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Dielectric spectroscopy for the prediction of pork quality during the post-mortem time

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ABSTRACT

Dielectric spectroscopy was used in this study to predict and classify pork quality during the post-mortem time. Eighty ~1 kg- *longissimus dorsi* muscles were collected and stored at 4 ± 1 °C and pH, instrumental color, and dielectric properties (ε' and ε'') were subsequently determined in the microwave range (0.5–9 GHz) at 3, 4, 5, 6, 7, 8, 9, 10 and 24 h post-mortem (hpm), as well as moisture at 8 hpm and drip weight loss at 24 hpm. Of the 80 pork samples, two types of meat were found. RFN (33) and DFD (47) between males and females. Quality parameters: RFN (pH=5.708–5.714; L*=43.341–43.692; moisture (%) = 68.857–69.604; drip loss = 1.655–1.833) and DFD (pH=6.154–6.177; L*=40.152–41.91; moisture (%) = 69.032–69.9; drip loss = 1.129–1.693). Quality parameter predictions during muscle-to-meat transformation showed R^2 of 0.743 (pH), 0.811 (L*) and 0.603 (C*) for DFD meats with PLSR (full) and R^2 of 0.359 (pH), 0.558 (L*) and 0.284 (C*) for RNF meats with PLSR (optimized) from male pigs. R^2_{cv} of 0.412–0.637 for pH, L* and c* for RFN and DFD meats from female pigs with PLSR (optimized). Dielectric spectroscopy predicts pork quality moderately well, but models that are more robust are needed to improve predictions of internal pork quality.

1. Introduction

In Peru, pork production has increased over the last 20 years to such an extent that it has become one of the three most consumed types of meat after chicken and beef, reaching a per capita consumption of 5.5 kg/year per person due to its nutritional properties such as proteins, vitamins, fats, and minerals, which are essential for the proper functioning of the human body. The principal pork-producing regions are Lima (45 %), Libertad (11 %), Arequipa (7 %), Huánuco (4 %), and Cajamarca (4 %) (MIDAGRI, 2020).

In the Cajamarca region, approximately 6.3 thousand tons of pork are produced annually (MIDAGRI, 2020). Chota is one of the provinces with the highest production and commercialization of pork; however, this product is consumed without a previous physicochemical analysis to determine its physicochemical quality and the type of meat that the population consumes, which leads to the consumption of meat that does not meet quality standards.

The conversion from muscle to meat is a complex process involving a series of physical, chemical, and biochemical transformations responsible for the meat quality (Gispert et al., 2000). Likewise, when blood flow is interrupted, the muscle stops receiving oxygen supply, glucose, fatty acids, amino acids, and glycogen metabolism changes from aerobic to anaerobic, producing the accumulation of lactic acid, ATP depletion, pH decrease, protein denaturation, and temperature decrease, originating new intracellular conditions which are responsible for meat quality (Barbut et al., 2008; Huff-Lonergan, 2010).

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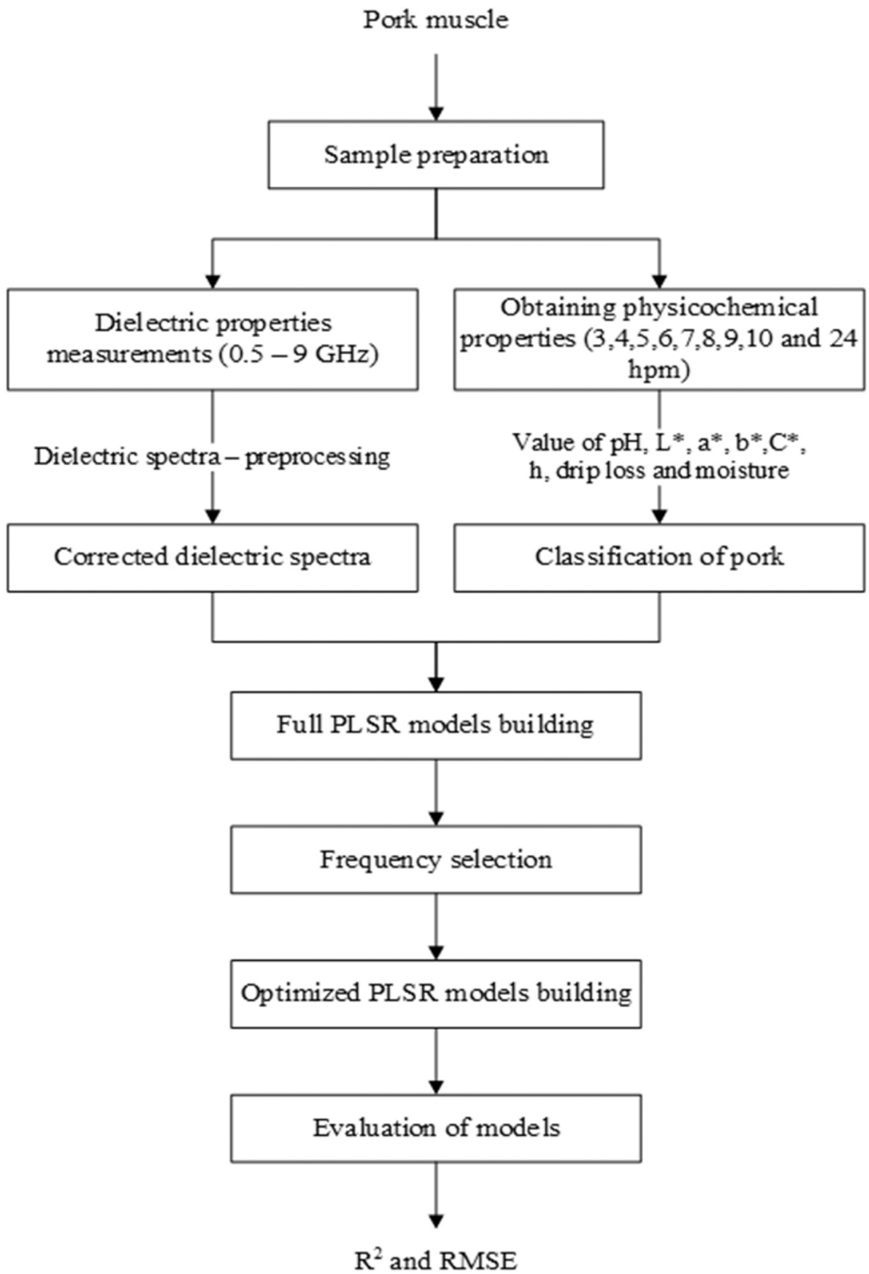


Fig. 1. The experimental diagram.

Meat quality is given by a set of characteristics, such as organoleptic (color, tenderness, flavor, and odor), nutritional and technological (pH, color, water retention capacity, drip loss, and texture), which are determined by traditional methods that often have disadvantages such as being destructive, costly, time-consuming and requiring trained personnel for such analyses (Gispert et al., 2000; Novgorodska and Verbytskyi, 2023).

For this reason, it is necessary to look for new alternative technologies to the traditional ones, such as Near Infrared Spectroscopy (NIR), Hyper Spectral Imaging (HSI), Raman Spectroscopy (RS), Visible Reflectance Spectroscopy (VIS) and Dielectric Spectroscopy (DS). These methods have the advantage of being non-destructive, obtaining results quickly and with greater accuracy; they are environmentally friendly, and, above all, they can be used in production lines as a tool for quality control of different agri-food products (Castro-Giraldez et al., 2010). DS is a technique based on the rotation of molecules in the presence of electromagnetic field stimulation in the frequency ranges of 30 Hz-300 GHz (radiofrequency) and 0.3–300 GHz (microwave) (Blakey and Morales-Partera, 2016). DS is also described by the complex permittivity ($\varepsilon^* = \varepsilon' + \varepsilon''$), where the dielectric constant (ε') and the loss factor are the real and imaginary parts of the complex permittivity, respectively. The dielectric constant is related to the ability of the material to store energy, and the dissipation factor is related to the absorption and dissipation of electromagnetic energy into other types of energy (Castro-Giráldez, Aristoy, et al., 2010; Castro-Giráldez, Fito, et al., 2010).

In the last decade, several efforts have been made in the application of the DS technique, such as detection of quality defects in pork muscle during the post mortem period (Castro-Giráldez, Aristoy, et al., 2010), determination of key biochemical markers of pork quality (Castro-Giráldez et al., 2011), salting processes of pork meat (Castro-Giráldez, Fito, et al., 2010), determination of added water in pork products (Kent et al., 2002), it has been applied in chicken meat to know the relationship between dielectric properties with biochemical

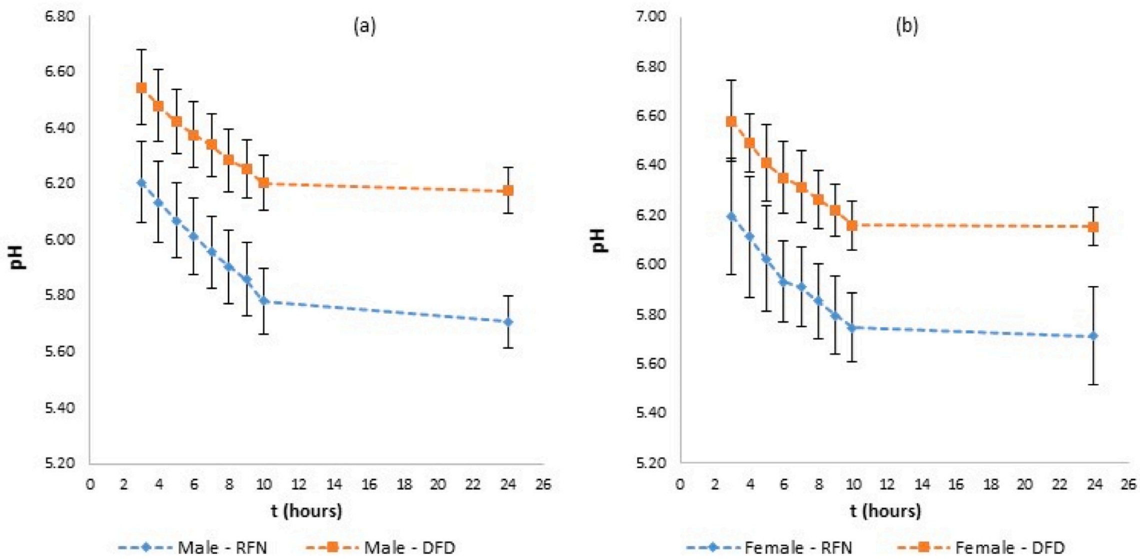


Fig. 2. Evolution of pH of RFN and DFD samples during the muscle-to-meat conversion: (a) for male pigs and (b) for female pigs.

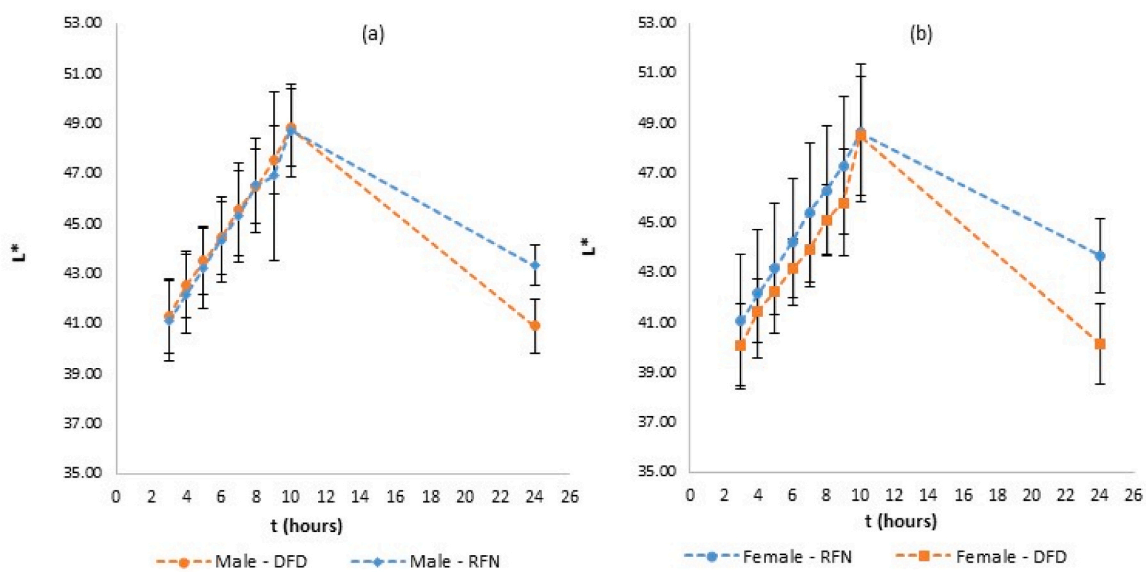


Fig. 3. Evolution of the L* coordinate of RFN and DFD samples during the muscle-to-meat conversion: (a) for male pigs and (b) for female pigs.

metabolism (M. V. Traffano-Schiffo et al., 2021), dielectric characterization of chicken meat during post-mortem period (M. V. Traffano-Schiffo et al., 2021), determination of internal quality of chicken meat (M. V. Traffano-Schiffo, Castro-Giraldez, Colom, et al., 2018), determination of deep pectoral myopathy in chicken meat (M. V. Traffano-Schiffo, Castro-Giraldez, Herrero, et al., 2018), it has also been applied to detect defects in chicken breast (M. Traffano-Schiffo et al., 2017). However, no recent studies have been identified on the application of chemometric techniques in the prediction of internal quality during muscle-to-meat processing. In this context, and in order to broaden the application of dielectric spectroscopy in meat types, the aim of this research is to analyze the feasibility of using microwave dielectric spectroscopy as a tool for grading pork meat according to its quality

2. Materials and methods

The experimental diagram shown in Fig. 1 was used to obtain the data, described in detail in the following paragraphs.

2.1. Sample preparation

Eighty "Longissimus dorsi" muscles were selected from 54 male and 26 female Creole pigs, with an average weight of 85 kg and an age range of 5–12 months. Once the samples were obtained, they were placed in an isothermal box with blocks of ice and transferred to the Research Institute for Productive Improvement laboratory of the National Autonomous University of Chota for subsequent analysis.

Likewise, the samples were classified in relation to parameters of pH, color (L*) and drip loss obtained at 24 h, agreeing with studies realized by Castro-Giraldez et al. (2010); Torres Filho et al. (2018) and Trevisan and Brum, 2020 for obtain meat as PSE (Pale, Soft, and Exudative), RSE (Red, Soft, and Exudative), DFD (Dark, Firm, and Dry), and RFN (Red, Firm, and Non-exudative).

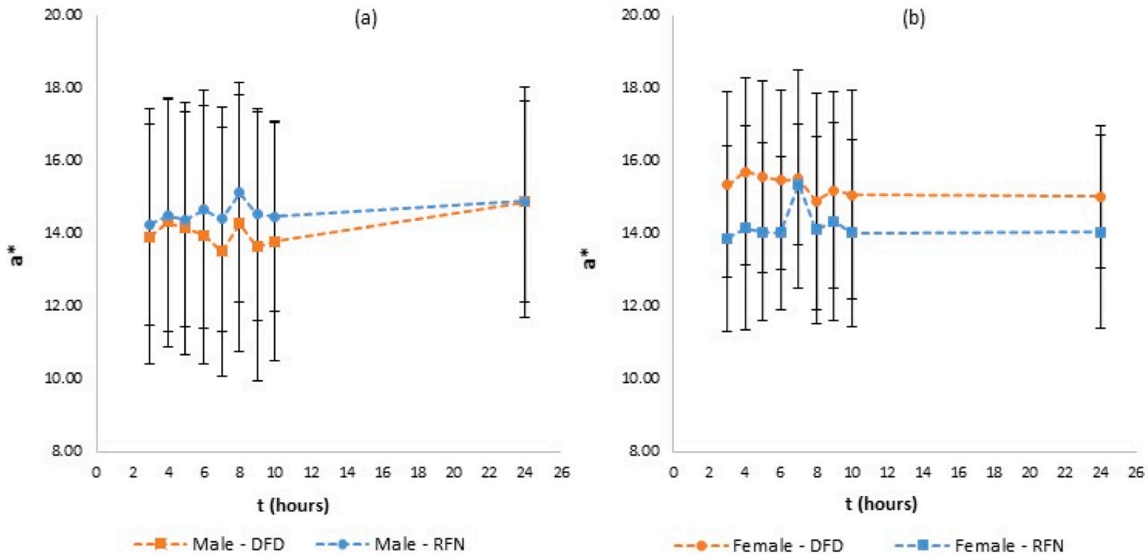


Fig. 4. Evolution of the a* coordinate of RFN and DFD samples during the muscle-to-meat conversion: (a) for male pigs and (b) for female pigs.

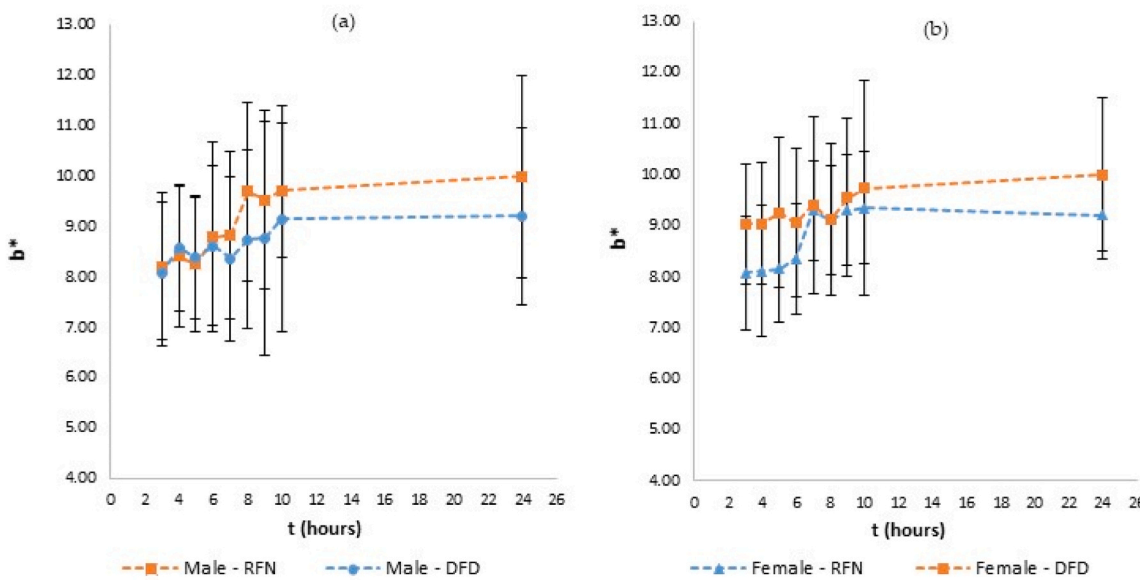


Fig. 5. Evolution of the b* coordinate of RFN and DFD samples during the muscle-to-meat conversion: (a) for male pigs and (b) for female pigs.

2.2. Obtaining physicochemical properties

2.2.1. pH determination

A Thermo Scientific pH meter, model VSTAR50, was used. The pH measurement began with the equipment calibration in three buffer solutions with pH 4, 7 and 10 at a temperature of 4 ± 0.1ºC, with a calibration adjustment of 99.6 %. Subsequently, 10 g of sample were weighed, crushed in a mortar, and homogenized with 90 ml of distilled water. The electrode was placed in the previously prepared solution in triplicate to determine the pH during 3, 4, 5, 6, 7, 8, 9, 10, and 24 h post-mortem (Castro-Giraldez et al., 2010).

2.2.2. Color determination

A 3nh NR200 colorimeter was used. The equipment calibration was carried out by measuring the black and white mosaics. Color measurement was realized with D65 illuminant and 10° observer, placing the colorimeter lens on the sample, obtaining L*, a*, and b* coordinates of the different samples at 4 ± 1 °C, during 3, 4, 5, 6, 7, 8, 9, 10 and 24 h post-mortem, all measure was realized per triplicate and different points of the sample (Castro-Giráldez, Botella, et al., 2010; Castro-Giraldez et al., 2010).

2.2.3. Moisture determination

An AE ADAM PMB 202 Moisture Balance was used. For the measurement, 5 g of sample were taken at 8 h post-mortem, placed on the balance plate, closed, and subjected to a temperature of 140 °C for 30 min (Yang et al., 2009). The moisture percentage obtained automatically by this equipment was then recorded in triplicate.

2.2.4. Drip water loss

At 24 hpm, three pieces of pork of approximately 100 g each were cut and placed in pre-weighed polyethylene bags and immediately stored in a refrigerator (LG, model GT39WPPDC) at 4°C for 72 h. The bags were kept suspended and completely closed to avoid evaporation losses. The bags were kept suspended and completely closed to avoid evaporation losses. Likewise, the samples were prevented from coming

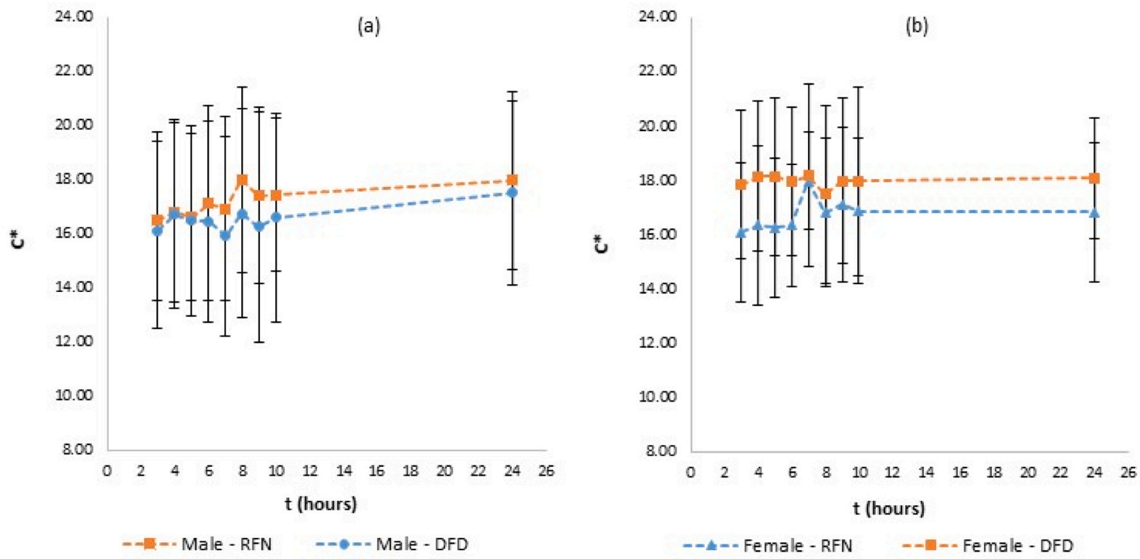


Fig. 6. Evolution of chroma (C*) of RFN and DFD samples during muscle-to-meat conversion: (a) for male pigs and (b) for female pigs.

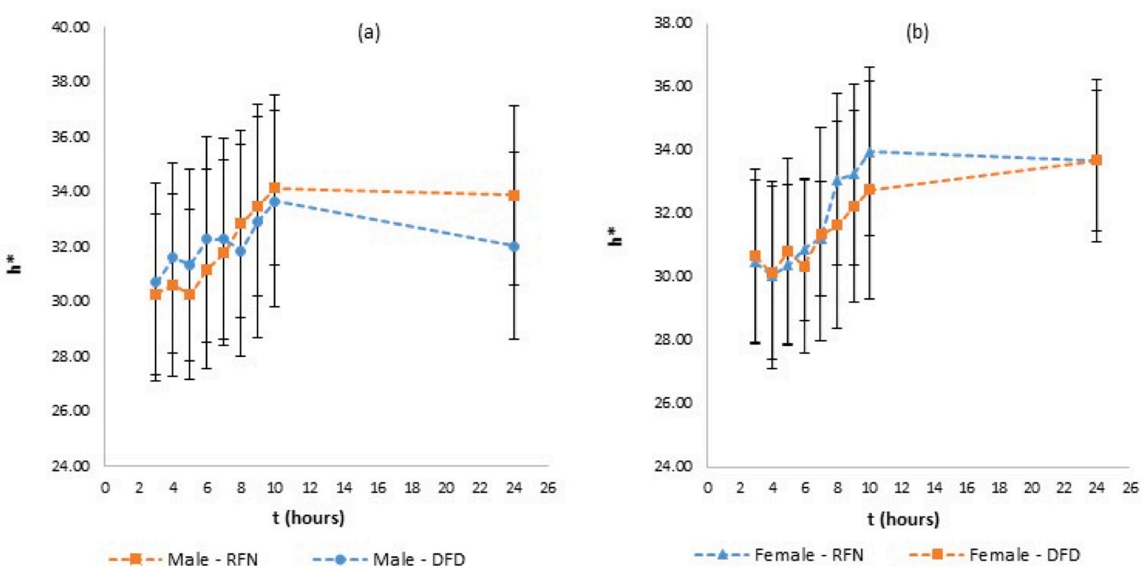


Fig. 7. Pitch evolution (h*) of RFN and DFD samples during muscle-to-meat conversion: (a) for male pigs and (b) for female pigs.

Table 1
Physicochemical parameters obtained at 24 hpm for RFN and DFD samples and tukey's test.

Parameters		$pH_{3\ h}$	$pH_{24\ h}$	$L^*_{24\ h}$	$C^*_{24\ h}$	$h^*_{24\ h}$	Moisture (%)	Drip loss (%)
RFN	Female	6.197 ± 0.235[a]	5.714 ± 0.197[a]	43.692 ± 1.486[a]	16.827 ± 2.557[a]	33.691 ± 4.116[a]	68.857 ± 1.230[a]	1.655 ± 1.004[a]
	Male	6.208 ± 0.145[a]	5.708 ± 0.094[a]	43.341 ± 0.802[a]	17.964 ± 3.269[a]	33.898 ± 3.333[a]	69.604 ± 1.823[a]	1.833 ± 1.060[a]
DFD	Female	6.581 ± 0.162[b]	6.154 ± 0.077[b]	40.152 ± 1.634[b]	18.073 ± 2.236[a]	33.684 ± 3.336[a]	69.900 ± 1.524[a]	1.129 ± 0.417[a]
	Male	6.547 ± 0.135[b]	6.177 ± 0.084[b]	41.910 ± 1.075[b]	17.522 ± 3.410[a]	32.035 ± 3.984[a]	69.032 ± 1.892[a]	1.693 ± 1.037[a]
p_value		0.000*	0.000*	0.000*	0.734*	0.237*	0.287*	0.162*

[*] Analisys of variance of one-away (α=0.05); the superscripts of the same letters of the mean values in each physicochemical parameter of the types of male and female pork, indicate the existence of no significant differences according to the Tukey test (pvalue < 0.05).

into contact with the bag to avoid exudate by pressure. Subsequently, the samples were removed from the refrigerator and weighed separately (meat and bag), and, finally, the percentage of exudate was calculated through Eq. 1 (Castro-Giráldez, Aristoy, et al., 2010; Qiao et al., 2007).

$$Drip\ loss(\%) = \frac{weight\ of\ the\ bag\ with\ exudate - bag\ weight}{initial\ sample\ weight} x \quad 100 \qquad (1)$$

2.3. Dielectric properties measurements

The dielectric properties (ε' and ε'') were acquired in the microwave range, at a frequency from 0.5 GHz to 9 GHz, using an open-ended coaxial probe (N1501A-001) connected to a KEYSIGHT N9915A vector network analyzer. The probe was fixed to a universal stainless steel

Table 2
Meat type classification at 24 hpm for male and female pigs, according to pH, color, and Drip loss (L*).

Meat type	Male pigs	Female pigs	total
PSE	0	0	0
RSE	0	0	0
RFN	23	10	33
DFD	32	15	47
Total	55	25	80

Meat pH and meat colour are effective indicators for the identification of RFN and DFD pork.

support to measure the dielectric properties to avoid possible phase changes due to cable movement. Subsequently, the equipment was calibrated using three types of loads: air, short circuit, and distilled water at 4°C before each experiment (Castro-Giráldez, Aristoy, et al., 2010). Once the equipment was calibrated, the dielectric properties of the distilled water were measured to check the calibration suitability and thus ensure that it was stable. The dielectric properties were measured in quitupled by placing the coaxial probe on the sample surface in line with the fiber during 3, 4, 5, 6, 7, 8, 9, 10, and 24 h post-mortem (Castro-Giráldez et al., 2011).

2.4. Statistics analysis

A one-way analysis of variance was carried out on the physicochemical parameters of the types of pork followed by Tukey's multiple comparisons test with a margin of error of α= 0.05 to determine remarkable distinctions among maturity stages. The data was processed in Statgraphics Centurion XVIII software.

Before the statistical analysis of the modeling of quality prediction during the muscle-to-meat conversion, data matrices were created in *.xlsx format in MS Excel according to the type of meat. Each data matrix consisted of each spectrum of ε' and ε'' with its respective

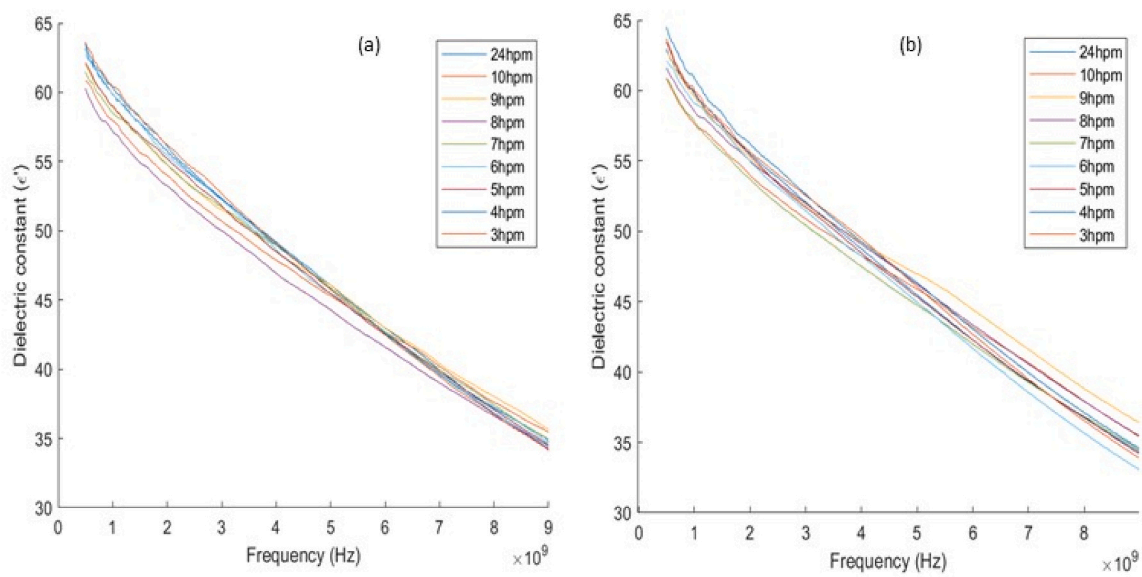


Fig. 8. Evolution of the dielectric constant of RFN samples during 10 h post-mortem: (a) for male pigs and (b) for female pigs.

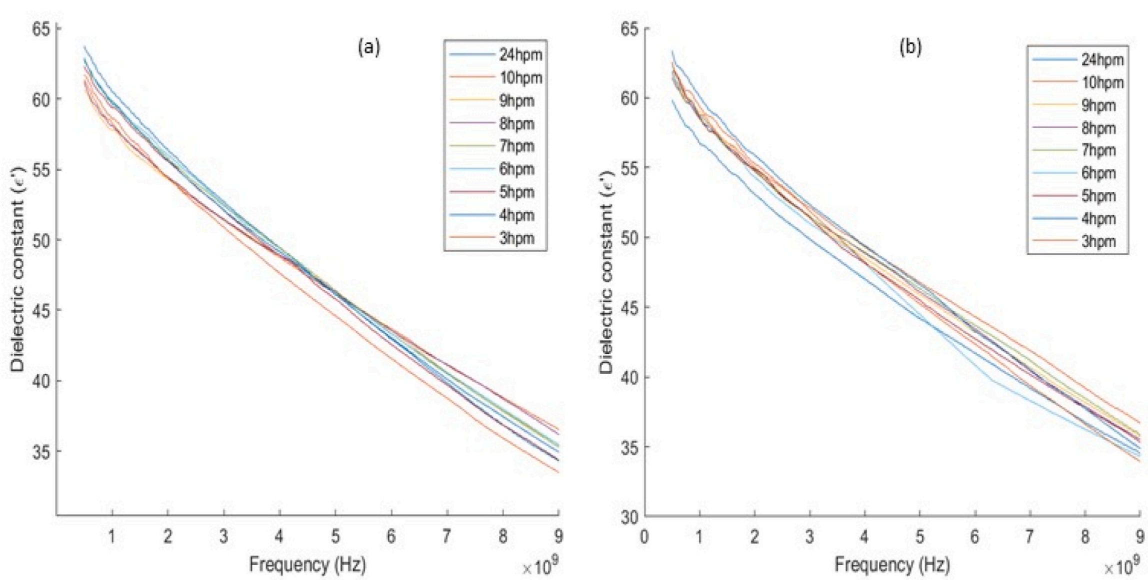


Fig. 9. Evolution of the dielectric constant of DFD samples, from 3 to 10 h post-mortem: (a) for male pigs and (b) for female pigs.

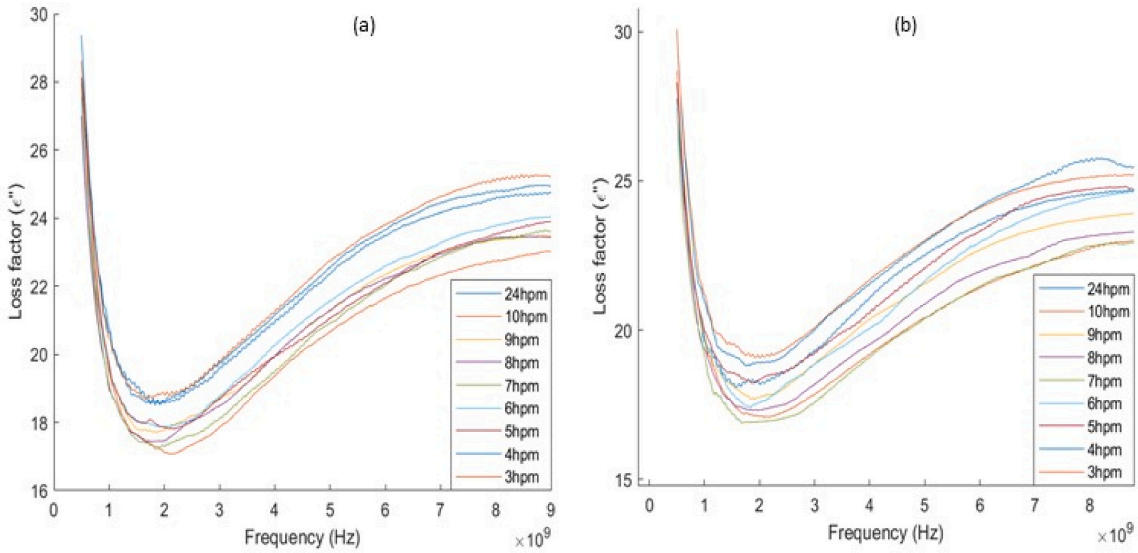


Fig. 10. Evolution of the loss factor of RFN samples, from 3 to 10 h post-mortem: (a) for male pigs and (b) for female pigs.

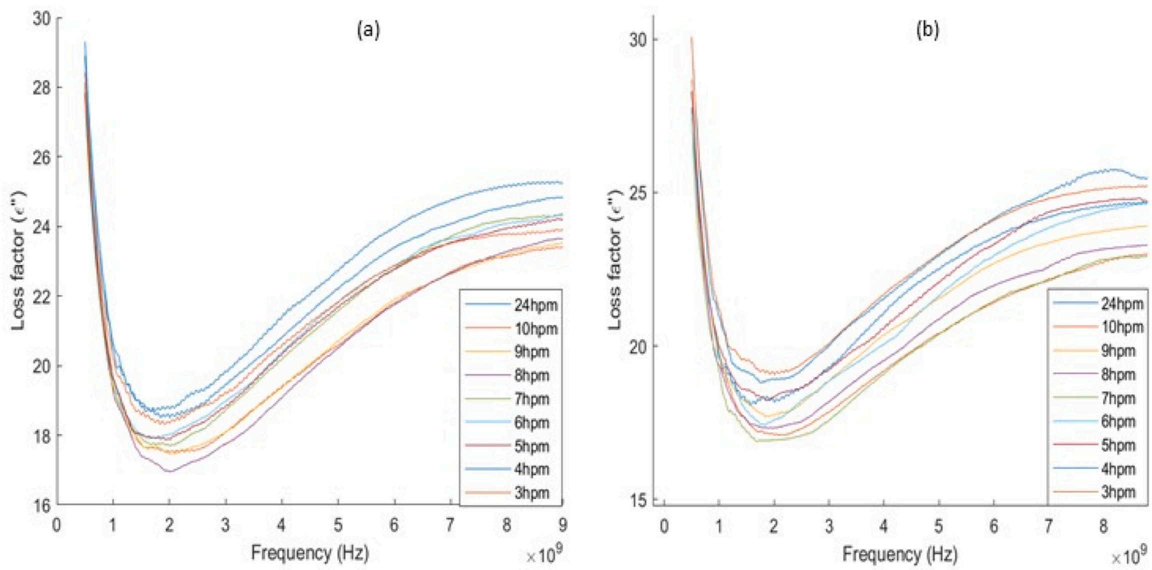


Fig. 11. Evolution of the loss factor of DFD samples, from 3 to 10 h post-mortem: (a) for male pigs and (b) for female pigs.

physicochemical reference value. Then, the algorithm proposed by Chuquizuta et al. (2022) for data processing was modified and carried out in Matlab 2022b software.

2.4.1. Modeling according to PLSR

2.4.1.1. Data pre-processing. A second-order Savitzky-Golay filter, with 9 points, was used for the dielectric spectra of the dielectric constant (ε') and the loss factor (ε'') to eliminate the noise generated by the electronic devices during the data collection. This filter consists of performing the least squares fitting of a small set of consecutive data to a polynomial and taking the center point of the fitted polynomial curve as new smoothed data (Flores et al., 2017; Geesink et al., 2003).

2.4.1.2. Modeling according to PLSR. The partial least squares regression (PLSR) model was used to model the dielectric spectra and physicochemical characteristics. This statistical model, popular in multivariate analysis, aims to obtain a linear model which predicts a response variable, Y, from a large set of X variables, as shown in Eq. 2 (Andersen et al., 2021; Khan et al., 2020).

$$Y = X\beta + E \tag{2}$$

Where X is a size matrix (n x m), n is the intensity value according to the hours post-mortem, and m is the intensity value according to the frequency regarding the dielectric constant (ε'); Y is the reference information (n x1) of the physical-chemical properties, β is the vector of regression coefficients or beta coefficients (m x 1) and E is the error of the vector.

2.4.1.3. Evaluation of models. The prediction models were constructed on the complete dataset, utilising the five-fold (k-fold) cross-validation methodology to prevent over-fitting. To assess the accuracy of both the full and optimised models derived from PLSR, Eqs. 3 and 4 were used to determine the coefficient of determination (R^2_{cv}) and the mean square error (Andersen et al., 2021; Khan et al., 2020; Y. Yang et al., 2021; Zhao et al., 2016).

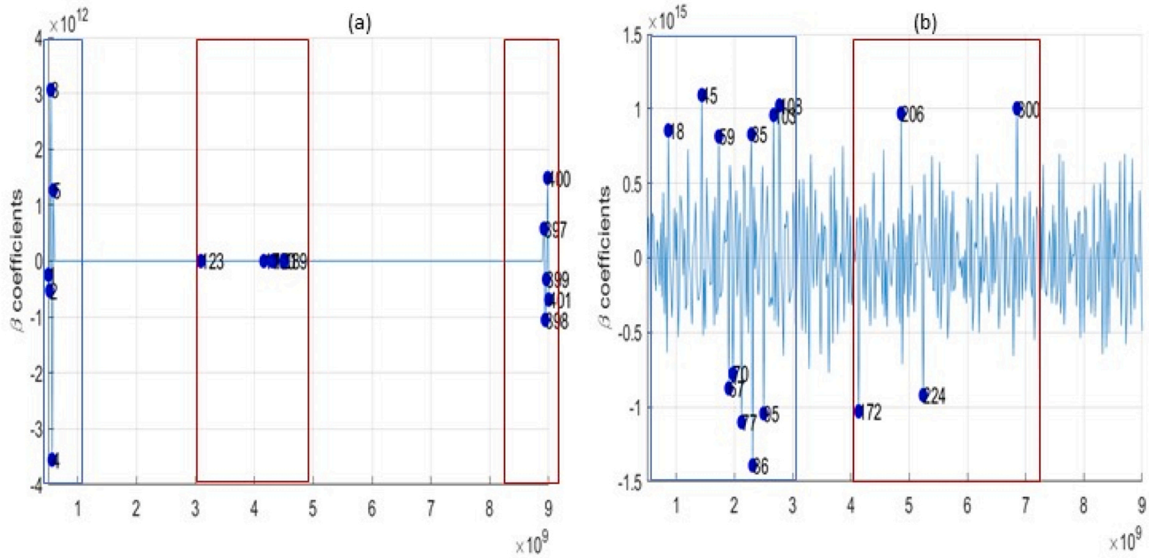


Fig. 12. β Coefficient of pH of RFN samples: (a) for male pigs and (b) for female pigs.

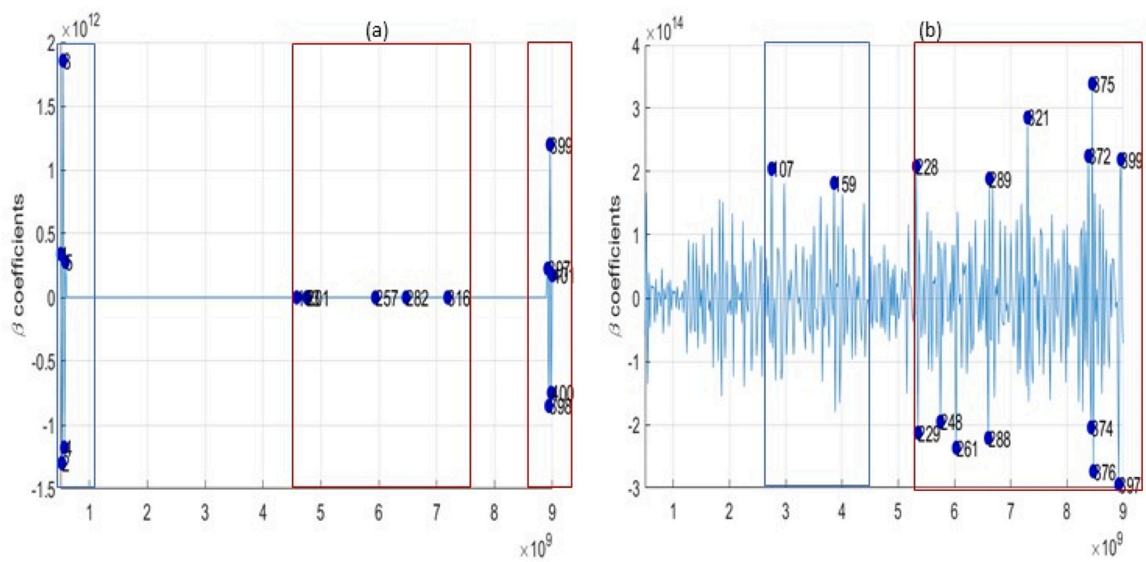


Fig. 13. β Coefficient of pH of DFD samples: (a) for male pigs and (b) for female pigs.

$$R_{cv}^2 = 1 - \frac{\sum_{i=1}^{n} -(Y_i - \widehat{Y}_i)^2}{\sum_{i=1}^{n} -(\widehat{Y}_i - \overline{Y})^2} \quad (3)$$

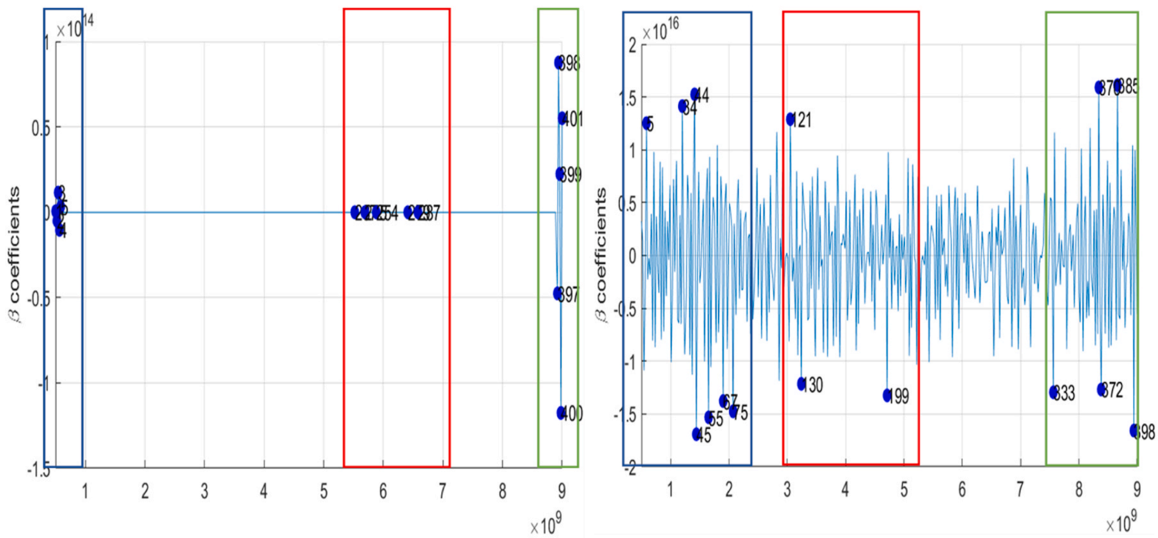
$$RMSE = \left(\frac{\sum_{i=1}^{n} -(Y_i - \widehat{Y}_i)^2}{\text{n}} \right)^{0.5} \quad (4)$$

Where $\widehat{Y}_i$ and Y_i are the predicted and reference values of a sample (i); $\overline{Y}$ is the mean of reference values of all samples.

3. Results and discussions

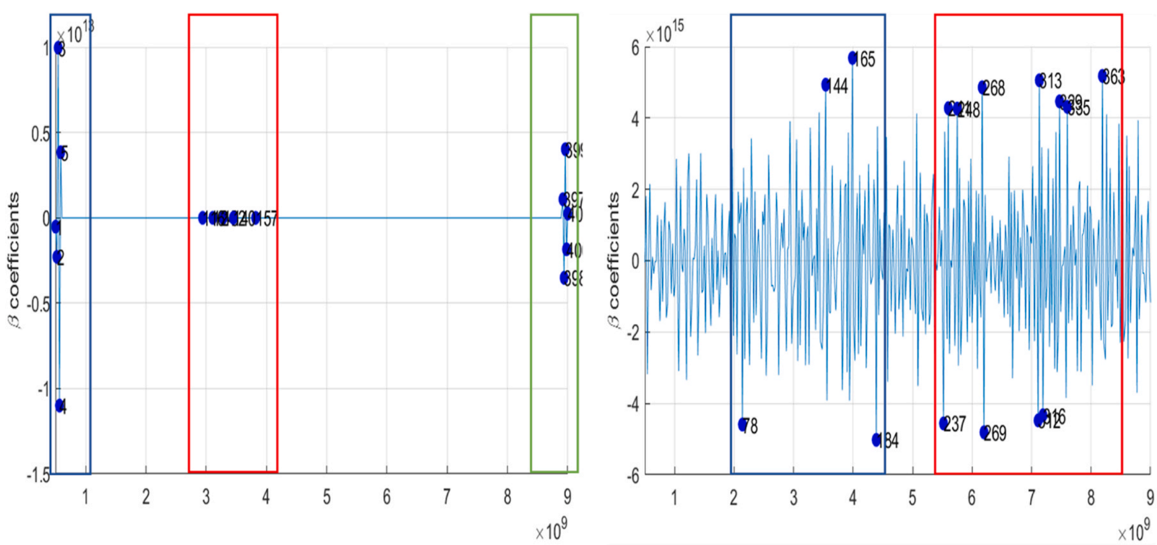
3.1. Physicochemical characteristics of muscle-to-meat conversion

Fig. 2 shows, the pH evolution of the RFN and DFD samples during the muscle-to-meat conversion. The RFN samples show a decrease in pH from 6.21 to 5.71 and from 6.20 to 5.71 in male and female pigs, respectively, until 24 hpm, which is attributed to the degradation of glycogen produced by glycolysis, besides the production of lactate and phosphate, which are responsible for the denaturation of sarcoplasmic and myofibrillar proteins; this particular case is characterized by following a normal (Faucitano et al., 2010; Huff-Lonergan, 2010; M. V. Traffano-Schiffo et al., 2018). Similarly, our results of the RFN muscle-to-meat conversion kinetics, shown in Fig. 1a-b, are similar to those obtained by Chmiel et al. (2014), Liu et al. (2021), and Maganhini et al. (2007), whose pH decrease was from 6.10 to 5.52 for male pigs and to those by Castro-Giraldez et al. (2010), Furtado et al. (2019) and Qiao et al. (2007), whose pH decrease was from 5.99 to 5.5 for male and female pigs, during 24 hpm; however, several authors describe that such difference is due to intrinsic factors such as genetics, breed, age, sex, weight, and muscle type, and extrinsic factors such as production system, climatic conditions, antemortem management, and postmortem management (Čandek-Potokar et al., 2024; Trevisan and Brum, 2020).



(a) (b)

Fig. 14. β Coefficient of color (L*) of RFN samples: (a) for male pigs and (b) for female pigs.

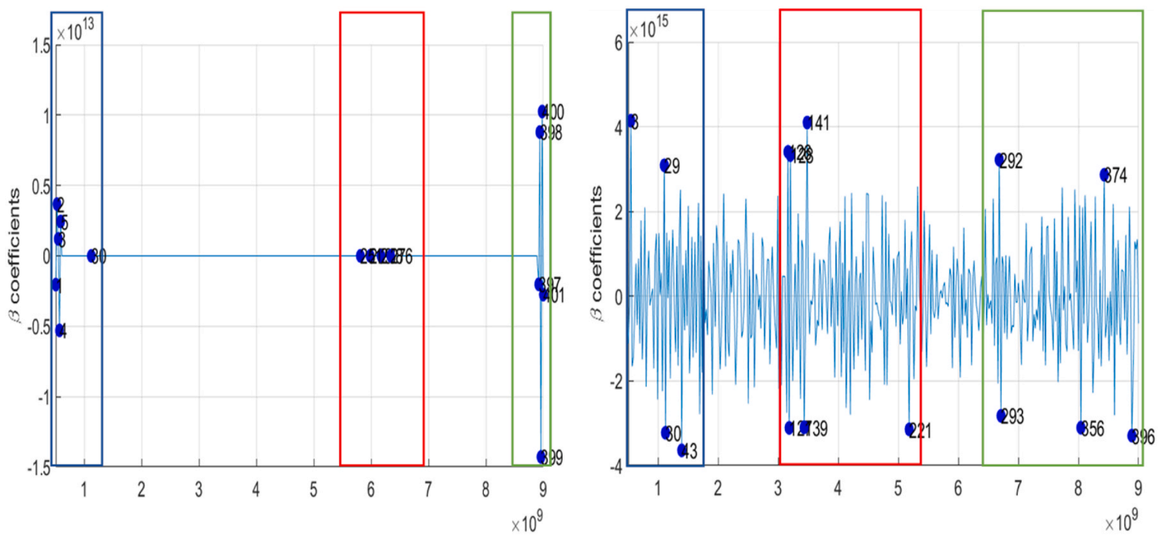


(a) (b)

Fig. 15. β Coefficient of color (L*) of DFD samples: (a) for male pigs and (b) for female pigs.

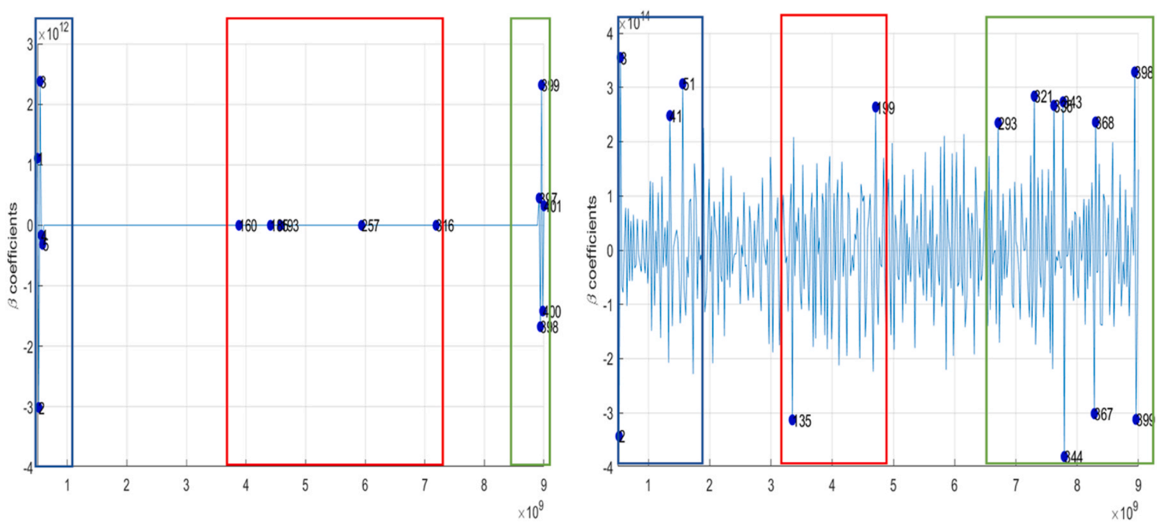
In the case of DFD meats, the samples show a slight decrease in pH from 6.55 to 6.18 and from 6.58 to 6.15 for male and female pigs, respectively, due to the abnormal biochemical process in glycolysis during the muscle-to-meat conversion, caused by prolonged chronic stress in the animals during fasting, loading and unloading, transport, resting, and stunning (Jerez-Timaure et al., 2020; M. V. Traffano-Schiffo, Castro-Giraldez, Colom, et al., 2018). This stress generates glycogen depletion, low lactic acid production, low protein denaturation, and high water retention capacity (Čobanović et al., 2016; Jerez-Timaure et al., 2020; M. V. Traffano-Schiffo, Castro-Giraldez, Colom, et al., 2018). Likewise, our results shown in Fig. 1a- b are similar to those reported by Castro-Giraldez et al. (2010), whose pH decrease was from 6.22 to 5.90 in male and female pigs, and to those by Maganhini et al. (2007), who reported a pH of 5.80 ± 0.16, at 24 hpm.

The color kinetics in the L*, a*, b* and coordinates of male and female pig samples during the muscle-to-meat conversion are shown in Figs. 3–5. In obtaining RFN meats, it has been observed that the L* coordinate (lightness) gradually increases in male pigs from 41.11 to 48.73; and in female pigs, from 41.05 to 48.63 until 10 hpm and decreases to 43.34 in the case of male pig samples and to 43.69 in female pigs, respectively, at 24 hpm, as can be seen in Fig. 3a-b. Likewise, it is evident that our results of L* at 24 hpm are different from those reported by Chmiel et al. (2014), Liu et al. (2021) and Maganhini et al. (2007), who reported L* in the range from 46.85 to 50.34 at 24 hpm in male pigs and those by Castro-Giraldez et al. (2010) who obtained L* = 51.8 ± 1.8 at 24 hpm in male and female pigs. According to Matarneh et al. (2023), Huff-Lonergan (2010),Chmiel et al. (2014), and Gispert et al. (2000), these differences are due to light scattering and absorption during sampling and to the level of myoglobin present in the muscle, which may vary according to breed, age, sex, castration, weight, feeding, type of cut, type of muscle, and temperature. On the other hand, coordinate a* (Red-green) for RFN meats presents a slight increase between 3 and 27 hpm, from 14.25 to 14.89 and 13.88–14.05 for male and female pigs, respectively. In addition, coordinate b* (Yellow-blue) shows similar



(a) (b)

Fig. 16. β Coefficient of color (C*) of RFN samples: (a) for male pigs and (b) for female pigs.



(a) (b)

Fig. 17. β Coefficient of color (L*) of DFD samples: (a) for male pigs and (b) for female pigs.

behavior of a* from 8.21 to 9.99 and 8.07–9.20 for male and female pigs, respectively, as shown in Fig. 3a-b and 4 a-b, results that are different from those acquired by Chmiel et al. (2014) and Maganhini et al. (2007), who obtained values from 1.34 to 2.2 and from 7.93 to 10.8 in the a* and b* coordinates in male pigs, during the 24 hpm.

For DFD samples, coordinate L* increases progressively in male pigs from 41.29 to 48.83 and female pigs from 40.09 to 48.51 during the 10 hpm. It then decreases at 24 hpm to 40.91 and 40.15, respectively. Our results, see Fig. 2a - b, coincide with those obtained by Faucitano et al. (2010) and Maganhini et al. (2007), who obtained L* values from 40.54 to 43.95 for male pigs at 24 hpm, but differ from those reported by Castro-Giraldez et al. (2010), who obtained L* of 49.4 ± 0. 2 at 24 hpm in male and female pigs. Likewise, it can be observed that coordinate a* presents a slight increase in male pigs from 13.92 to 14.86 and a slight decrease in female pigs from 15.35 to 15.02 during the 27 hpm (see Fig. 3a - b). In the same way, coordinate b* shows an increase in male pigs from 8.06 to 9.20 and female pigs from 9.03 to 10.00 during the 27 hpm (see Fig. 4a - b). Our results are different from those acquired by Maganhini et al. (2007), who obtained in male pigs values of 1.17 ± 0.74 and 6.37 ± 0.63 in the a * and b* coordinates at 24 hpm. These differences are mainly due to the increase of myoglobin because of the advanced age and prolonged chronic stress, which generates low oxygen scattering, glycogen reduction, high pH, slow protein denaturation, low light scattering, and bacterial contamination (Castro de Jesús et al., 2021; Huff-Lonergan, 2010; Matarneh et al., 2023; M. V. Traffano-Schiffo et al., 2018).

Regarding chroma (C*) and hue (h*), it has been observed that in RFN samples, chroma increases in a range from 16.48 to 17.96 for male pigs and in a range from 16.09 to 16.83 for female pigs, during the 24 hpm. 83 for female pigs, during the 24 hpm; something similar can be observed in the tone, since it increases from 3 hpm to 24 hpm in a range of 30.28–33.90 for male pigs and in a range of 30.47–33.69 for female pigs, as shown in Fig. 6a-b and 7 a-b. In the DFD samples, both chroma and hue increased from 3 hpm to 24 hpm; in the case of chroma, it

Table 3
Summary of PLSR values obtained for pH, L* and C* according to type of meat.

	PLSR		Male		Female	
			RFN	DFD	RFN	DFD
pH	Full	R^2_{cv}	0.310 ± 0.059	**0.743 ± 0.018**	0.052 ± 0.039	0.0436 ± 0.029
		RMSE	0.033 ± 0.021	0.013 ± 0.009	***	***
	Optimized	R^2_{cv}	**0.359 ± 0.012**	0.399 ± 0.012	**0.418 ± 0.030**	**0.412 ± 0.009**
		RMSE	0.004 ± 0.002	0.002 ± 0.002	0.002 ± 0.002	0.001 ± 0.001
L*	Full	R^2_{cv}	0.403 ± 0.077	**0.811 ± 0.032**	0.061 ± 0.044	0.048 ± 0.040
		RMSE	0.745 ± 0.513	0.450 ± 0.313	***	***
	Optimized	R^2_{cv}	**0.558 ± 0.007**	0.614 ± 0.007	**0.637 ± 0.009**	**0.536 ± 0.011**
		RMSE	0.068 ± 0.035	0.107 ± 0.064	0.043 ± 0.017	0.011 ± 0.007
C*	Full	R^2_{cv}	**0.289 ± 0.037**	**0.603 ± 0.017**	0.043 ± 0.037	0.045 ± 0.033
		RMSE	0.148 ± 0.070	0.019 ± 0.020	***	***
	Optimized	R^2_{cv}	0.284 ± 0.016	0.366 ± 0.008	**0.307 ± 0.028**	**0.285 ± 0.020**
		RMSE	0.016 ± 0.010	0.010 ± 0.006	0.0144 ± 0.005	0.0194 ± 0.020

***High error value; the stability of the prediction models was tested through 30 repetitions.

increased in a range of 16.48–17.96 for males and 16.09–16.83 for females; something similar happened with hue, which increased in a range of 30.28–33.90 and 30.47–43.34 for males and females, respectively. These results were different from those obtained by Barbin et al. (2013) who obtained values in the range of 45.95–8.36 for chroma and values of 10.91–3.50 for tone (he does not specify the type of meat); likewise, our results were different from those reported by Castro-Giraldez et al. (2010) who obtained values of 70.39 for RFN samples and 68.29 for DFD samples, in relation to tone. These differences are attributed to the physicochemical changes produced during the conversion of muscle to meat, which can generate variations in pH content, myoglobin, oxygen dispersion, light diffusion and, above all, protein denaturation (Castro de Jesús et al., 2021; Matarneh et al., 2023; M. V. Traffano-Schiffo, Castro-Giraldez, Herrero, et al., 2018).

Then, the pH and color of pork meat undergo changes during post-mortem processing, with slight differences influenced by the sex of the animal for both RFN and DFD samples.

3.2. Classification of pork according to physicochemical parameters

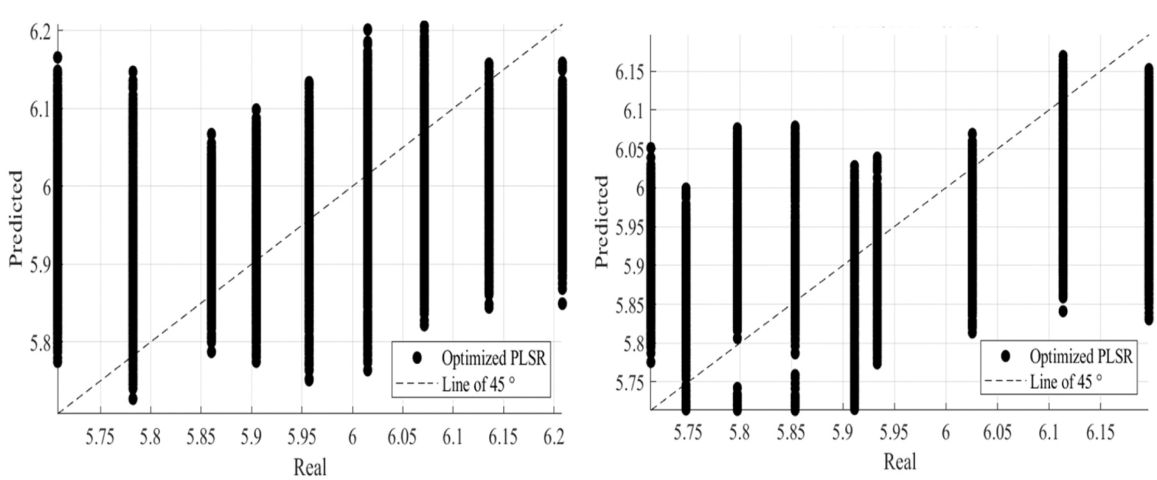
Table 1 shows the physicochemical parameters obtained at 24 hpm and Tukey's test for RFN and DFD samples. For the RFN samples, pH < 6, L* > 40, C* > 15, h* > 30, H% > 60 and drip loss < 2 can be observed for both male and female pigs; for the DFD samples, pH > 6, L* > 40, C* > 15, h* > 30, H% > 60 and drip loss < 2 can be observed. Regarding the results obtained according to the Tukey test, a significant difference ($p > 0.05$) can be observed for the parameters of pH and color in the *L chordate for both RFN and DFD samples; however, for the parameters of chroma, tone, humidity and drip loss, no significant difference was found; it is worth mentioning that the parameters of pH, L* and drip loss are the ones that will allow us to classify the quality of the meat.

Table 2 shows the meat type classification for male and female pigs based on the parameters of pH, color (L*), and drip loss at 24 hpm, resulting in 0 PSE samples, 0 RSE samples, 33 RFN samples, and 47 DFD samples, for a total of 80 samples.

3.3. Dielectric spectra during muscle-to-meat conversion

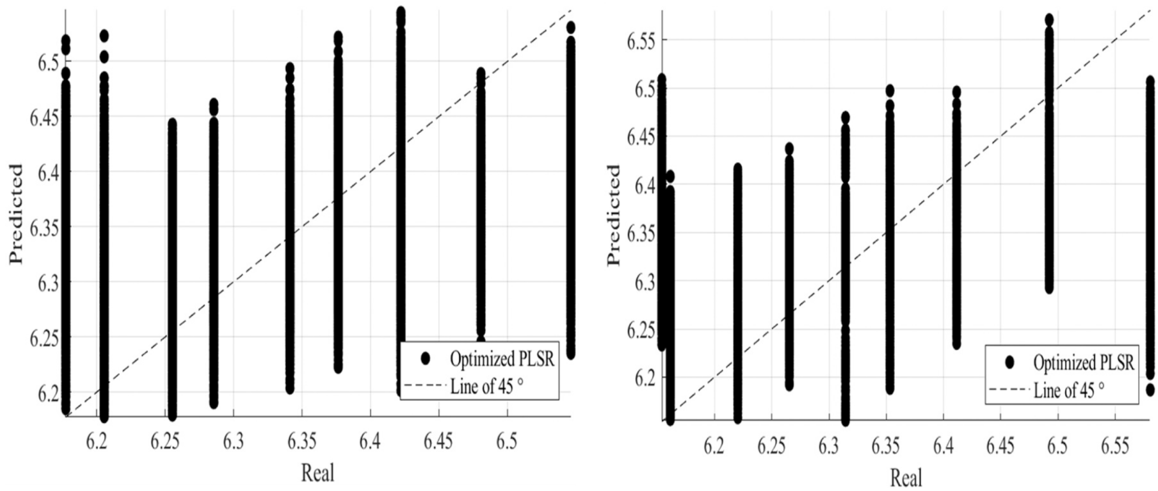
Figs. 8 and 9 show the dielectric constant (ε') values of the RFN and DFD male and female samples from 3 to 24 h post-mortem, which decrease with increasing frequency. This behavior is similar to that reported by Castro-Giráldez, Aristoy, et al. (2010). The behavior of the ε' spectra of males and females is a product of biochemical and structural changes, which include a series of oxidative, electrolyte, proteolytic, and other processes. Similarly, the before-mentioned changes are attributed to lactic acid accumulation, pH decrease, and protein denaturation, causing a decrease in water retention capacity, the release of ions (Mg^{2+}, Ca^{2+}, K^+, Cl^- and Na^+), and the formation of myosin-actin cross-links in the samples (Paredi et al., 2012), similar biochemical behavior in chicken meat (M. V. Traffano-Schiffo et al., 2021).

In DFD samples, the behavior of the ε' spectra of male and female



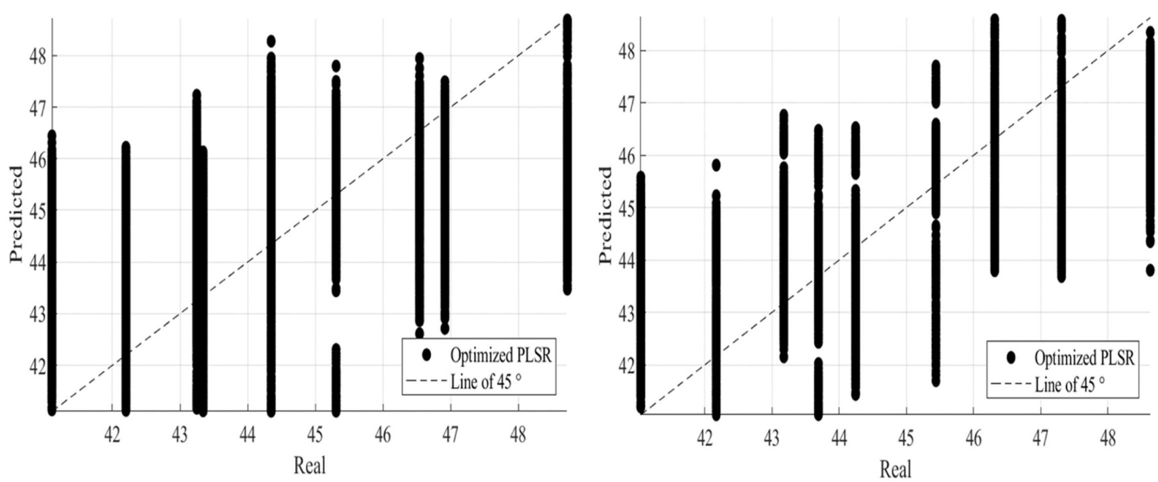
(a) (b)

Fig. 18. Results of PLSR model prediction for pH of RFN samples: (a) $R^2_{cv} = 0.36$ for male pigs and (b) $R^2_{cv} = 0.43$ for female pigs.



(a) (b)

Fig. 19. Results of PLSR model prediction for pH of DFD samples: (a) $R^2_{cv} = 0.40$ for male pigs and (b) $R^2_{cv} = 0.42$ for female pigs.



(a) (b)

Fig. 20. Results of PLSR model prediction for color (L*) of RFN samples: (a) $R^2_{cv} = 0.57$ for male pigs and (b) $R^2_{cv} = 0.64$ for female pigs.

pigs is due to the low availability of ATP, lactic acid, and phosphate ions, the slow decrease in pH, high water retention capacity, protein denaturation, and degradation of the muscle structure, which affect ionic conductivity and the dipolar relaxation phenomenon (Castro-Giráldez, Aristoy, et al., 2010; M. V. Traffano-Schiffo, Castro-Giraldez, Colom, et al., 2018). Due to the lower availability of glucose and the limited glycogen content, the glycolysis route is limited, which causes this type of meat to take alternative sources of energy production, such as the degradation of amino acids, mainly alanine, and glycine. Due to these processes, ε' is lower for DFD samples in contrast to the other quality classes (M. V. Traffano-Schiffo, Castro-Giraldez, Colom, et al., 2018).

Figs. 10 and 11 show the intensity values of the loss factor (ε'') along the electromagnetic spectrum (0.5–9 GHz) of the RFN and DFD samples of males and females from 3 to 24 h post-mortem. In both figures, the intensity values ε'' decrease from 0.5 to 2 GHz and then increase until 9 GHz, forming a "U"- shaped spectrum. This U-shape is because, after slaughter, the muscle cells reduce the production of nutrients and oxygen, increasing ionic strength and osmotic pressure from the animal's death until rigor mortis. When the pH approaches its isoelectric point (pH close to 5.4), the proteins start to become disabled, and their capacity for absorbing cations (Mg^{2+} and Ca^{2+}) decreases, thus increasing the free ions in the sarcoplasm and the ionic conductivity (Castro-Giráldez, Aristoy, et al., 2010). Likewise, the dielectric spectra formed from the intensity values of ε'' for RFN samples are similar to those reported, showing that the behavior of ε'' spectra in males and females is due to ATP depletion and pH decrease, causing the release of free ions from proteins and the increase of metabolites, such as lactate and nucleotides (Castro-Giráldez, Aristoy, et al., 2010). In DFD samples, the behavior of the intensity values of the ε'' spectra is due to the low lactic acid content and the late onset of rigor mortis in contrast to the other types of samples.

3.4. *Prediction of quality parameters by dielectric spectroscopy*

3.4.1. *Relevant frequencies for the optimization of the prediction model*

The coefficient β allows finding the highest absolute values, which measure the level of relationship between variables X and Y (Khan et al., 2020). In this investigation, a total of 15 relevant or specific frequencies of 401 were found from the intensity values of ε' and ε'', referred to pH values. In the case of RFN samples, three relevant frequency subgroups

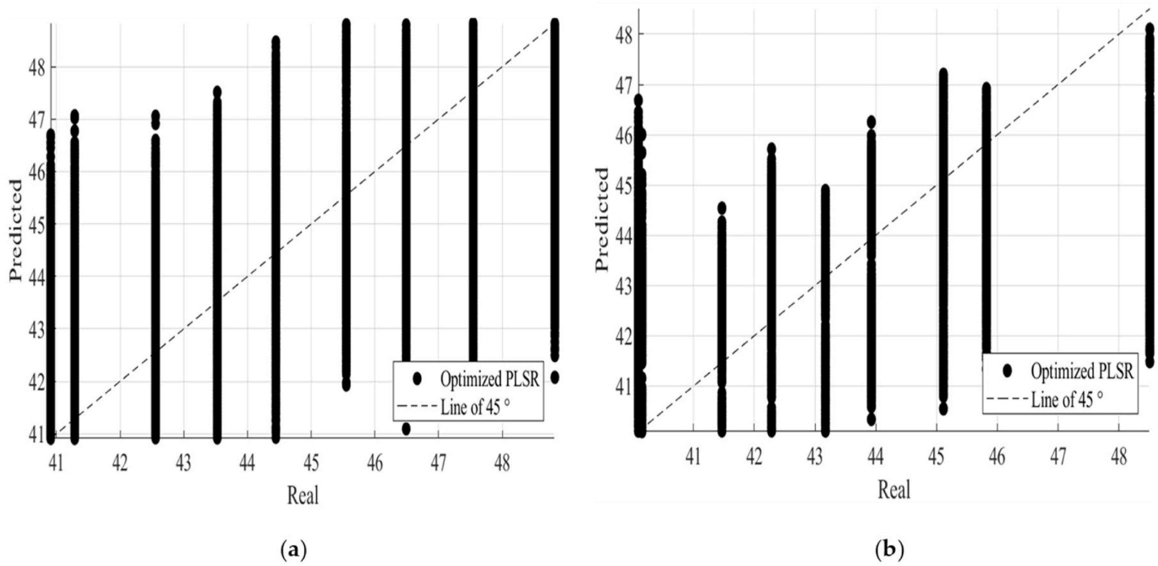


Fig. 21. Results of PLSR model prediction for color (L*) of DFD samples: (a) $R^2_{cv} = 0.62$ for male pigs and (b) $R^2_{cv} = 0.51$ for female pigs.

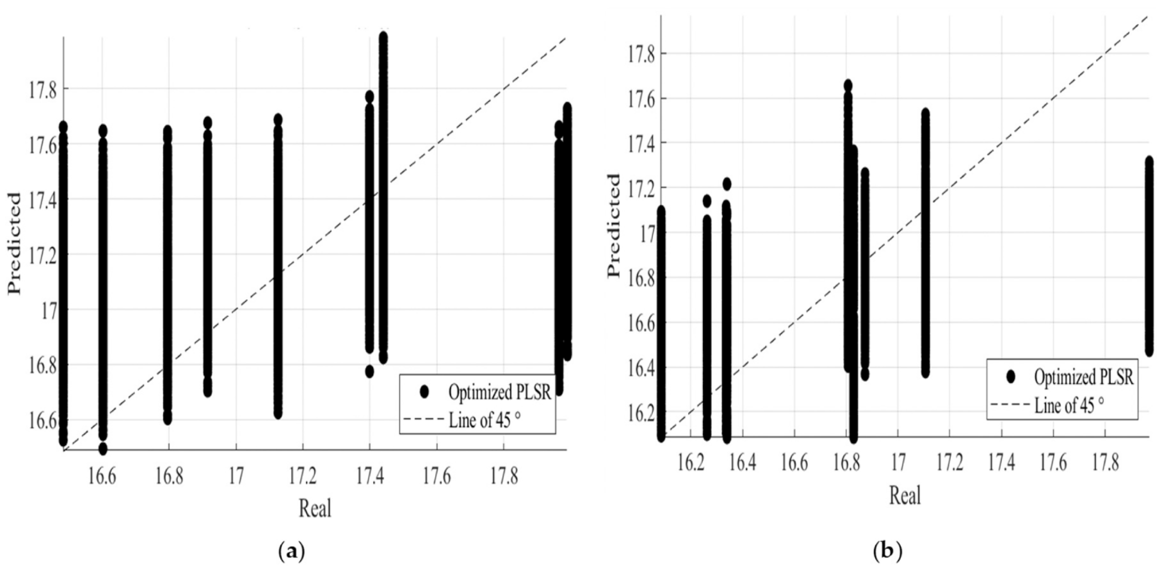
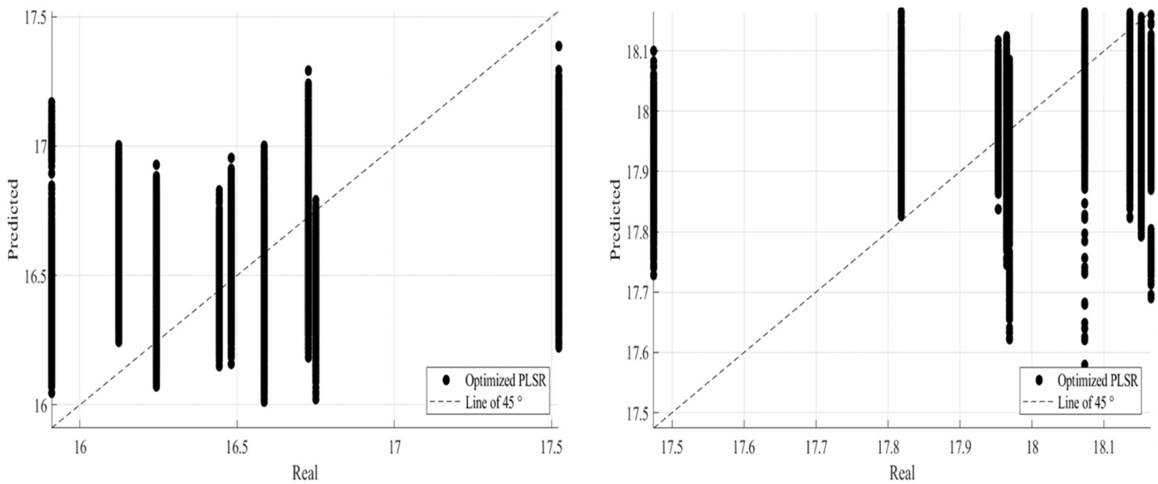


Fig. 22. Results of PLSR model prediction for color (C*) of RFN samples: (a) $R^2_{cv} = 0.29$ for male pigs and (b) $R^2_{cv} = 0.32$ for female pigs.

have been observed in the ranges of 0.5–1 GHz, 3–5 GHz and 8.5–9.0 GHz for male pigs and for female pigs two subgroups have been observed in the ranges of 0.5–3 GHz and 4.0–7.0 GHz, as evidenced in Fig. 12 a - b. The DFD samples also present three relevant frequency subgroups in the ranges of 1.5–6.0 GHz, 4.5–7.5 GHz and 7.2–8.9 GHz for male pigs and two subgroups in the ranges of 2.5–4.0 GHz and 5.3–9.0 GHz for female pigs, as shown in Fig. 13 a-b.Unlike those reported by Andersen et al. (2018), who obtained 3 relevant variables (RVs) in the range from 400 to 1850 nm; Andersen et al. (2021), who obtained 5 RVs in the range from 400 to 1800 cm^{-1}; and Balage et al. (2015), who obtained 105 RVs in the range from 390 to 1380 nm through Marten's uncertainty test; Barbin et al. (2012) has found 5 RV out of 237 bands, and Barbin et al. (2013) obtained 14 RV out of 237 bands in the range from 928 to 1645 nm and from 947 to1680 nm through weighted regression coefficient; Geesink et al. (2003) found two subgroups of RVs in the range from 1000 to 1860 nm and from 2100 to 2450 nm through the multiplicative scattering correlation (MSC); Qiao et al. (2007) found 6 RVs out of 80 spectra in the range from 494 to 978 nm through the simple correlation coefficient. The differences between our research and the others are mainly due to the selection methods of relevant variables and the data collection technique, which were performed using hyperspectral imaging, near-infrared, and Raman spectroscopy, among others, in different ranges of the electromagnetic spectrum.

Figs. 14 and 15 show the most relevant frequencies for color prediction (L*) of the RFN and DFD samples for males and females. In the case of the RFN samples, three subgroups with relevant values (RV) are observed in the ranges of 0.5–1.0 GHz, 5.2–7.0 GHz and 8.5–9.0 GHz for male pigs and in the ranges of 0.5–2.5 GHz, 3.0–5.2 GHz and 7.5–9.0 GHz for female pigs, as shown in Fig. 14 a-b. Similarly, the DFD samples present three RV subgroups in the ranges of 0.5–1.0 GHz, 2.8–4.0 GHz and 8.5–9.0 GHz for male pigs and for female pigs two subgroups in the ranges of 2.0–4.5 GHz and 5.5–8.5 GHz, as evidenced in Fig. 15 a - b. In our research, 15 specific frequencies have been found for color(L*) prediction, unlike those reported by Balage et al. (2015), who obtained 63 RVs in the range from 405 to 1365 nm through the



(a) (b)

Fig. 23. Results of PLSR model prediction for color (C*) of DFD samples: (a) $R^2_{cv} = 0.36$ for male pigs and (b) $R^2_{cv} = 0.28$ for female pigs.

Martens' uncertainty test; Barbin et al. (2012, 2013), who reported 6 RVs in the range of 947–1654 nm and 14 RVs in the range from 928 to 1645 nm, respectively, through the weighted regression coefficient; Geesink et al. (2003) found two major frequency subgroups in the range from 1000 to 1860 nm and 2100–2450 nm through the multiplicative scatter correlation; and Qiao et al. (2007) found 6 RVs in the range from 434 to 703 nm through the simple correlation coefficient.

Figs. 16 and 17 show the most relevant frequencies for chroma (C*) prediction of RFN and DFD samples for male and female pigs. In the case of RFN samples, three subgroups with relevant values (RV) are observed in the ranges 0.5–1.3 GHz, 5.5–7.0 GHz and 8.5–9.0 GHz for males and in the ranges 0.5–1.5 GHz, 3.0–5.3 GHz and 6.5–9 GHz for females, as shown in Fig. 15 a-b. Similarly, DFD samples present three RV subgroups in the ranges of 0.5–1.0 GHz, 2.8–4.0 GHz and 8.5–9.0 GHz for males and for females in the ranges of 0.5–1.8 GHz, 3.2–5.0 and 6.5–9.0 GHz, as evidenced in Fig. 16 a - b. In our research, 15 specific frequencies have been found for chroma (C*) prediction, unlike those reported by Barbin et al. (2012), who obtained 6 RVs in the range of 947–1214 nm using the weighted regression coefficient.

3.4.2. *Prediction of physicochemical parameters during the muscle-to-meat conversion: modeling using e′ for the prediction of physicochemical parameters*

Table 3 shows the values obtained from the full and optimised PLSR for each of the parameters determined (pH, L* and C*) according to the type of meat. The results show that the optimised PLSR gives better results than the full PLSR for the parameters pH and L* in both types of meat and sex; however, for the parameter C*, the full PLSR gives high values for male pigs in both types of meat and the optimised PLSR gives low values.

Figs. 18 and 19 show the prediction of pH from the dielectric constant (ε') for the RFN and DFD male and female samples. For RFN samples, a pH prediction of $R^2_{cv} = 0.36$ for male pigs and $R^2_{cv} = 0.43$ for female pigs was obtained (Fig. 18 a - b); and for DFD samples, $R^2_{cv} = 0.40$ for male pigs and $R^2_{cv} = 0.42$ for female pigs could be predicted (Fig. 19 a - b), different to the results reported by Andersen [8], who obtained an R2 = 0.72 for male pigs; (Balage et al., 2015), (Furtado et al., 2019) and (Savenije et al., 2006), who recorded an R2 in the range from 0.67 to 0.71 for male and female pigs; and (Kapper et al., 2012) and (Qiao et al., 2007), who recorded an R2 in the range from 0.55 to 0.70 for pigs (not specifying sex). These similarities occur even though they have used different techniques to obtain spectra, such as Raman spectroscopy (RS), Fourier transformation infrared spectroscopy (FT - IR), visible reflectance spectroscopy (VIS), near-infrared spectroscopy (NIR), and hyperspectral imaging (HSI). When comparing our results of pork quality prediction with those performed on other types of meats, it can be observed that our results are similar to those by (Y. Yang et al., 2021), who obtained a pH prediction of $R^2 = 0.80$ in chicken, beef, pork, and turkey meat, but lower than those by (Hashem et al., 2021), who obtained a pH prediction of $R^2 = 0.95$ in beef meat. These similarities and/or differences are due to the above-mentioned in Fig. 2.

Figs. 20 and 21 show the color prediction (L*) from the dielectric constant e′ for RFN and DFD samples for males and females, respectively. For RFN samples, an L* prediction of $R^2_{CV} = 0.57$ for male pigs and $R^2_{cv} = 0.64$ for female pigs was obtained; and for DFD samples, $R^2_{cv} = 0.62$ for male pigs and $R^2_{cv} = 0.54$ for female pigs could be predicted, similar to the reported results by Balage et al. (2015), Furtado et al. (2019) and Savenije et al. (2006), who recorded an R^2 in the range from 0.63 to 0.84 for male and female pigs through VIS/NIR spectroscopy; and those obtained by other authors (Barbin et al., 2012; Kapper et al., 2012; Qiao et al., 2007), who recorded an R^2_{cv} in the range from 0.75 to 0.91 for pigs (not specifying sex) through FT – IR, NIR and HIS spectroscopy. When comparing our results of pork quality prediction with those performed on other types of meats, it can be observed that our results are lower than those by Yang et al. (2021), who obtained an L* prediction of $R^2 = 0.93$ in chicken, beef, pork, and turkey meat; and those by Hashem et al.(2021), who obtained a pH prediction of $R^2 = 0.96$ in beef meat, summarizing Fig. 3.

Figs. 22 and 23 show the color prediction (C*) from the dielectric constant e′ for RFN and DFD samples for male and female pigs, respectively. For RFN samples, a C* prediction of $R^2_{cv} = 0.29$ for male pigs and $R^2_{cv} = 0.32$ for female pigs was obtained; and for DFD samples, it was possible to predict $R^2_{CV} = 0.35$ for male pigs and $R^2_{cv} = 0.28$ for female pigs, different from the results reported by Barbin et al. (2012) who recorded an $R^2_{cv} = 0.83$ for pigs (no sex specified) by NIR and HIS spectroscopy, due to the reflection of surface light that the sample offers, however, for the case of prediction from dielectric properties the performance is low due to the degradation of tissue structure and reduction - oxidation of myoglobin due to the decrease in pH during the transformation from muscle to meat (Castro-Giráldez, Aristoy, et al., 2010; Castro-Giraldez et al., 2010; Castro-Giráldez et al., 2011).

The partial least squares regression (PLSR) technique has the capacity to predict significant characteristics of post-mortem pork, thereby enabling the identification of the quality grade of pork.

4. Conclusion

The transformation of muscle into meat for males and females has shown that the intensity values of the dielectric constant and loss factor decrease as the frequency increases. This allows the types of DFD and RFN meat for samples of males and females to be differentiated at 24 hpm.

Robust models were created using PLSR to predict internal quality during muscle to meat transformation. Performance was moderate for male pig meat. R^2_{cv} of 0.743 (pH), 0.811 (L*) and 0.603 (C*) for DFD meat with PLSR (full) and R^2_{cv} of 0.359 (pH), 0.558 (L*) and 0.284 (C*) for RNF meat with PLSR (optimized). R^2_{cv} of 0.412–0.637 for pH, L* and C* for RFN and DFD meat from female sows with PLSR (optimized). New chemometric models are needed to improve the prediction of internal pork meat quality.

Author statement

We declare that we have all reviewed the revised and corrected version of the scientific manuscript "Dielectric spectroscopy for the prediction of pork quality during the post-mortem time"

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CRediT authorship contribution statement

Wilson Castro: Writing – review & editing, Supervision, Conceptualization. **Marta Castro-Giraldez:** Writing – original draft, Supervision, Methodology. **Fito Pedro:** Writing – review & editing, Supervision. **Tony Chuquizuta:** Writing – original draft, Investigation, Conceptualization. **Magaly Peralta:** Investigation, Conceptualization. **Jimy Oblitas:** Methodology, Investigation. **Segundo G. Chavez:** Writing – review & editing, Formal analysis. **Sideli Medina:** Formal analysis, Conceptualization. **Hubert Arteaga:** Methodology, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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