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ORIGINAL PAPER

Dry-cured loin characterization by ultrasound physicochemical and sensory parameters

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Abstract

The aim of this study was to evaluate the ability of ultrasound inspection and quality determinations to characterize two commercial categories of dry-cured pork loin, labelled as green (GL) and red (RL). For this objective, ultrasound inspection was carried out for two different frequencies (500 and 1000 kHz), considering parameters of ultrasonic pulse velocity (UPV), frequency components related to the fast Fourier transform (FFT), and variables related to the attenuation. Physicochemical (moisture and fat content, water activity, instrumental color), instrumental texture (TPA) and sensory analyses (QDA) were also carried out. Moreover, quality and ultrasonic parameters were subjected to a correlation analysis (Pearson). Several physicochemical, instrumental texture and sensory parameters allowed to discriminate the dry-cured loin category. Moreover, high significant correlations were found among quality and acoustics parameters. Thus, ultrasound inspection can determine quality parameters indirectly without the limitations of traditional methodologies, postulating as a tool for characterizing dry-cured loin samples of different category with a promising predictive nature. This work has showed new findings for dry-cured meat products that may be of interest to the meat industry.

Keywords Dry-cured loins · Ultrasound inspection · Pearson correlation · Quality parameters

Introduction

Meat products from the Iberian pig are highly valued by consumers, being the dry-cured loin one of the most recognized ones, due to its appreciated sensory characteristics and its lipid composition, with a reasonable amount in monounsaturated fatty acids [1]. Labelling of Iberian products have been regulated based on genetics and the rearing system of the animal [2], being classified in different commercial categories. Current and recent Spanish legislation [3] differentiates the following labels: white label products ('Cerdo Ibérico') correspond to animals with at least 50% Iberian breed and fed with concentrates; green label products ('Cebo de Campo Ibérico') require at least 50% Iberian breed and fed with natural resources and concentrates; red label products ('Bellota Ibérico 50%'), with at least 50% Iberian breed and fed exclusively on natural resources; and black label products ('Bellota Ibérico 100%), from pure 100% Iberian breed and fed only from natural resources. The use of crossbred animals, Iberian × Duroc pigs instead of pure breed, and the substitution of acorn and pasture by concentrate diet in Iberian pigs, mainly influence negatively in the final quality of Iberian products [4, 5].

Traditional methods, such as physicochemical analysis, instrumental texture or sensory analysis, have been decisive to characterize the quality of meat products [6, 7]. Sensory evaluation is one of the tools that has given the best results to determine and discriminate commercial categories of cured pork loin following the previous legislation [8–10]. Among the different sensory tests, the Quantitative Descriptive Analysis (QDA) [11] is postulated as one of the most applied in foods, including cured pork loin [12]. Unfortunately, all these types of methodologies are high time-consuming, and

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require the destruction of the sample and also a trained panel to evaluate the samples in the case of the sensory analysis. This has led to the evaluation of the capability of different technique to analyze quality characteristics of meat products [13–15]. Low intensity ultrasound inspection is one of the most reliable recent technologies to characterize the quality in food [16, 17], and its ability has also been proven in pork loins [18–20]. Moreover, non-destructive ultrasonic inspection has been used for the ultrasound characterization of different dry-cured meat products [21], to assess textural changes in vacuum packaged sliced Iberian ham [22], and to monitor the pork loin and ham dry-salting process [23, 24]. As other authors have described [17], this methodology is faster and more cost-effective than most modern instrumental techniques (compared to magnetic resonance imaging-MRI, for example), standing out for its non-destructive nature. In addition, ultrasonic tests have the ability to assess the whole sample (compared to near infrared spectroscopy-NIR, for example, which only manages to non-destructively test the surface of the part). Ultrasonic inspection allows the determination of certain acoustic parameters that work, among other functionalities, to discriminate different food samples. Generally, the scientific literature tends to consider exclusively parameters related to the velocity of the wave, as well as the attenuation. Recently, non-common acoustic parameters were considered in the literature, such as frequency components related to the fast Fourier transform (FFT), and the attenuation (without the presence of echoes) quantified in terms of the time taken to receive energy. These new parameters have already been applied successfully in various foods, such as honey [25], milk [26], cheese [27, 28], and cooked pork loins [19]. The main aim of this work was to evaluate the ability of acoustic and quality parameters to characterize two categories of dry-cured pork loins, and thus to correlate these acoustics results with quality parameters. In this way, this work provides results of interest to address one of the main limitations of ultrasonic inspection, such as the fact that it is a little studied technique in process monitoring and product quality control in the meat sector.

Materials and methods

Samples

Iberian dry-cured loins (vacuum packaged) of two commercial category were purchased from Montesano Extremadura S.A. (Badajoz, Spain): ‘Bellota 50% Ibérico’ with red label (RL), from 50% Iberian × Duroc crossbreed pigs extensively reared and exclusively fed on natural resources, and ‘Cebo de Campo Ibérico’ with green label (GL), from 50% Iberian × Duroc crossbreed pigs extensively reared and fed on natural resources and concentrate. In addition to the pork loin, the following ingredients were also added: salt, paprika, sucrose, spices, antioxidant (E 301) and preservative (E 250). Six pork loins from different production batches of each category were acquired. Each loin was divided into two parts for the subsequent analyses: one part was used for the physicochemical, instrumental texture and sensory analysis, and the ultrasonic inspection was carried out on the other part. Figure 1 shows the procedure scheme followed in this study.

Quality parameter determinations

Physicochemical analyses

Moisture content was analyzed by drying the samples (5 g) at 102 °C following the procedure of the official methods of Association of Official Agricultural Chemists (AOAC International reference method 935.29) [29]. Water activity (a_w) was measured by a water activity measuring equipment (Lab Master-aw; NOVASINA AG, Lachen, Switzerland). Fat content was determined according to the methodology described by Folch et al. (1957) with chloroform:methanol (2:1). Instrumental color was determined using a Minolta CR-300 colorimeter (Konica Minolta, Osaka, Japan) with illuminant D65, a 0° standard observer and a 2.5 cm port/viewing area. The measurements were carried out in the transversal section. The analysis was performed according to the principles from the Commission International d’Eclairage [31] and each sample was measured three times. Lightness (L^*), redness (a^*), and yellowness (b^*) were the color coordinates measured. All physicochemical determinations were carried out in triplicate.

Instrumental texture analysis

The instrumental texture analysis was carried out using a texturometer Texture Analyser TA XT Plus (Stable Micro Systems Ltd., UK). Texture Profile Analysis (TPA) was applied, using for this method a cylindrical probe with 5 cm in diameter. From each sample, five cubes (1 cm^3) were prepared and analyzed, being axially compressed to 50% of the original height [32]. Following the definitions of previous works [25, 32], the instrumental texture parameters calculated were: hardness (g); adhesiveness (g × s); springiness (g); gumminess (g); cohesiveness (dimensionless); chewiness (g); and resilience (J·m – 3).

Sensory evaluation

Iberian dry-cured loins of this study were subjected to a QDA [11]. Fourteen trained panelists (5 males and 9 females, ranging among 24–59 years old) participated in this analysis, being all of them staff of the University of

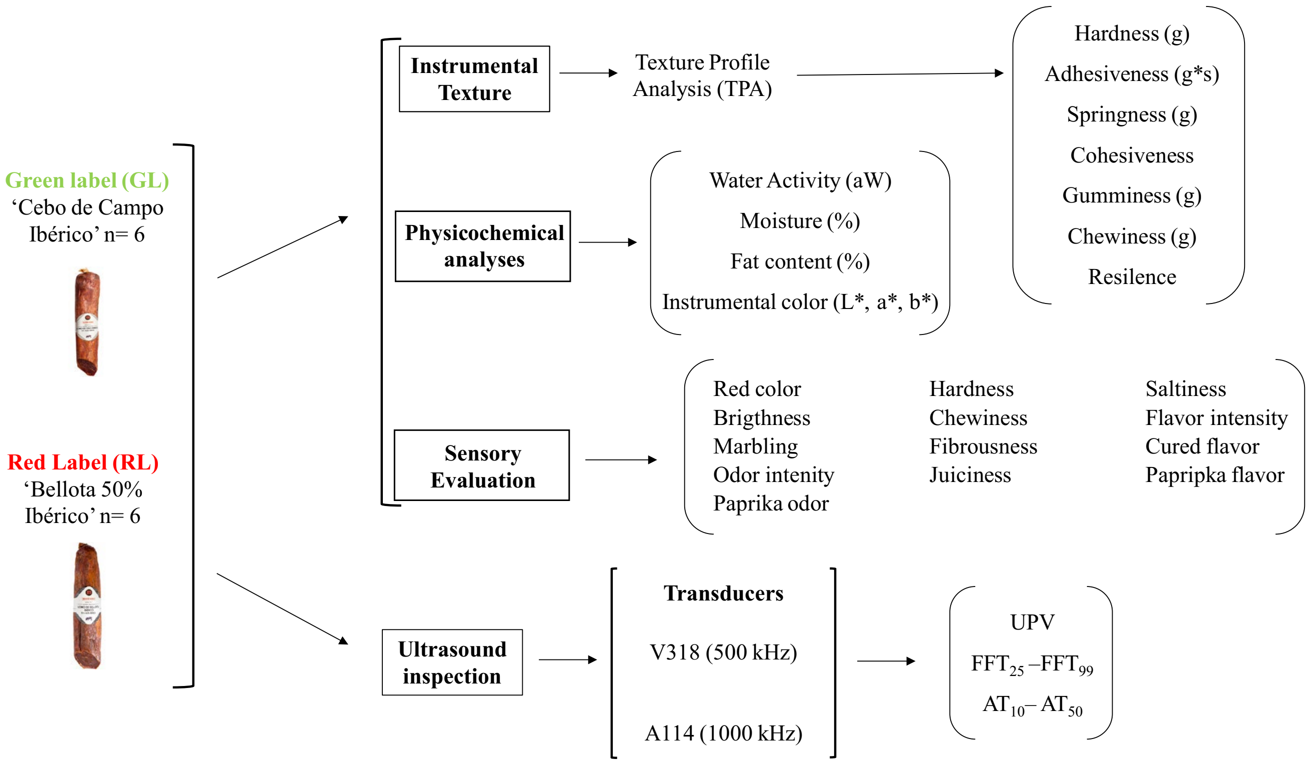

Fig. 1 Scheme of the procedure and data analysis. Footnote: *UPV* ultrasound pulse velocity, *FFT25/ FFT99* fast Fourier transform corresponding to the 25th and 99th percentiles, *AT10/ AT50* attenuation corresponding to reaching 10, and 50% of the energy

Extremadura. Four samples were assessed during three sessions. Therefore, a total of twelve samples (six RL and six GL samples) were evaluated by each panelist. Dry-cured loins were sliced using a slicer meat machine TGI 300 OMS S.r.l. (TGI, Italy), obtaining slices of 3 mm and approximately 5 g. Samples were served one per plate, with a glass of mineral water and a piece of unsalted cracker to follow the rinsing protocol among loins. Evaluations were developed according to the UNE-EN-ISO 8589:2010 regulation, in a sensory room with controlled temperature (21–22 ℃), and with white fluorescent light. The samples order was randomized according to the Williams Latin square design. Finally, for collecting the data, FIZZ software 2.20 C version (Biosystèmes, Couternon, France, 2002) was used. The attributes of this study were selected based on the previous experience of the authors in sensory evaluation of meat products [33, 34]. Selected attributes and definitions are displayed in Table 1. A 10 cm unstructured scale was used for

Table 1 Attributes and descriptions for the quantitative-descriptive sensory analysis

Attribute	Description
Red color	Refers to the redness of the sample
Brightness	Refers to the reflection of light
Marbling	Refers to the visible intramuscular fat
Odor intensity	Refers to the overall odor intensity
Paprika odor	Refers to the aroma perception characteristic of paprika
Hardness	Refers to the big effort required to convert the sample in a swallowable state
Chewiness	Refers to the number of chews until to reach a state ready for swallowing
Fibrousness	Refers to the fiber perception during chewing
Juiciness	Refers to the impression of lubricated food during chewing
Saltiness	Refers to the primary salty taste
Flavor intensity	Refers to the overall flavor intensity
Cured flavor	Refers to the flavor perception characteristic of cured meat products
Paprika flavor	Refers to the aroma perception characteristic of paprika

attributes scoring, and verbal anchors were fixed as ‘little’ to ‘very much’ for all evaluated attributes.

Ultrasound testing

Set up of ultrasound inspection

The ultrasonic inspection equipment and procedures coincide with those described in previous works by the authors [18, 35]. For this reason, we will limit ourselves here to briefly describe them, emphasizing those most interesting and novel aspects.

Ultrasound measurements were carried out inside temperature-controlled chamber (RIVACOLD RC325-45ED, Italy), with a constant temperature of 7.0 ± 0.2 ℃. Dry-cured loins were inspected using a contact technique in through-transmission (T–T) mode. Two Olympus Panametrics-NDT Model V318-SU piezoelectric transducers were used to transmit 500 kHz signals. In the same way, 1000 kHz signals were transmitted by two Olympus Panametrics-NDT Model A114S transducers. The characteristics of these pairs of transducers are shown in Table 2. The use of other higher frequency transducers was discouraged due to the high attenuation experienced by the transmitted signal, particularly noticeable at higher frequencies. The tests were carried out in triplicate in the axial direction, facing the transducers in the center of both sides of each piece, with a distance between transducers of 20.0 ± 0.3 cm. Emitter transducer was positioned on the cranial face, and the receiver transducer on the caudal one. Due to the irregularities of the lateral surface of the pieces and the fact that their diameter was similar (if not less) than the near-field length *N* (Table 2), the possibility of conducting inspections in the radial direction was rejected. In addition, a water-soluble coupling gel from Olympus was applied to the samples surfaces to facilitate the transmission of the waves. Panametrics-NDT Model 5077PR Pulse-Receiver from Olympus was used to emit and receive the ultrasound signals. All the tests were carried out establishing the following parameters of the pulser-receiver: Pulser Voltage 100 V; Transducer Freq 0.5 MHz for V318 and 1 MHz for A114; Gain + 10 dB for V318 and + 20 dB for A114; High pass filter OUT; and Low pass filter 10 MHz. This pulser-receiver was connected to an InfiniiVision DSO-X 3032A oscilloscope from KEYSIGHT for the acquisition and digitalization of the signals. The files were saved in 10 000 points record length (in ‘.csv’ format) for the subsequent processing and analysis of the data. Two A-scans were recorded from each inspection: the first, in which the trigger pulse and the arrival of the signal at the receiver were collected, with a time interval of 20 µs, and the second, including the entire transmitted signal, with 60 µs.

Ultrasound parameters

Different ultrasound parameters were obtained from the A-scan. The ultrasound inspection study was done in six replications per sample. Thus, the ultrasonic parameters obtained in each inspection corresponded to the mean value of those obtained in the six replicates. Figure 2 shows a typical A-scan obtained with the A114 transducers. The ultrasound pulse velocity (UPV) is based on the ‘time of flight’ (TOF), i.e., the time lapsed from the signal’ emission until its reception. This method had already been applied to

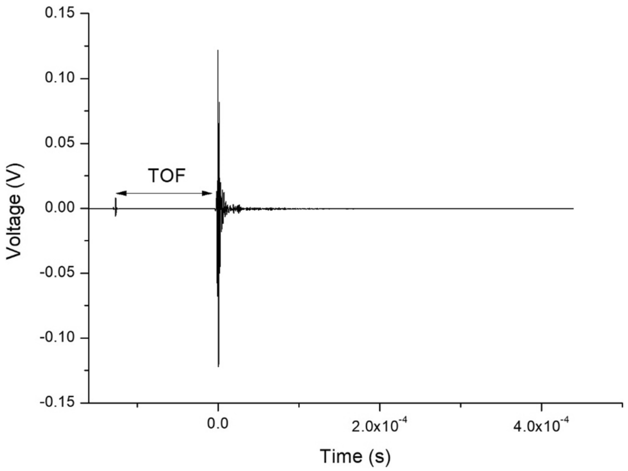

Fig. 2 A-scan obtained with the Panametrics A114 transducers for a RL pork loin

Table 2 Main characteristics of the transducers model used

Model	Diameter (cm)	Frequency (kHz)	− 6 dB bandwidth (%)	λ (mm)	N (mm)	φ (°)
Panametrics A114S	1.9	1000	64.59	1.75	51.57	6.45
Panametrics V318-SU	1.9	500	61.93	3.50	25.79	12.99

The UPV value for A114S and V318-SU were 1750 m/s, taking for the calculation of λ, N, and φ

λ wavelength

N near-field length

φ beam angle

determine the ultrasonic velocity in pork loins [18]. Since the distance d between both transducers is known, the velocity is calculated with the following equation:

$$UPV = \frac{d}{\mathrm{TOF}}.$$

Regarding frequency parameters, these are calculated using the fast Fourier transform presented by Cooley and Tukey (1965) [36]. Figure 3 shows the FFT of the signals received in the inspection displayed in Fig. 2. The frequency distributions (Fig. 3) are not close to Gaussian at all, so the highest amplitude frequency of the FFT (FFTCentral) is not a priori a meaningful value to characterize the inspected samples. In order to facilitate the subsequent analysis, the cumulative frequency periodograms are constructed to show the FFT frequencies corresponding to the 25t and 99th percentiles of the received signals [18, 19], i.e., if the cumulative frequency corresponding to the 25th percentile is at f Hz for an specific inspection, this means that 25% of the received signals had a frequency of less than f Hz. Thus, for each A-scan and subsequent FFT and frequency periodogram, the parameters of the different percentiles of the signals received were denoted as FFT25 and FFT99.

Finally, and as far as attenuation is concerned, the absence of clearly visible echoes in the A-scan obtained (Fig. 2), makes it unfeasible to determine it with the traditional calculation [25, 26]. Then, given that the nature of dry-cured loins makes it impossible to distinguish echoes, the attenuation was evaluated from the signal's progressive energy loss, obtaining the parameters as a function of time taken to receive determined energy percentages [18, 19, 35], particularly, 10, and 50%, (AT10 and AT50, respectively), expressed as a multiple of the TOF (n·TOF). Thus defined, a value of AT50 equal to 1.063, for example, would indicate that 50% of the energy that reaches the receiver transducer does so once 1.063 times the TOF have elapsed. Following this argument, the higher the ATxx value, the less attenuating the sample.

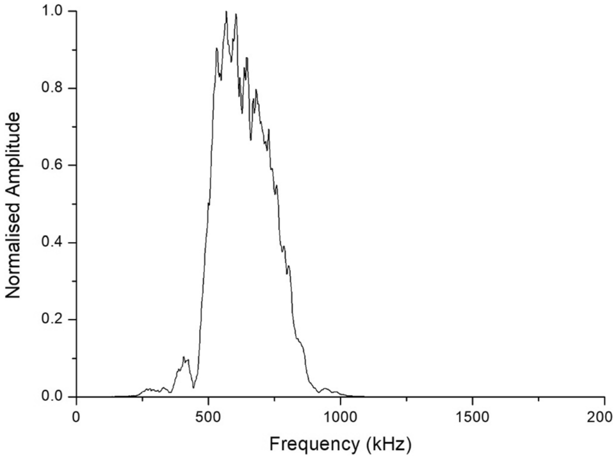

Fig. 3 FFT of the A-scan from Fig. 1

Data analysis

Differences between GL and RL dry-cured loins were statistically evaluated. The normality of physicochemical, TPA, sensory, and ultrasound parameters were evaluated using Shapiro–Wilk test. Depending on the obtaining results of normality test, Student T test ($p > 0.05$) or U Mann–Whitney test ($P < 0.05$) were applied. IBM SPSS v.22 (IBM Co., New York, U.S.A) statistic software package was used to carry out the former analysis. Pearson's correlation coefficient (R) between physicochemical, TPA, sensory characteristics and ultrasound parameters was calculated using the XLSTAT software package (Addinsoft Pearson Edition, Paris, France).

Results and discussion

Quality parameters of dry-cured loins

Table 3 displays GL and RL significant differences of physicochemical, TPA, and sensory data. Several similarities were found among the obtained results and those found in the scientist literature for dry-cured loins. Moisture and a^* parameter presented significant differences among samples. RL provided higher mean values for both parameters, being these samples redder and having higher moisture values. This significant difference in the amount of water will also

Table 3 Physicochemical (triplicate), and instrumental texture (quintuplicate) results (mean values ± SE), and p values obtained in the statistical analysis between pork loin categories

	GL ($n = 6$)	RL ($n = 6$)	P value
aW	0.908 ± 0.003	0.914 ± 0.004	0.20
L^*	35.09 ± 0.53	34.86 ± 0.03	0.70
a^*	9.73 ± 0.36	11.08 ± 0.34	0.01
b^*	5.41 ± 0.21	5.27 ± 0.13	0.58
Moisture (%)	39.51 ± 0.52	42.14 ± 1.02	0.03
Lipid g/100 (%)	11.75 ± 0.96	12.85 ± 0.74	0.37
Hardness (g)	152.5 ± 13.25	112.5 ± 6.56	0.02
Adhesiveness (g × s)	68.42 ± 10.33	87.33 ± 14.65	0.22
Springiness (g)	0.41 ± 0.01	0.42 ± 0.01	0.55
Cohesiveness	0.38 ± 0.01	0.38 ± 0.01	0.82
Gumminess (g)	5786 ± 705	4445 ± 328	0.20
Chewiness (g)	2600 ± 327	1850 ± 132	0.58
Resilience (J·m − 3)	0.15 ± 0.01	0.12 ± 0.01	0.04

GL green label, RL red label

lead to significance in the properties of instrumental and sensory texture between the samples, since humidity exerts an important influence on parameters such as hardness or juiciness in dry-cured loins [12, 37]. Mean values of *a** parameter are possibly a result derived from some physicochemical process, probably related to the amount of water and/or fat that defines the difference in redness (*a**) between samples [38]. The mean values obtained for instrumental color were consistent with those obtained in other previous works for these products [39–41]. Moisture values were also found in concordance with literature, ranged from 38.42 to 41.39% [42, 43]. Regarding the lipid content, similar results were also obtained in the present work in comparison with other works [12, 44]. Finally, the aW did not present significant differences among the categories. The mean values of aW were consistent with the literature that showed a range of values between 0.88 and 0.91 depending on the drying process and the type of sample [45, 46]. On the other hand, the pH values of this kind of products are pointed among 5.61–5.63 [47, 48]. To the best of our knowledge, there are no studies focusing on the category dry-cured loin characterization by physicochemical parameters.

TPA results are shown in Table 3. Only the hardness and resilience parameters showed significant differences between GL and RL. The aforementioned significant difference in the amount of water may be the origin of the significance in the properties of instrumental and sensory texture between the samples, since humidity exerts an important influence on parameters such as hardness or juiciness in dry-cured loins [12, 37]. Thus, as observed in the moisture determination, RL samples have a higher amount of water, and, therefore, their hardness is reduced due to its influence, hence the result provided by the instrumental hardness is consistent. Moreover, these results are coherent with the literature, since previous studies showed that the dry-cured loins of pigs fed exclusively with natural resources had lower hardness values than those fed with natural resources and concentrates [1]. On the other hand, the resilience, which is the effort exerted by the sample to recover its original state, was higher for GL samples, which a priori, also seems coherent due to loins with higher moisture values would require less effort to recover their original height. The obtained TPA results are very similar to other works following the previous legislation [1].

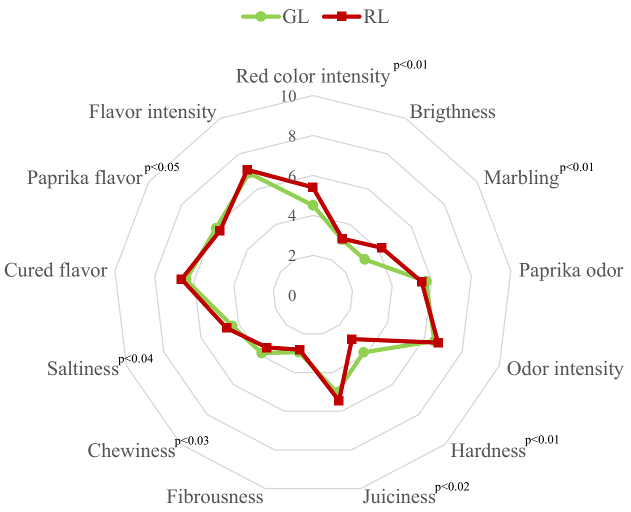

Fig. 4 Results from sensory analysis of GL ($n=6$) and RL ($n=6$) by the fourteen panelists: the attributes are assessed within a 10 cm scale (from extremely low to extremely high), and the significant levels are expressed in p values

Figure 4 shows QDA attributes results of GL and RL dry-cured loins. Several attributes displayed differences according to the category. GL dry-cured loins were harder, chewer, and with higher paprika flavor values. Meanwhile, RL samples presented higher red color intensity, marbling, juiciness, and saltiness mean values. These differences mostly agree with physicochemical, instrumental color and texture results, and they may be closely linked to the differences in the water content between batches, as previously explained. Both hardness and red color intensity coincided with the results of the instrumental and physicochemical texture, respectively. RL loin was considered the reddest, following the same behavior shown in instrumental color results. Once again, and probably due to the influence of the water, sensory hardness showed significant differences between the samples, being GL sample it should be noted that hardness is one of the most prominent sensory parameters in dry-cured loins [12], being perceived mainly at the beginning of the intake of these products. GL presented higher mean values of paprika flavor, probably to improve its organoleptic qualities. On the contrary RL sample is well accepted by consumers, and, therefore, it is not necessary higher values of paprika flavor to improve its organoleptic profile [2]. RL samples were perceived juicier than GL ones, being this fact consistent since RL samples had higher moisture values. Fat content can also influence this parameter; however, the results were not significantly different between both categories. Finally, the RL samples were perceived as saltier probably related to its higher moisture content, which increases the perception of salt.

Considering these results, it is necessary to stand out that the sensory evaluation is more effective than the physicochemical and textural determinations studied to discriminate between the commercial categories of dry-cured pork loin, as the application of novel sensory techniques pointed out [49]. Moreover, it is important to know that in fresh loins, physicochemical and textural parameters showed a samples distribution similar to sensory attributes in dry-cured loins [20]. Therefore, the scope of sensory analysis is of utmost importance to characterize these kinds of products and their categories.

Ultrasound inspection results

Table 4 displays the ultrasound parameters results for V318 transducers. The acoustics parameters had not the ability to discriminate significantly the studied commercial categories of dry-cured loin. The results of the 1000 kHz transducers, the A114, are also shown in Table 4. As occurred with V318, the pair of A114 transducers also did not present any significant difference for the dry-cured loin categories. The UPV obtained with both transducers (V318 and A114) oscillates in a range of 1726–1746 m/s. These results are similar to those obtained in previous studies on dry-cured products [22], with a velocity range between 1700 and 1720 m/s obtained at lower temperatures. Unfortunately, there are no comparable works in the scientific literature based on the frequency components or the attenuation determined without visible echoes for these meat products.

Furthermore, it should be noted two relevant facts. First, the fact that the mean values obtained for FFT25 and FFT99 with the A114 transducers are clearly higher than those of the V318. This fact is consistent, since the resonant frequency of A114 is higher than V318. In this sense, it is also noteworthy that the FFT99 values for both pairs of transducers are lower than their respective nominal frequencies, which indicates that the attenuation is greater at higher frequencies. Second, we highlight the fact that the ATxx values are lower in the parameters corresponding to the A114 transducers. It is also a coherent result since the A114 transducers work at a higher resonant frequency than the V318 ones, therefore, the energy will be more quickly attenuated, and consequently, their ATxx values will be lower.

Table 4 Ultrasound parameters of V318 and A114 transducers (triplicate) results (mean values ± SE) and *p* values obtained in the statistical analysis between pork loin categories

	GL (*n* = 6)	RL (*n* = 6)	*P* value
UPV V318 (m/s)	1746 ± 8	1726 ± 19	0.20
FFT25 V318 (Hz)	171,521 ± 32,693	139,705 ± 27,106	0.63
FFT99 V318 (Hz)	505,601 ± 6428	500,285 ± 15,119	0.75
AT10 V318	1.036 ± 0.001	1.032 ± 0.001	0.12
AT50 V318	1.063 ± 0.01	1.061 ± 0.01	0.75
UPV A114 (m/s)	1732 ± 9	1734 ± 7	0.86
FFT25 A114 (Hz)	465,390 ± 21,137	457,149 ± 32,601	0.84
FFT99 A114 (Hz)	843,530 ± 16,765	849,088 ± 18,392	0.83
AT10 A114	1.026 ± 0.01	1.028 ± 0.01	0.35
AT50 A114	1.033 ± 0.01	1.037 ± 0.01	0.17

GL green label, RL red label

Correlation study

Table 5 shows linear correlation coefficients among ultrasound parameters of both pair of transducers, and physicochemical and TPA results. Several significance correlations were found. *L**, *b**, and moisture showed significant correlations with the acoustics parameters. Instrumental color parameters, *L** and *b**, correlated significantly and inversely with UPV of the A114 transducers, a trend that is maintained in the case of the V318 but with less significance. The instrumental color parameters are derived from chemical changes during the dry-cured process of these meat matrices, reflected in physical changes produced on the surface of the food. The fact of the correlation among these parameters with the acoustic ones does not mean a direct correlation, but an indirect one of the chemical changes aforementioned. Probably both correlations, *L** and *b**, are resulted from the differences in fat, and especially from the moisture of the samples.

On the other hand, moisture is also inversely related to UPV ($R = -0.89$), particularly significant in the case of V318 transducer (Fig. 5). Thus, this fact would indicate that the ultrasonic signal would pass slower through the samples with higher moisture values, i.e., the less hard samples. This correlation is extremely important, since it suggests the sensitivity of the ultrasonic propagation velocity in the assessment of the water content, which was observed in other meat products [18], however, it has not been studied in dry-cured pork loins of different categories.

Regarding the correlations of the acoustic determinations with the instrumental texture parameters, the frequency and attenuation parameters, and not the velocity parameters, are now the ones that seem to be related with higher significance. Thus, first of all, we highlight the negative correlation of springiness and FFT25 with V318 transducers. This result would indicate that the samples that recover a lower height in the time elapsed between the end of the first compression and the beginning of the second in the texture evaluation, favor the transmission of higher ultrasonic frequencies in percentage terms. From the point of view of physics, the fact that these samples recover less height is equivalent to that their elastic constant is lower, i.e., their inverse, the elastic modulus is higher, and, therefore, these samples are more elastic. In principle, a higher elasticity allows the transmission of higher frequencies [50], hence these results are consistent. Although this same correlation is not significant for the FFT25 with A114 transducers. In the same sense, it should be noted the positive correlation of the FFT25 obtained with the A114 transducers with the resilience, indicating the effort of the sample to recover the original height in the texture determination.

Likewise, the samples with higher elasticity are also those that show lower attenuation when acoustic waves

Table 5 Linear correlation coefficients between the ultrasound parameters of A114 and A114 transducers with physicochemical and TPA parameters (UPV = ultrasound pulse velocity; FFT25/FFT99 = fast Fourier transform corresponding to the 25t, and 99th percentiles of the received signal; AT10/ AT50 = attenuation corresponding to reaching 10%, 50%, of the energy)

	Physicochemical parameters						TPA parameters						
	aW	L*	a*	b*	Moisture	Lipids content	Hardness	Adhesiveness	Springiness	Cohesiveness	Gumminess	Chewiness	Resilience
UPV A114	− 0.4698	− 0.2842	− 0.4252	− 0.2036	− 0.8949	0.0102	0.1889	− 0.0649	− 0.0460	− 0.0150	0.1199	0.1928	− 0.2277
FFT25 A114	− 0.1686	0.1912	0.1466	0.1837	− 0.2562	− 0.1078	− 0.1590	− 0.0890	− 0.5868	− 0.0159	− 0.2122	− 0.2408	− 0.2370
FFT99 A114	− 0.1560	0.1381	− 0.2217	− 0.1466	− 0.1830	0.0914	0.1589	0.0383	− 0.2323	0.4884	0.1914	0.1782	0.2115
AT10 A114	− 0.4590	− 0.2949	− 0.2429	−0.1166	− 0.4959	− 0.3177	0.4595	0.3241	− 0.2179	− 0.2541	0.3826	0.3496	0.1155
AT50 A114	− 0.0477	− 0.3482	− 0.2979	− 0.5064	0.0633	0.4153	0.5578	0.3706	0.1403	0.4743	0.6191	0.6426	0.6137
UPV A114	− 0.3738	− 0.8229	− 0.4988	− 0.7019	− 0.5598	0.3088	− 0.1328	− 0.0118	− 0.2926	0.0149	− 0.1253	− 0.0992	− 0.3801
FFT25 A114	0.3568	0.0905	− 0.1326	0.0004	0.4329	0.0327	0.3442	0.2893	0.1825	0.3150	0.4029	0.3768	0.5868
FFT99 A114	0.1667	-0.0620	− 0.2085	0.0182	0.1727	− 0.1532	0.0034	− 0.2048	0.1029	0.0368	0.0390	0.0540	0.3004
AT10 A114	− 0.0930	0.2625	0.5352	0.2909	0.2340	− 0.4514	− 0.2099	− 0.1566	− 0.4386	− 0.2999	− 0.2278	− 0.3552	− 0.1512
AT50 A114	− 0.0761	0.1123	0.5176	0.0737	0.2800	− 0.1872	− 0.2416	− 0.0906	− 0.4577	− 0.1641	− 0.2322	− 0.3499	− 0.1873

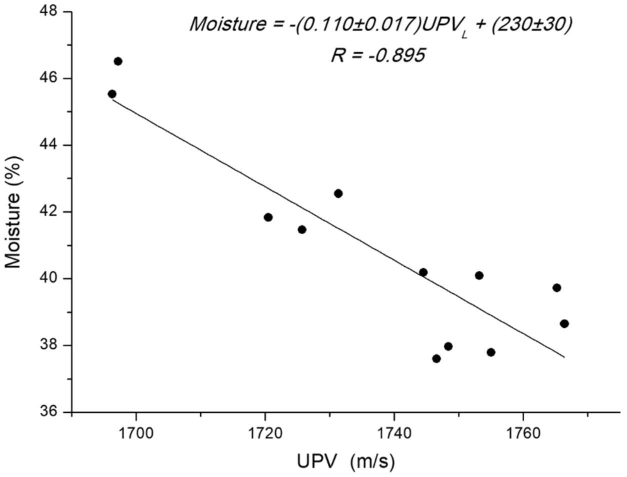

Fig. 5 Linear regression of Moisture with UPV measured with V318 transducers

passing through them [50]. The positive correlations found between AT50 with V318, and the gumminess, resilience, and chewiness parameters would respond, therefore, to this trend. Once again when ATxx value is higher the samples are less attenuating.

When this same correlation analysis is carried out with the A114 transducers, this trend is not appreciated, probably due to the shorter wavelength of the waves generated by these transducers, which makes their attenuation higher. In fact, no attenuation parameter obtained with A114 transducers correlates significantly with any physicochemical or texture parameter.

Table 6 shows linear correlation coefficients among ultrasound parameters of both pair of transducers, and sensory results. No significant correlations were observed between acoustic parameters and the sensory attributes of appearance, odor, and flavor. These correlations are difficult to discuss from the point of view of mechanic properties, and, therefore, these correlations would have been difficult to interpret. As has been provided in previous works, the ultrasonic parameters are highly sensitive to the physical changes produced in meat products [51], and as expected, several significant correlation coefficients were found between the acoustic parameters and the sensory attributes of texture. The hardness parameter obtained a positive significant correlation with the UPV for the A114 transducers and slightly less significant with the V318 transducers. These results are consistent with those observed in the scientific literature, since UPV is very sensitive to the instrumental hardness of the inspected sample [52]. Moreover, hardness has also been detected instrumentally and, therefore, has been a discriminating element for both categories of dry-cured loin, thus being highly relevant correlations, which would allow an indirect characterization with ultrasound inspection.

Table 6 Linear correlation coefficients between the ultrasound parameters of A114 transducer (UPV = ultrasound pulse velocity; FFT25/FFT99 = fast Fourier transform corresponding to the 25th, and 99th percentiles of the received signal; AT10/ AT50 = attenuation corresponding to reaching 10%, 50%, of the energy) with sensory parameters

	Sensory parameters												
	Red color intensity	Brightness	Marbling	Paprika odor	Odor intensity	Hardness	Juiciness	Fibrousness	Chewiness	Saltiness	Cured flavor	Paprika flavor	Flavor intensity
UPV A114	− 0.4433	0.0387	− 0.3378	− 0.3231	− 0.2882	0.5106	− 0.3778	0.5724	0.7803	− 0.5054	0.0330	− 0.1139	− 0.1109
FFT25 A114	− 0.4379	0.3709	− 0.1137	− 0.1605	− 0.3234	0.1137	0.0661	− 0.0367	0.2146	− 0.1724	0.0233	− 0.4656	0.0595
FFT99 A114	− 0.4983	-0.0632	− 0.1237	− 0.1829	− 0.1234	0.0382	0.0672	− 0.2080	0.2165	0.1523	0.2978	− 0.1650	0.2949
AT10 A114	− 0.2036	-0.1431	− 0.1660	− 0.3827	− 0.3615	0.2814	− 0.2289	0.4819	0.4453	− 0.4397	-0.1700	− 0.0904	− 0.1379
AT50 A114	0.1549	-0.4495	− 0.0519	− 0.0492	− 0.0879	0.1840	− 0.3622	0.1761	0.1517	0.3861	-0.2212	0.4975	0.0457
UPV A114	0.0100	-0.3237	− 0.3236	− 0.2118	0.0805	0.5793	− 0.3811	0.8198	0.7241	0.0203	0.1127	0.0803	0.1786
FFT25 A114	-0.0773	-0.5351	− 0.2506	0.1864	− 0.0984	− 0.0626	− 0.0448	− 0.2918	− 0.2463	0.3652	-0.0153	0.2354	0.1921
FFT99 A114	− 0.0665	-0.4052	− 0.3294	− 0.0271	0.0359	0.0337	0.0883	0.0512	− 0.1510	0.3596	0.4900	0.1341	0.4953
AT10 A114	0.1173	0.3470	0.4907	− 0.3947	− 0.0543	− 0.5653	0.5792	− 0.2797	− 0.4361	-0.0079	0.2359	− 0.5101	0.2347
AT50 A114	0.2596	0.3239	0.5484	− 0.3555	0.0218	− 0.5194	0.4871	− 0.2166	− 0.3763	0.1149	0.1269	− 0.4834	0.1902

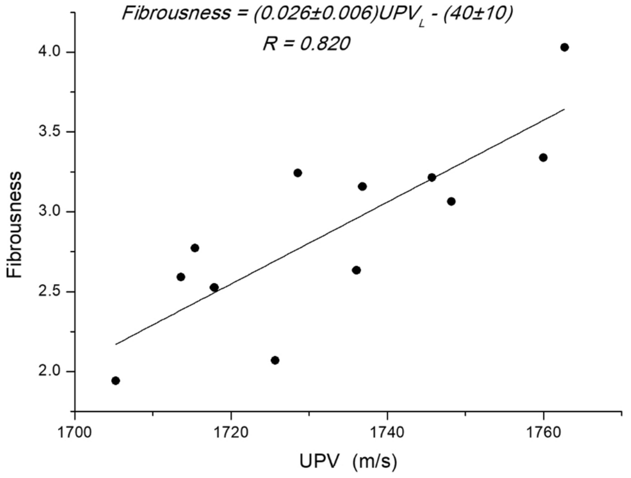

Fig. 6 Linear regression of Fibrousness with UPV measured with A114 transducers

AT10 of A114 transducers showed a significant positive correlation with juiciness, probably due to the significance of moisture and fat content of the samples. Thus, it is presumable to assume a lower attenuation of the ultrasonic energy in samples with higher water and fat contact that act as a coupling between the meat fibers. Fibrousness and UPV with 1000 kHz transducers (A114) significantly correlated ($R = 0.82$), as can be observed in Fig. 6. The fibrousness already showed several significant correlations with the acoustic parameters in cooked pork loins [18]. This parameter determines the perception of the fibers during chewing. It is important to note that the orientation of the fibers is parallel to wave propagation, hence these fibers favoring the transmission velocity of the wave. In this sense, it should be noted the significant correlation found between chewiness and UPV, since the chewiness of a loin sample should increase when its fibrousness increases, being this fact coherent. Furthermore, these high correlations are showed for both pairs of transducers.

Conclusions

The results of low-intensity ultrasound inspection, despite not directly discriminating the samples, obtained significant correlations, hence discriminatory parameters could be determined indirectly without the limitations of traditional methodologies. Thus, the study of different ultrasonic parameters, several of them not frequently considered by the scientific literature, provides the possibility to correlate and probably predict quality parameters.

This study has presented new contributions of ultrasonic inspection for dry-cured meat products that could be of interest to the meat industry, either to assess quality rapidly and non-destructively by determining the properties of these meat matrices or to avoid possible cases of fraud. It would be interesting to consider other categories of the dry-cured loin that may show differences through ultrasound inspection, and thus can discriminate these kinds of samples directly. In addition, it would be necessary for future works to consider prediction equations, and thus study the scope of ultrasound inspection as discriminating tool.

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Statements and Declarations

Conflict of interest The authors have no financial or proprietary interests to disclose.

Compliance with Ethics requirements All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

References

1. Soto E, De La Hoz L, Ordóñez JA et al (2009) The feeding and rearing systems of iberian pigs affect the lipid composition and texture profile of dry-cured loin. J Anim Feed Sci 18:78–89. https://doi.org/10.22358/jafs/66370/2009
2. Soto E, Hoz L, Ordóñez JA et al (2008) Impact of feeding and rearing systems of Iberian pigs on volatile profile and sensory characteristics of dry-cured loin. Meat Sci 79:666–676. https://doi.org/10.1016/j.meatsci.2007.10.031
3. BOE 2014 (2014) Real Decreto 4/2014, de 10 de enero, por el que se aprueba la norma de calidad para la carne, el jamón, la paleta y la caña de lomo ibérico
4. Tejeda JF, Gandemer G, Antequera T et al (2002) Lipid traits of muscles as related to genotype and fattening diet in Iberian pigs: total intramuscular lipids and triacylglycerols. Meat Sci 60:357–363. https://doi.org/10.1016/S0309-1740(01)00143-7
5. Pérez-Palacios T, Antequera T, Durán ML et al (2010) MRI-based analysis, lipid composition and sensory traits for studying Iberian dry-cured hams from pigs fed with different diets. Food Res Int 43:248–254
6. Biswas AK, Mandal PK (2020) Chapter 1 - Current perspectives of meat quality evaluation: techniques, technologies, and challenges. In: Meat Quality Analysis. PKBT-MQA (eds). Academic Press, p 3–17
7. Ventanas S, González-Mohino A, Estévez M, Carvalho L (2020) Innovation in sensory assessment of meat and meat products. Meat Qual Anal. https://doi.org/10.1016/B978-0-12-819233-7.00021-5
8. Lorido L, Estévez M, Ventanas S (2018) Fast and dynamic descriptive techniques (Flash Profile, Time-intensity and Temporal Dominance of Sensations) for sensory characterization of dry-cured loins. Meat Sci. https://doi.org/10.1016/j.meatsci.2018.06.028
9. Ventanas S, Ruiz J, García C, Ventanas J (2007) Preference and juiciness of Iberian dry-cured loin as affected by intramuscular fat content, crossbreeding and rearing system. Meat Sci 77:324–330. https://doi.org/10.1016/j.meatsci.2007.04.001
10. Ventanas S, Ventanas J, Ruiz J (2007) Sensory characteristics of Iberian dry-cured loins: Influence of crossbreeding and rearing system. Meat Sci 75:211–219. https://doi.org/10.1016/j.meatsci.2006.07.003
11. Stone H, Sidel J, Oliver S et al (1974) Sensory evaluation by quantitative descriptive analysis. Food Technol 28:24–34
12. Lorido L, Estévez M, Ventanas S (2014) A novel approach to assess temporal sensory perception of muscle foods: application of a time-intensity technique to diverse Iberian meat products. Meat Sci 96:385–393. https://doi.org/10.1016/j.meatsci.2013.07.035
13. Antequera T, Caballero D, Grassi S et al (2021) Evaluation of fresh meat quality by hyperspectral imaging (HSI), nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI): a review. Meat Sci 172:108340. https://doi.org/10.1016/j.meatsci.2020.108340
14. Barbin DF, Badaró AT, Honorato DCB et al (2020) Identification of Turkey meat and processed products using near infrared spectroscopy. Food Control 107:106816. https://doi.org/10.1016/j.foodcont.2019.106816
15. Geronimo BC, Mastelini SM, Carvalho RH et al (2019) Computer vision system and near-infrared spectroscopy for identification and classification of chicken with wooden breast, and physicochemical and technological characterization. Infrared Phys Technol. https://doi.org/10.1016/j.infrared.2018.11.036
16. Awad TSS, Moharram HAA, Shaltout OEE et al (2012) Applications of ultrasound in analysis, processing and quality control of food: a review. Food Res Int 48:410–427. https://doi.org/10.1016/j.foodres.2012.05.004
17. Gallo M, Ferrara L, Naviglio D (2018) Application of ultrasound in food science and technology: a perspective. Foods. https://doi.org/10.3390/foods7100164
18. González-Mohino A, Jiménez A, Rufo M et al (2021) Correlation analysis between acoustic and sensory technique data for cooked pork loin samples. LWT 141:110882
19. González-Mohino A, Jiménez A, Rufo M et al (2019) Changes of ultrasonic parameters as a tool to determine the influence of cooking in pork loin samples. Acta Acust united with Acust 105:943–952
20. González-Mohino A, Jiménez A, Rufo M et al (2022) Ultrasound parameters used to characterize Iberian fresh pork loins of different feeding systems. J Food Eng 314:110795. https://doi.org/10.1016/j.jfoodeng.2021.110795

21. Corona Jimenez E, García-Pérez JV, Ventanas Canillas S, Benedito Fort JJ (2013) Ultrasonic characterization of the fat source and composition of formulated dry-cured meat products. Food Sci Technol Int 20:275–285. https://doi.org/10.1177/1082013213482915
22. Corona E, Garcia-Perez JV, Gomez Alvarez-Arenas TE et al (2013) Advances in the ultrasound characterization of dry-cured meat products. J Food Eng 119:464–470. https://doi.org/10.1016/j.jfoodeng.2013.06.023
23. de Prados M, Garcia-Perez JV, Benedito J (2017) Non-invasive ultrasonic technology for continuous monitoring of pork loin and ham dry salting. Meat Sci 128:8–14. https://doi.org/10.1016/j.meatsci.2017.01.009
24. Garcia-Perez JV, de Prados M, Martinez G et al (2019) Ultrasonic online monitoring of the ham salting process. Methods for signal analysis: time of flight calculation. J Food Eng 263:87–95. https://doi.org/10.1016/j.jfoodeng.2019.05.032
25. González-Mohino A, Jiménez A, Paniagua MJ et al (2019) New contributions of ultrasound inspection to the characterization of different varieties of honey. Ultrasonics. https://doi.org/10.1016/j.ultras.2019.02.010
26. Jiménez A, Rufo M, Paniagua JM et al (2017) Contributions to ultrasound monitoring of the process of milk curdling. Ultrasonics 76:192–199. https://doi.org/10.1016/j.ultras.2017.01.007
27. Crespo A, Martín A, Ruiz-Moyano S et al (2020) Application of ultrasound for quality control of Torta del Casar cheese ripening. J Dairy Sci. https://doi.org/10.3168/jds.2020-18160
28. Crespo A, Jiménez A, Ruiz-Moyano S et al (2022) Low-frequency ultrasound as a tool for quality control of soft-bodied raw ewe's milk cheeses. Food Control 131:108405. https://doi.org/10.1016/j.foodcont.2021.108405
29. AOAC (2000) Association of Official Analytical Chemists. Official methods of analysis the of AOAC International. Washington (USA)
30. Folch J, Lees M, Sloane Stanley GH (1957) A simple method for the Isolation and purification of total lipides from animal tissues; a rapid method of total lipid extraction and purification. Can J Biochem Physiol 226:497–509
31. CIE (1986) Commission Internacionale de l'Eclairage. In: Colorimetry 2nd Edition. Publ. 15.2. Cie, Vienna
32. Perez-Palacios T, Caballero D, González-Mohíno A et al (2019) Near infrared reflectance spectroscopy to analyse texture related characteristics of sous vide pork loin. J Food Eng 263:417–423. https://doi.org/10.1016/j.jfoodeng.2019.07.028
33. González-Mohino A, Antequera T, Ventanas S et al (2018) Near-infrared spectroscopy-based analysis to study sensory parameters on pork loins as affected by cooking methods and conditions. J Sci Food Agric. https://doi.org/10.1002/jsfa.8944
34. González-Mohino A, Pérez-Palacios T, Antequera T et al (2020) Monitoring the processing of dry fermented sausages with a portable NIRS device. Foods. https://doi.org/10.3390/foods9091294
35. Cerrillo C, Jiménez A, Rufo M et al (2014) New contributions to granite characterization by ultrasonic testing. Ultrasonics 54:156–167. https://doi.org/10.1016/j.ultras.2013.06.006
36. Cooley JW, Tukey JW (1965) An algorithm for the machine calculation of complex fourier series. Math Comput. https://doi.org/10.1090/S0025-5718-1965-0178586-1
37. Ventanas S, Ventanas J, Ruiz J et al (2005) Iberian pigs for the development of high-quality cured products. Recent Res Dev Agric food Chem 6:27–53
38. Ledward DA (1971) Metmyoglobin formation in beef muscles as influenced by water content and anatomical location. J Food Sci 36:138–140
39. Contador R, Ortiz A, del Rosario RM et al (2021) Physico-chemical and sensory qualities of Iberian sliced dry-cured loins from various commercial categories and the effects of the type of packaging and refrigeration time. Lwt 141:110876
40. Rosario DKA, Furtado MR, Mutz YS et al (2020) A Chemometric approach to establish underlying connections between lipid and protein oxidation and instrumental color and texture characteristics in Brazilian dry-cured loin. Foods 9:536
41. Ortiz A, Tejerina D, Contador R et al (2021) Quality traits of dry-cured loins from Iberian pigs reared in montanera system as affected by pre-freezing cure. Foods 10:48
42. Lorido L, Pizarro E, Estévez M, Ventanas S (2019) Emotional responses to the consumption of dry-cured hams by Spanish consumers: a temporal approach. Meat Sci 149:126–133
43. Lorido L, Hort J, Estévez M, Ventanas S (2016) Reporting the sensory properties of dry-cured ham using a new language: time intensity (TI) and temporal dominance of sensations (TDS). Meat Sci 121:166–174. https://doi.org/10.1016/j.meatsci.2016.06.009
44. Caballero D, Rodríguez PG, Caro A et al (2022) An experimental protocol to determine quality parameters of dry-cured loins using low-field magnetic resonance imaging. J Food Eng 313:110750. https://doi.org/10.1016/j.jfoodeng.2021.110750
45. Pateiro M, Franco D, Carril JA, Lorenzo JM (2015) Changes on physico-chemical properties, lipid oxidation and volatile compounds during the manufacture of celta dry-cured loin. J Food Sci Technol 52:4808–4818. https://doi.org/10.1007/s13197-014-1561-x
46. Ruiz-Ramírez J, Serra X, Arnau J, Gou P (2005) Profiles of water content, water activity and texture in crusted dry-cured loin and in non-crusted dry-cured loin. Meat Sci 69:519–525. https://doi.org/10.1016/j.meatsci.2004.09.007
47. Belloch C, Neef A, Salafia C et al (2021) Microbiota and volatilome of dry-cured pork loins manufactured with paprika and reduced concentration of nitrite and nitrate. Food Res Int 149:110691. https://doi.org/10.1016/j.foodres.2021.110691
48. Kim H, Chin KB (2022) Physicochemical properties of reduced-salt cured pork loin as affected by different freezing temperature and storage periods. Anim Biosci 35:494–502. https://doi.org/10.5713/ab.21.0320
49. González-Mohino A, Ventanas S, Estévez M, Olegario LS (2021) Sensory characterization of Iberian dry-cured loins by using check-all-that-apply (CATA) analysis and multiple-intake temporal dominance of sensations (TDS). Foods 10:1983
50. Kinsler LE, Frey AR, Coppens AB, Sanders JV (1999) Fundamentals of acoustics. John wiley & sons, USA
51. Contreras M, Benedito J, Quiles A et al (2020) Assessing the textural defect of pastiness in dry-cured pork ham using chemical, microstructural, textural and ultrasonic analyses. J Food Eng. https://doi.org/10.1016/j.jfoodeng.2019.109690
52. Fariñas L, Contreras M, Sanchez-Jimenez V et al (2021) Use of air-coupled ultrasound for the non-invasive characterization of the textural properties of pork burger patties. J Food Eng 297:110481. https://doi.org/10.1016/j.jfoodeng.2021.110481