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INNOVATIVE PHOTONIC SYSTEM IN RADIOFREQUENCY AND MICROWAVE RANGE TO DETERMINE CHICKEN MEAT QUALITY

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ABSTRACT

Nowadays, one of the most important challenges of poultry industry is to determine individually the meat quality class (pale, soft and exudative, normal and dark, firm and dry meats) by non-invasive, accurate and fast technique. For this purpose, dielectric spectra in radiofrequency and microwave ranges were studied. In radiofrequency range, the permittivity was measured by a non-destructive sensor conformed by three points with blunt-ended electrodes connected to an *Agilent* 4294A impedance analyser, and in microwave range an *Agilent* 85070E open-ended coaxial probe connected to an *Agilent* E8362B Vector Network Analyser were used. This work demonstrates the direct relation between the pH evolution and the dielectric constant at α-dispersion, and also, that the main structural proteins degradation has direct relation with the dielectric constant at β-dispersion, being possible to segregate meat depending on the level of protein degradation. Finally, this paper ends with a classification model for quality poultry meat based on a photonic analysis at radiofrequency range by using the Traffano-Schiffo model.

Keywords: poultry meat, quality, permittivity, radiofrequency, microwave, dispersion.

1. Introduction

Meat sector is one of the most important in Europe (Traffano-Schiffo et al., 2014), being poultry meat which shows one of the highest consumption increases all over the world (Barbin et al., 2016) since it is considered one of the healthiest meats of the diet (Barbin et al., 2015). Normal poultry meat is considered when the pH range is between 5.8 to 6.0 at 12 hours post-mortem time (pmt), due to the right post mortem pathways (Zhang, & Barbut, 2005). However, one of the most frequent defects of poultry meat is the Pale, Soft and Exudative (PSE) and Dark, Firm and Dry (DFD) meats, which causes quality and stability problems in processed products (Adzitey, & Nurul, 2011; Langer et al., 2010; Swatland, 2008). At practical level, the industry uses discrimination techniques based on pH, Normal (5.8 to 6), PSE (< 5.7) and DFD (> 6.1) at 12 h pmt (Zhang & Barbut, 2005), or colour measurements on the poultry dismembered to characterize its quality, obtaining relatively high mistakes, due to the poultry meat have light colours (Fletcher, 2002).

PSE meat is characterized by a significantly lower pH, higher L* colour value, soft texture and low water retention (Petracci et al., 2015; Barbut et al., 2005). The main cause of these meat defects is an accelerated post-mortem glycolysis rate, causing sarcoplasmic and myofibrillar protein denaturation (Sosnicki et al., 1998). Some reports have linked the PSE meat with two genetic mutations in pigs: Ryanodine receptor or Halothane gene mutation, causing Porcine Stress Syndrome or Malignant Hyperthermia; however, these gene mutations have not been demonstrated in poultry (Barbut et al., 2008). It has been reported that the incidence in PSE chicken meat is higher than 37% (Woelfel et al., 2002; Woelfel et al., 1998), which represents high economic losses.

In contrast, DFD meat is characterized by a dark colour and a short shelf life due to the high pH value (Allen et al., 1997), being susceptible to microbiological contamination. This quality issue is mainly caused by a prolonged chronic stress, such as long transportation periods, which depletes muscle glycogen, and therefore the drop in the pH is limited by the amount of

the glycogen available. Besides the microbiological contamination problems, another important factor is the dark appearance, which affects the colour of processed products and consumer acceptability (Chan et al., 2011).

Despite efforts to develop a rapid and non-invasive detection system of PSE and DFD meats, nowadays this problem remains being one of the major challenges for the food industry. New techniques of surface measurements or with low penetration depth, such as hyperspectral (Jia et al., 2017), NIR (Barbin et al., 2015) and image analysis (Chmiel et al., 2011; Barbin et al., 2016) were developed; nevertheless, these techniques do not solve the detection in whole poultry, needing the dismembering of the animal. Therefore, sensors based on photonics at radiofrequency (RF) and microwave (MW) ranges, with the capacity to quantify some chemical species involved in the meat metabolisms, can provide a huge improvement on the monitoring system.

Spectrophotometry technique allows obtaining the physical property that describes the electric interactions of a photon flux with any biological system, called permittivity. Permittivity defined by Maxwell´s equations (Pozar, 1998) must be explained as a vector, polar or complex number. As a complex number, the real term or dielectric constant (ε') is related to the tissue´s ability to store electric energy and the imaginary term or dielectric loss factor (ε'') is related to the absorption and dissipation of the electric energy (Traffano-Schiffo et al., 2017; Castro-Giráldez et al., 2010a). In RF and MW ranges, it is possible to distinguish different dispersions along the electric spectra, being α, β, and γ the most relevant (Schwan, 1957).

α-dispersion, appears from few Hz to few kHz, is related with the phenomenon of the orientation of charges with mobility, soluble or suspended (electrolytes, charges with low molecular weight and high charge) in liquid phase.

β-dispersion usually occurs in the frequency region from tens of kHz to tens of MHz. This dispersion covers all the mechanisms involved in the orientation of fixed charges in solid surfaces in macromolecules such as proteins. These charges may belong to the chemical structure of the food or can be produced by the surface tension of the structure matrix. At higher frequency range of β-dispersion the main interactions are the surface tension charges; this interaction is called Maxwell-Wagner effect (Wolf et al., 2012).

In the range of microwaves, the interaction of the electric field with biological tissue produces two effects, γ-dispersion and ionic conductivity (Traffano-Schiffo et al., 2015). The first one can be observed at GHz frequencies (Mohiri et al., 2011; Venkatesh & Raghavan, 2004) and it is due to the dipolar molecules orientation and induction, being the water the main dipolar molecule of the muscle tissue. Other important effect in microwave range is ionic conductivity at frequencies from Hz to MHz. The application of an electric field to biological tissue causes vibration of ions increasing the internal energy of the molecules, therefore, the ionic conductivity only affects to the loss factor (Traffano-Schiffo et al., 2018; Talens et al., 2016).

The aim of this research was to analyse the viability of using the dielectric spectroscopy (in RF and MW ranges) to identify PSE, normal and DFD quality classes in chicken breast meat.

2. Materials and methods

The experiments were carried out using boneless and skinless broiler breasts (Pectoralis major) obtained from SADA Group slaughterhouse located in Rafelbunyol, Valencia, Spain. After slaughter, male broilers (from different flock of birds) of 42 d were bled, plucked, tempered in a cooling tunnel at 4 ºC during 3 h and finally dismembered. Samples were transported to the laboratory of Institute of Food Engineering for Development (IuIAD) at the Polytechnic University of Valencia (UPV) using an isothermal bag with ice blocks, in order to

maintain the samples at 2 ºC. Once in the laboratory, samples were maintained at 4 ºC until 12 hours of pmt till its analysis. 46 breasts were used, which were classified according to its pH and L* coordinate at 12 hours of pmt (Zhang & Barbut, 2005).

The pH and colour of the samples were measured in the ventral side of the Pectoralis major. The pH was measured with a punch pH-meter S-20 SevenEasy™ (Mettler Toledo, Barcelona, Spain). The colour was measured by the surface reflectance spectra in a spectrocolorimeter Minolta CM-3600D (Minolta Co. Ltd., Tokio, Japan). The colour coordinates CIE L*a*b* (CIE, 1978) were instrumentally calculated based on D65 illuminant and 10° observer. The water activity was determined by a dew point Hygrometer Decagon (Aqualab®, series 3 TE) with a precision of ± 0.003. The analysis of moisture was accomplished following the ISO 1442 (1997) by drying the samples at 110 ºC at atmospheric pressure during 48 hours until a constant weight was reached.

All measurements were made in triplicate.

2.1. Dielectric Spectroscopy Measurements

Permittivity in radiofrequency and microwave ranges was measured in the in the ventral side of the Pectoralis major.

2.1.1. Radiofrequency range

The system used consists on a non-destructive sensor conformed by three points with blunt-ended electrodes, developed by The Institute of Food Engineering for Development (IuIAD) and The Institute for Molecular Imaging Technologies (I3M), patented by the authors, WO2018011450A1 (Castro-Giraldez et al., 2016), connected to an impedance analyser *Agilent* 4294A (Agilent, Santa Clara, CA, USA) (Fig. 1). The frequency range measured was from 40 Hz to 1 MHz. Calibration of the equipment was performed in open (air) and short-circuit.

The signal obtained by the *Agilent* analyser is the impedance Z, and taking into account that the impedance is a vector and can be expressed as a complex number as $\overline{Z} = R + jX$, where the real part of the impedance is the resistance R and the imaginary part is the reactance X. It is possible to estimate ε', ε'' by using R and X parameters as follows:

$$\varepsilon' = \frac{-X}{(R^2 + X^2)} \frac{1}{2\pi C_0} \quad (1)$$

$$\varepsilon'' = \frac{R}{R^2 + X^2} \frac{1}{2\pi f C_0} \quad (2)$$

$$C_0 = \frac{\varepsilon_0 S}{d} \quad (3)$$

Where f is the frequency (Hz), C_0 is the capacitance in the vacuum (F), S is the surface of the electrodes (m^2), ε_0 is the vacuum permittivity (F/m) and d is the separation between the electrodes with differential tension (V_H-V_L) (m).

2.1.2. Microwave range

The system used consists on an *Agilent* 85070E open-ended coaxial probe (Agilent, Santa Clara, CA, USA) connected to an *Agilent* E8362B Vector Network Analyser (Agilent, Santa Clara, CA, USA). Calibration was performed by using three different types of loads: air, short-circuit and 4 °C Mili®-Q water. Once the calibration was made, 4 ºC Milli®-Q water was measured again to check calibration suitability. All determinations were made from 500 MHz to 20 GHz.

2.2. Statistical analyses

The dielectric constant spectra were fitted by the Traffano-Schiffo and co-workers model (Traffano-Schiffo et al., 2017) by using a nonlinear regression with Statgraphics Centurion XVI Software (Statgraphics, Virgina, U.S.A.).

147 The statistical analyses were performed by one-way ANOVA with Tukey`s post test by using
148 Prism 6 (GraphPad Software Inc., San Diego, CA, USA) in order to determine significant
149 differences between the mean values on the parameters. When the analysis of variance
150 indicates differences among means, a t test was used to differentiate means with 95 % of
151 confidence ($p < 0.05$).
152
153 **3. Results and discussion**
154 Based on pH and L* value 8 breasts were classified as PSE-like, 8 as DFD and 30 as normal
155 (Table 1) (Zhang & Barbut, 2005).
156 During the conversion of muscle to meat, complex biochemical reactions are produced in
157 normal meat and partially in low quality meat. After the animal slaughter, the oxygen content
158 in muscle decreases, causing anoxia and resulting in an anaerobic metabolism, which is
159 necessary to produce ATP in order to maintain the energy production inside the cell (Sams,
160 1999). As a consequence of an anaerobic metabolism, many reactions that change the
161 electrical properties of the biological tissue are produced. The endogenous enzymes and the
162 ATP breakdown are activated (Smulders et al., 2014) and produce lactic acid and adenosine
163 monophosphate, causing the drop of the pH and as a consequence, a modification in water
164 holding capacity and structural proteins denaturalization are produced (Adzitey & Nurul,
165 2011; Woelfel et al., 2002) (reaching the normal breast a pH value of 5.87 ± 0.12 at 12 h
166 pmt). As products of the proteolytic enzymatic actions, lower molecular weight peptides are
167 produced. Under controlled conditions, meat ageing affects positively to meat tenderness,
168 colour and flavour; however, PSE and DFD meats exhibits different behaviours due to the
169 uncontrolled glycolysis, which affect the final quality of the product (Adzitey & Nurul, 2011;
170 Lesiów & Kijowski, 2003).

PSE meat is characterized by lower-than-normal ultimate pH (Van Laack et al., 2000) (values of 5.63 ± 0.06 at 12 h pmt). The higher reduction of the pH, comparing with the rest of the meat qualities, is mainly due to the faster anaerobic degradation of glycogen and higher production of lactate and phosphate. This phenomenon causes the greater degradation and the collapse of the myofibrillar structure and the increase of the liquid phase in sarcoplasmic and intercellular compartments. The sarcoplasm (intracellular liquid phase) is governed by ions with high mobility such as Ca^{2+}, Cl^{-}, K^{+} and Na^{+} and the extracellular liquid phase by Cl^{-} and Na^{+} (Pliquett et al., 2003; Damez et al., 2008; Damez et al., 2007). Damez et al. (2008), also include the effect of the phosphate group (PO_4^-) in the intracellular liquid phase.

In contrast, DFD meats show high ultimate pH values (6.20 ± 0.07), mainly due to the limited availability of glycogen and ATP to obtain lactic acid by the anaerobic pathway and therefore the free PO_4^- groups content is also restricted. As a consequence, the degradation of the muscle structure is also restricted, thus, proteins remain contracted (Adzitey & Nurul, 2011; Feiner, 2006; Warner et al., 1997), retaining ions within its structure.

Consequently, these biochemical and structural transformations change the electrical equilibriums between the protein structure and the chemical compounds with charge flowing in the liquid phase; therefore, the permittivity of the muscle tissue is changing through the conversion from muscle to meat. From this point of view, any modification in the muscle transformation can be detected analysing the permittivity spectrum (Castro-Giráldez et al., 2010b).

As was aforementioned in the introduction along the permittivity spectra in RF and MW ranges, α, β and γ dispersions can be distinguished. However, one of the main problems of working with such a wide range of spectrum (40 Hz to 20 GHz) is to fit and to relate the dispersions with sigmoidal shape. In this context, the Gompertz sigmoidal model (Gompertz,

1825), has gained wide acceptance for applications in biological systems (Li, 2012; El-Gohary et al., 2013) and it could be a useful tool to describe the dispersions.

The Debye model (1929) is a physic model that explains the electric dispersions induced by orientation phenomenon, and allows fitting the permittivity tensor; however, it is difficult to adjust this model in the whole range of orientation phenomenon. In this sense, a sigmoidal math model can be used to fit the dielectric constant spectrum. In order to obtain the relaxation dielectric constant, which describes the three relaxations phenomena involved in RF and MW dispersions (frequency, dielectric constant of relaxation), Traffano-Schiffo model (Traffano-Schiffo et al., 2017) was used (Equation 4):

$$l\varepsilon'(\omega) = l\varepsilon'_{\infty} + \sum_{n=1}^{3} \frac{\Delta l\,\varepsilon'_n}{1+e^{\left(\left(l\omega^2 - l\omega_t^2\right)*\alpha_n\right)}} \quad (4)$$

Where, $l\varepsilon'$ represents the decimal logarithm of the dielectric constant, $l\varepsilon'_{\infty}$ the logarithm of the dielectric constant at high frequencies, $l\omega$ represents the decimal logarithm of the angular velocity (rad/s), $\Delta l\varepsilon'_n$ ($\Delta l\varepsilon'_n = \log \varepsilon'_n - \log \varepsilon'_{n-1}$) the magnitude of the dispersion, $l\omega_t$ the logarithm of the angular velocity at relaxation time for each dispersion n, and α_n are the dispersion slopes.

Figure 2 shows the data of dielectric constant and the adjusted model obtained for normal chicken breast meat), where data are plotted as dots and model as lines, where α, β and γ dispersion can be appreciated. All the parameters of the model can be observed in the figure.

According to the parameters of equation 4 and using equations 5 to 8, the relaxation frequencies and the dielectric constant of each relaxation can be calculated.

$$\varepsilon'_{\alpha} = 10^{\left(l\varepsilon'_{\infty} + \Delta l\varepsilon'_{\gamma} + \Delta l\varepsilon'_{\beta} + \frac{\Delta l\varepsilon'_{\alpha}}{2}\right)} \quad (5)$$

$$\varepsilon'_{\beta} = 10^{\left(l\varepsilon'_{\infty} + \Delta l\varepsilon'_{\gamma} + \frac{\Delta l\varepsilon'_{\beta}}{2}\right)} \quad (6)$$

$$\varepsilon'_{\gamma} = 10^{\left(l\varepsilon'_{\infty} + \frac{\Delta l\varepsilon'_{\gamma}}{2}\right)} \quad (7)$$

$$f_i = 10^{\frac{l\varpi_{ri}}{2\cdot\pi}} \quad (8)$$

Being i for equation 8 each dispersion (α, β and γ).

The dielectric constant and frequency, of each relaxation, obtained from equations 5 to 8, can be appreciated in Table 2, and in Figure 3, an average data and the corresponding fitted Traffano-Schiffo model of the dielectric constant spectra in radiofrequency and microwave ranges in each quality level is shown.

In the permittivity spectrum the three dispersions are affected by different chemical groups; in the alpha dispersion the orientation of chemical species with charge in liquid medium can be observed, in beta dispersion the orientation of structural macromolecules with charges are observed and finally in gamma dispersion, the effect corresponds to the dipolar chemical species (Traffano-Schiffo et al., 2017). In the case of normal chicken breast meat during in postmortem time, the chemical species with charges in liquid medium are the electrolytes and the lactate (Castro-Giráldez et al., 2010b), the macromolecules with fixed charges are the structural proteins (actin, myosin and collagen) (Gabriel et al., 1996) and the main dipolar molecule is the water (Traffano-Schiffo et al., 2015). Table 2 shows the dielectric constant and frequency of normal, PSE and DFD poultry meat, where α and β dispersions show significant differences among the three quality groups.

In case of α-dispersion, the maximum value of dielectric constant corresponds to PSE, where the anaerobic pathway was the highest of the three quality levels, and therefore the production of ion phosphate and lactate were also the highest. However, the lowest value corresponds to DFD, where the anaerobic pathway is limited by the low availability of glycogen and ATP, and thus this quality meat has the lowest quantity of lactate and ion phosphate. In order to understand the effect of lactate during the transformation of muscle to meat, some authors correlate the pH with the lactate generation (England et al., 2014; Zhu et al., 2011). It is possible to relate lactate content with pH values for poultry breast meat from 1 to 24 hours of

pmt (Huang et al., 2014). Therefore, lactate content for each quality meat was obtained using the following equation:

$$x_{lactate} = -29.566\, pH + 233.98 \quad (9)$$

Being $x_{lactate}$ the lactate content expressed in μmol/g.

Figure 4a shows the relationship of lactate content with regard to the dielectric constant in α-dispersion, where the dielectric constant increases when the lactate content in the muscle increases. Thus, PSE quality meat showed the highest dielectric constant values, and in contrast, DFD, the lowest, because PSE samples produces more lactate than the rest of quality levels as was explained before. In addition, Figure 4b shows the relationship of the lactate content of each meat quality with regard to the relaxation frequency in α-dispersion, where big differences among each quality can be appreciated, being PSE meat, which showed the lowest values of relaxation frequency and DFD, the highest. The relaxation frequency depends on the molecular weight of the orientated molecule. It should be taking into account that high content of lactate and ion phosphate (90-95 g/mol) is the main contribution in the signal in α-dispersion, however, other chemical species with ionic force, presented in meat liquid phase, also affect to the orientation phenomena (Ca^{2+}, Cl^{-}, K^{+}, Na^{+}, Mg^{2+} from 23-40 g/mol) (Pliquett et al., 2003). The effect of these molecules is higher as lower is the production of lactate and ion phosphate. Thus, PSE meat shows a relaxation frequency in α-dispersion mainly affected by lactate and ion phosphate. In contrast, DFD meats showed the lowest lactate content being the relaxation frequency also affected by the electrolytes of the liquid phase.

As Table 2 shows, the dielectric constant in β-dispersion for normal quality is 20 ± 4 and the relaxation frequency is 12.8 ± 1.3 MHz; in this dispersion, the main chemical group with fixed charges are the structural proteins. Throughout the maturation pathways, some proteins are fragmented by enzymatic reactions, producing polypeptides or fragments of the original

protein chain (Lametsch et al., 2002; Greaser, 1986). The most important degradation from the size reduction point of view, is the degradation of myosin into a globular myosin head fragment (Lametsch et al., 2002), in this degradation the original size of myosin was 250 kDa, producing a new fragment of 56 kDa (Li et al., 2012). The degradation of actin (43 kDa) derived in new fragments of 32 kDa and 40 kDa (Lametsch et al., 2002). Troponin-T, which is a portion of troponin (70 kDa) (Mudalal et al., 2014; Huff-Lonergan, & Lonergan, 1999), is degraded to others smaller polypeptides identified as fragments of 28, 30, 32 and 34 kDa (Huang et al., 2011). Desmin (53 kDa) in normal breast is also degraded during the first 12 hours of pmt (Li et al., 2012).

As was explained above, the ultimate pH in chicken is negatively correlated with the amount of glycogen stored in the muscle at slaughter. PSE meats present higher amount of glycogen stored than the DFD meats. This kind of quality follows glycolytic pathway to produce energy after the slaughter. It is important to highlight that the glycogen content for DFD meat quality is limited; therefore, this chicken quality takes alternative sources of energy production such as ketogenic amino acid degradation and lipid β-oxidation (Beauclercq et al., 2016).

The dielectric constant in β-dispersion for PSE quality is 35 ± 3 and the relaxation frequency is 7.1 ± 0.3 MHz (Table 1). PSE meat quality follows the same protein metabolic pathways as normal meat but faster, which means that this quality meat presents higher protein degradation than normal (Offer, 1991). Therefore, more fragments of proteins are generated, producing new active sites with orientation capacity (Li et al., 2012). Due to this, PSE quality meat shows higher value of dielectric constant than normal meat. Moreover, the protein degradation produces polypeptides with small molecular weight, and therefore, in an accelerated glycolysis pathway (PSE quality meat) this effect provokes the reduction of the relaxation frequency.

On the other hand, the dielectric constant of DFD meat quality in β-dispersion is 13.5 ± 0.5 and the relaxation frequency is 58 ± 18 MHz. Due to the less availability of glucose and glycogen storage in the muscle of DFD meat quality, the glycolysis pathway is limited. As a consequence, DFD meats take alternative metabolic routes as the ketogenic metabolic degradation which produces amino acids, mainly alanine and glycine to obtain energy (Beauclercq et al., 2016). This metabolism reduces the size of the structural proteins, producing amino acids without interactions in β-dispersion. This protein degradation provokes a reduction of charges with orientation capacity and therefore lower dielectric constant than the rest of meat qualities. Moreover, the remaining structural protein are the unique molecules with capacity to orientate, thus the molecular weight of remaining structural proteins are bigger than the rest of the quality meats, it can be appreciated in the higher relaxation frequency of β-dispersion.

Finally, γ-dispersion is produced by the orientation of dipolar molecules, being the water the main dipolar molecule in muscle tissue. The moisture and the water activity were measured obtaining non-significant differences among the three quality classes, being the average moisture 0.756 ± 0.006 kg_w/kg_T, and the average water activity 0.989 ± 0.003. In the same way, the gamma dispersion that explains the mobility of water did not show significant differences between the three categories (Table 2).

4. Conclusion

This paper presents a classification model for quality poultry meat based on a photonic analysis at radiofrequency and microwave ranges by using the Traffano-Schiffo model. It has been demonstrated the direct relation between the pH evolution and the dielectric constant at α-dispersion, extending this relation to the generation of lactic acid, at 12 h pmt. It has been demonstrated that the main structural proteins degradation has direct relation with the

dielectric constant at β-dispersion, being possible to segregate meat depending on the level of protein degradation.

Finally, it has been possible to join the dielectric constants at α and β-dispersions in order to classify poultry meat in PSE, normal and DFD meat qualities.

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482

Table 1. pH and L* coordinate of Pale, Soft and Exudative (PSE), Normal, and Dark, Firm and Dry (DFD) samples.

	PSE	Normal	DFD
pH	5.63 ± 0.06^{c}	5.87 ± 0.12^{b}	6.20 ± 0.07^{a}
L*	57 ± 1^{a}	51 ± 2^{b}	45 ± 1^{c}

a-c Different letters on the columns indicate significant differences between means for each parameter ($p < 0.05$). Mean ± standard deviation is informed.

Table 2. Relaxation dielectric constant and relaxation frequency of Pale, Soft and Exudative (PSE), Normal, and Dark, Firm and Dry (DFD) chicken breast meat at each dispersion (α, β and γ).

	ε'		
	α ($\cdot 10^6$)	β ($\cdot 10^2$)	γ
PSE	12 ± 1[a]	35 ± 3[a]	36.0 ± 1.4[a]
Normal	7 ± 2[b]	20 ± 4[b]	34.00 ± 0.90[a]
DFD	3.8 ± 0.2[c]	13.5 ± 0.5[c]	33.7 ± 0.5[a]
	f		
	α (kHz)	β (MHz)	γ (GHz)
PSE	1.23 ± 0.06[c]	7.1 ± 0.3[c]	8.5 ± 0.5[a]
Normal	2.5 ± 0.7[b]	12.8 ± 1.3[b]	10.0 ± 0.7[a]
DFD	3.7 ± 0.2[a]	58 ± 18[a]	10.54 ± 0.14[a]

a-c Different letters on the columns indicate significant differences between means for each parameter ($p < 0.05$). Mean ± standard deviation is informed.

HIGHLIGHTS

> Fast and non-destructive method to determine the meat quality has been developed

> Dielectric properties of PSE, normal and DFD chicken meat quality has been obtained

> Relaxation parameters in α, β and γ dispersions were obtained for each quality meat

> Relaxation parameters in α-dispersion are able to predict lactate content of each quality meat

> Main structural proteins degradation was related to the relaxation parameters in β-dispersion

Figure 1

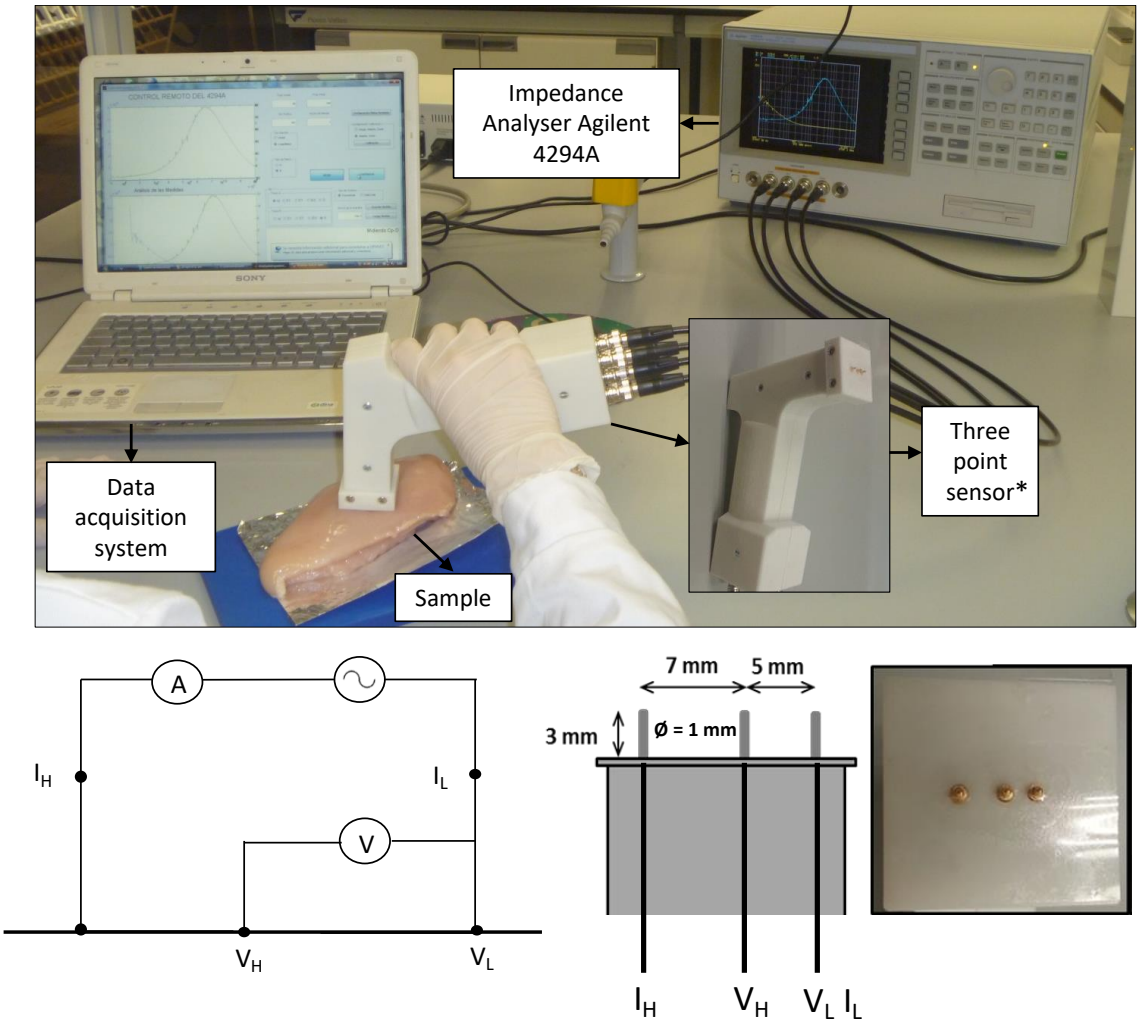

Figure 1.

Figure 2

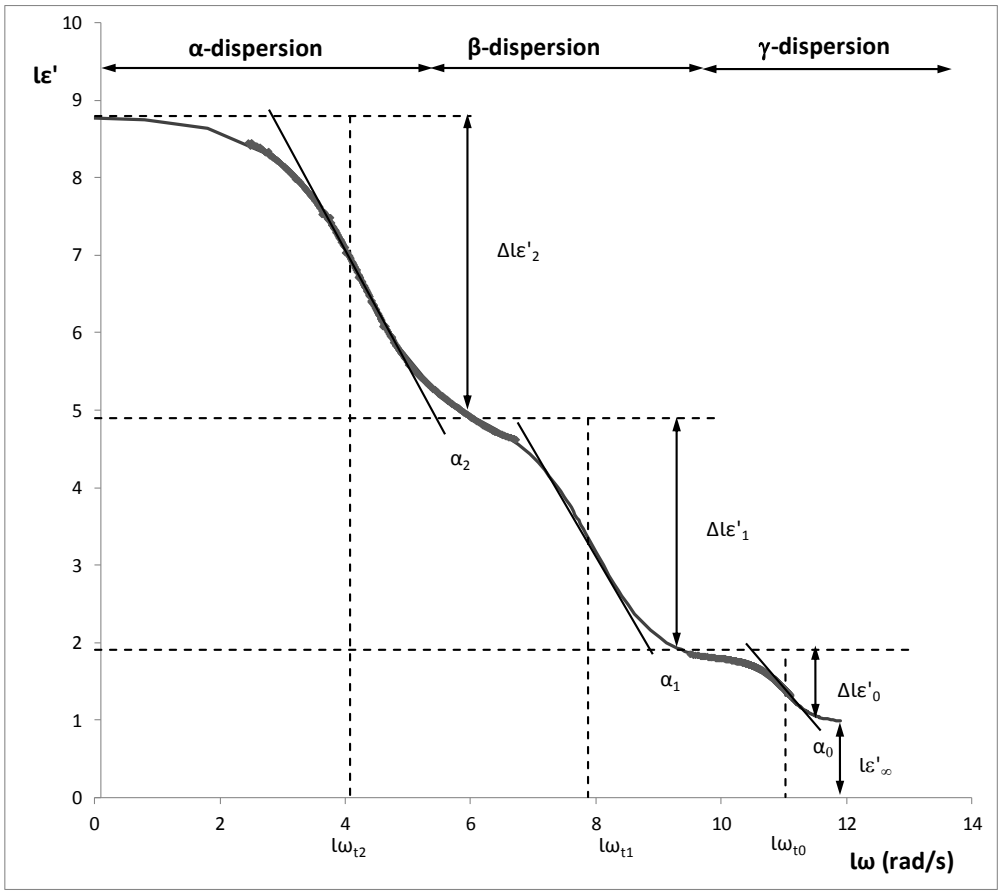

Figure 2.

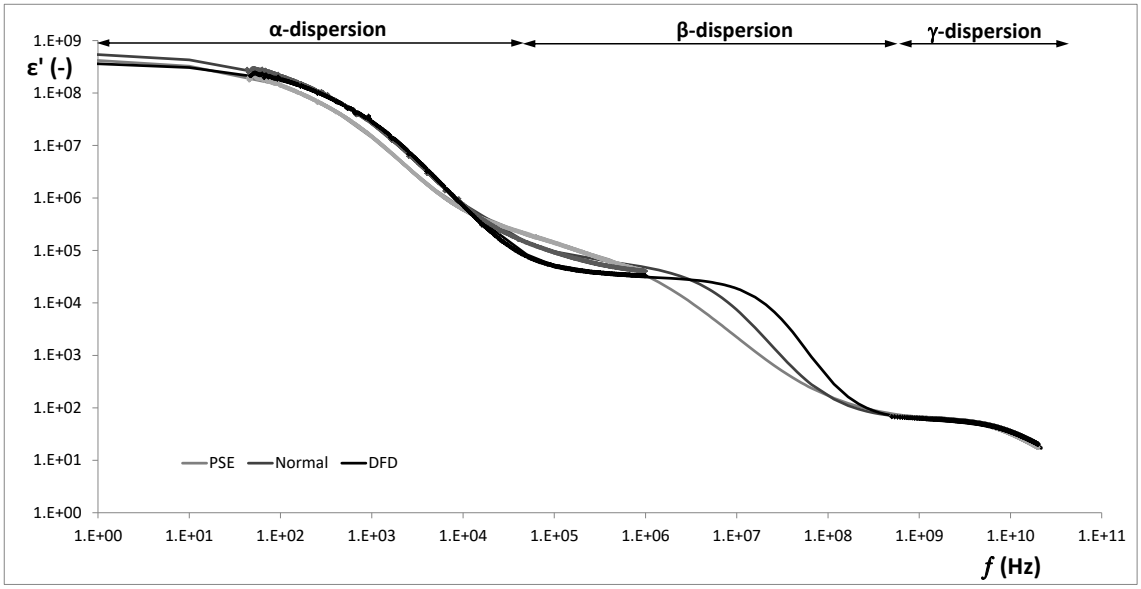
α-dispersion
β-dispersion
γ-dispersion
ε' (-)
1.E+09
1.E+08
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
PSE
Normal
DFD
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08
1.E+09
1.E+10
1.E+11
f (Hz)

Figure 3

Figure 4

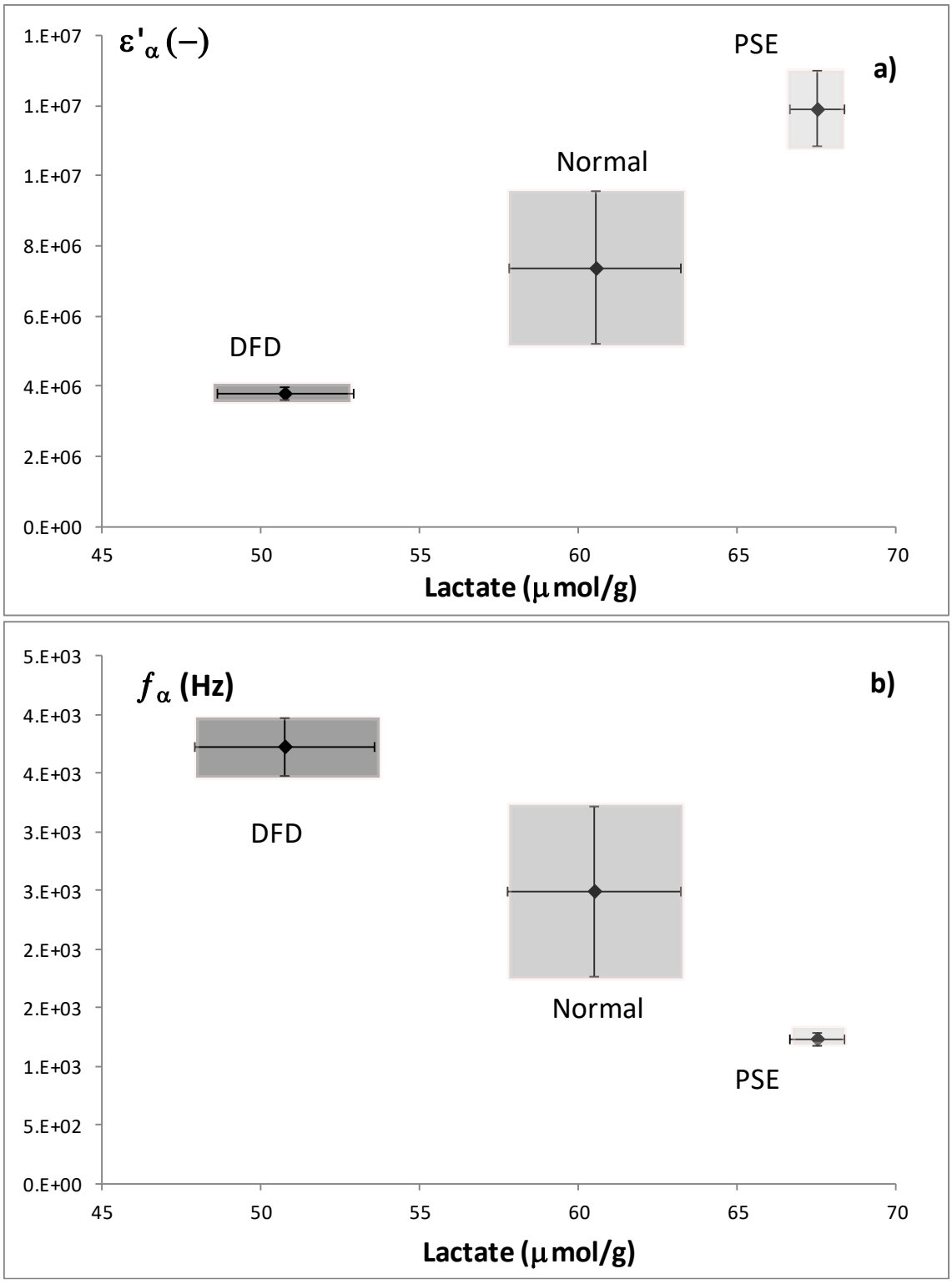

Figure 4.

FIGURE CAPTIONS

Figure 1. Experimental set-up for measuring meat dielectric properties in radiofrequency range. A: ampere meter; V: voltmeter; I_L: low current; I_H: high current; V_L: low voltage and V_H: high voltage. * Three points sensor: World Patent WO2018011450A1 (Castro-Giraldez et al., 2016).

Figure 2. Representation of the dielectric constant of normal chicken breast meat according to the angular velocity. Where (—) corresponds to the values of mathematical model and (♦) the experimental data.

Figure 3. Dielectric constant spectra in radiofrequency and microwave ranges of the (—) PSE, (—) Normal and (—) DFD meat qualities. The lines correspond to Traffano-Schiffo model and the points to the experimental.

Figure 4. Relationship between the lactate content and a) relaxation dielectric constant and b) relaxations frequencies in α-dispersions for each meat quality. Where: (■) corresponds to PSE, (■) normal, and (■) DFD.