and other physicochemical changes that affect consumer acceptance are generated during the storage of meat products (Gram & Dalgaard, 2002). In fish, freshness is mainly affected by the activity of endogenous autolytic enzymes and microorganisms, and during storage, numerous bacterial pathogens and toxins appear (Parlapani, Verdos, Haroutounian, & Boziaris, 2015). Therefore, the risk of consuming this type of food is higher, generating a strong demand from manufacturers to evaluate the quality of each product online, by monitoring the processing to obtain reliable and definitive quality information for customers and other processing manufacturers.

The state of maturation of the meat influences the structure and conductivity of its fibers, which leads to observable changes in its impedance. The relationship between the post-mortem state and the change in meat impedance has been characterized as a basis for developing methods to assess the freshness of beef, veal and pork (Guermazi et al., 2014; Nguyen & Nguyen, 2015). The EIS has the potential to establish the best destination for meat carcasses and reduce economic losses for industries and customers (Zhao et al., 2017).

Besides, the EIS allows evaluating the freshness of the sea bream (*Sparus aurata*), the sea bass (*Dicentrarchus labrax*) and the carp (*Cyprinus carpio*), both for its composition and storage time, correlating impedance measurements with total volatile basic nitrogen tests (TVB-N), as it possibly reflects the denaturation of proteins that occurs during storage (Pérez-Esteve et al., 2014; Sun et al., 2018; Vidaček et al., 2012). The EIS has the potential to evaluate the shelf life under refrigeration of the European squid, grouping the samples into three distinctive *post rigor mortis* groups (Zavadlav et al., 2016).

In cured meat products, the EIS has been used for the online monitoring of smoked salmon, to detect when the product has reached the optimum moisture, salt and water activity (Aw) content (Rizo et al., 2013), and in dry and cured hams, to discriminate between altered and unaltered products. Additionally, it has a tendency to classify the degree of deterioration (De Jesús et al., 2014). Further, it has also been used to measure the concentration of salt in pork during various curing processes, since in practice, conventional curing processes are performed empirically, and the concentration of salt inside the piece of meat is generally measured only at the end of curing and with destructive chemical methods; therefore, the desired salt percentage cannot be controlled according to customer preferences (Kaltenecker et al., 2013).

Characterization of thermal processes

Thermal processing is one of the most important unit operations in the food industry due to its numerous processing and preservation applications (Rattan & Ramaswamy, 2014). Simultaneous phenomena of mass and energy transfer occur during cooking, due to the movement of water in the form of steam from the food to the cooking medium and the movement of the medium to the food. These phenomena generate an exchange of chemical substances that produce physical and chemical changes in the food, influenced by their nature, size, shape, and intensity of the heat source (García-Segovia, Andrés-Bello, & Martínez-Monzó, 2008).

The state of the cell wall and the cell membrane structure is related to the physical properties of plants, so that changes in food texture that might occur during processing, can be evaluated and predicted (Ando et al., 2017).

This technique has been used to know the microstructural and texture changes in potatoes cooked in water (Fuentes et al., 2014; Imaizumi et al., 2015), in the establishment of optimal spinach scalding conditions (Watanabe et al., 2017), as well as for the determination of firmness during the cooking of Japanese radish (Ando et al., 2017); moreover, also to know the physiological state of dehydrated potato tissue (Ando et al., 2014) and the texture of dehydrated, frozen and rehydrated carrots (Ando et al., 2016), as well as the changes generated in the banana stem tissue (Bera et al., 2016).

Changes in the impedance in thermal processes depend largely on the presence of water in the food. In the case of water heating, destruction of the cell membranes that increase the number of free electrolytes in the extracellular space of the tissue is generated, increasing, in turn, the conductivity, and producing a decrease in impedance (Fuentes et al., 2014). On the other hand, in late drying processes (after cell membrane disruption), there is a decrease in conductivity associated with moisture loss and, therefore, with an increase in impedance (Ando et al., 2014; Kertész et al., 2015; Wu, Ogawa, & Tagawa, 2008).

Detection of microorganisms

Traditional techniques, such as spectrophotometric methods, plate count and dye reduction, are efficient to detect and establish the viability of microorganisms but require prolonged incubation times (24-48 h), as well as the preparation of sterilized material (Grossi et al., 2008). The EIS is being used in the food industry for rapid detection, identification, quantification and monitoring of bacterial contents (Arora, Sindhu, Dilbaghi, & Chaudhury, 2011). It also allows bacterial counts of harmless microorganisms, as well as dangerous pathogens that can severely endanger humans. The impedance is obtained by measuring the real and complex component that emerges between a pair of electrodes immersed in a cell that contains the culture medium (Felice, Madrid, Olivera, Rotger, & Valentinuzzi, 1999).

The EIS was used to monitor the growth of *Lactobacillus acidophilus*. The results obtained show that microbial growth was recorded in short times compared to the plate count that takes six more hours. The resistance of the medium was the most efficient for the estimation of the growth parameters compared to the value of the capacitance of the system. Therefore, the EIS was able to detect the early growth stage of the microorganism in a pure culture medium, compared to the plate counting technique (Villa-García et al., 2013).

Bacterial infection remains as one of the leading causes of death in developing countries and accounts for approximately 40 % of the deaths. For example, strain O157:H7 of *Escherichia coli* is considered one of the most dangerous pathogens transmitted by foods. *Escherichia coli* infections are usually caused by eating food or drinking contaminated water or coming into direct contact with someone who is sick or with an animal that carries the bacteria. The EIS allows detecting *E. coli* in milk at initial concentrations as low as 7 cells/mL; therefore, it could be an appropriate method to detect bacterial contamination in dairy farms and processing plants (Liu, Settu, Tsai, & Chen, 2015).

Salmonella is also one of the most common bacteria responsible for foodborne illnesses. It is transferred through the consumption of eggs, meat or milk, and causes a wide variety of diseases such as salmonellosis, typhoid fever, food poisoning, gastroenteritis and septicemia (Joshi et al., 2009). EIS has been successfully implemented to detect *Salmonella typhimurium* in milk with satisfactory results, in a linear range of 1.0 × 103 to 1.0 × 107 CFU/mL (Dong et al., 2013).

Biofilms in the food industry cause problems such as corrosion, unpleasant odors, plugging of pipes, equipment failures and deficiency in heat transmission, which generates high cleaning and maintenance costs (Porras, Castillo, & Sánchez, 2010). The EIS is a convenient method for the detection of *Yersinia enterocolitica* biofilms formed on stainless steel surfaces that saves time and effort since compared to plate counting it does not imply dislodging biofilms from surfaces (Wang, Palmer, & Flint, 2016). The ability to detect and control the presence and growth of Staphylococcus epidermidis biofilms has also been demonstrated (Paredes, Becerro, & Arana, 2014).

Brettanomyces bruxellensis is considered one of the most important rotting yeasts in the production of alcoholic beverages, which can cause changes in the characteristics of the product, ruining its aroma and flavor; therefore, it decreases the quality of the final products and generates significant economic losses. The detection by EIS is based on changes in the electrical characteristics of the medium caused by the presence of microorganisms, either because they adhere to the sensor surface forming biofilms (yeasts adhered to the surface embedded in an extracellular polymer matrix of its own production) or because by the metabolic activity, the chemical composition of the medium changes. This technique could be applied for the early detection of rotting yeasts in the wine and cider industries (Tubia et al., 2018).

Conclusions

The review showed that the EIS has a broad scope of action in the food industry. It allows characterizing raw materials that will be stored without any additional process or processed to give them an added value, knowing the changes that are generated in the tissues to be subjected to different thermal treatments, as well as detecting toxic substances or elements that should not be part of the food; furthermore, it is also useful to discover adulteration in different food matrices and to detect the presence of pathogenic and beneficial microorganisms.

The EIS has aroused great interest due to its great potential as a quick, economical, non-invasive and simple method of analysis. However, some factors such as the effect of electrode polarization, measurement temperature, structure, materials, and distance between electrodes can affect electrical responses. Therefore, it is necessary to apply measurement protocols and equipment calibration routines.

Finally, studies should be carried out to ensure that measurements can be extrapolated to the food industry since in real conditions it is difficult to control all the variables of the production process, which could undoubtedly affect the validity of the model used.

Disclaimer

The authors agree with the publication of this article and declare that there are no conflicts of interest that affect the results.

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