Journal of Food Engineering

Ultrasound parameters used to characterize Iberian fresh pork loins of different feeding systems

--Manuscript Draft--

Manuscript Number:	JFOODENG-D-21-00749R2
Article Type:	Research Article
Keywords:	Ultrasound inspection; Pearson correlation; commercial pork loin; physicochemical analysis; instrumental texture.
Corresponding Author:	Alberto González-Mohino Cáceres, SPAIN
First Author:	Alberto González-Mohino, Dr.
Order of Authors:	Alberto González-Mohino, Dr.
	Antonio Jiménez Barco
	Montaña Rufo
	Jesus M. Paniagua
	Teresa Antequera
	Trinidad Perez-Palacios
Abstract:	<p class="LO-Normal" style="text-align:justify;text-justify:inter-ideograph; line-height:200%">The objective of this work was to characterize different commercial categories of pork loin non-destructively by inspection using low-intensity ultrasound at different frequencies. To this end, such ultrasound parameters as the ultrasound pulse velocity (UPV) and variables related to the attenuation and to the frequency components obtained from the fast Fourier transform (FFT) were considered. The acoustic parameters and those obtained using traditional instrumental analyses (physicochemical and texture) were subjected to a Pearson correlation analysis. Several ultrasound parameters allowed the two categories explored to be distinguished. Also, the acoustic determinations yielded many significant correlations with the rest of the parameters studied. The results show that ultrasound can be postulated as an instrument for characterizing and distinguishing samples of different categories of loin, and that it has a promising predictive character.<o:p></o:p></p>

08/22/2021

Dear Editor Ferruh Erdogdu,

Thank you for appreciating the opportunity to resubmit our work for publication. Please find attached the file 'Detailed Response to Reviewers'. We hope the present version is suitable for publication in *Journal of Food Engineering*.

Yours sincerely,

Alberto González-Mohino Jiménez

PhD Food Science
Department of Food Technology, Meat and Meat Products Research Institute, University of Extremadura. Av. de la Universidad s/n, 10003, Cáceres, Spain.
E-mail: albertogj@unex.es
Tel.: +34 927 25 10 44

Reviewer #3

I recommend accept the manuscript.

- Thank you so much for your decision. We are pleased that our responses were satisfactory.

Reviewer #4

This is an interesting but not strikingly novel, well written short study.

However, a total of 8 loins, 4 of each type, is not enough for any degree of statistical confidence for a paper to be published in a recognised Peer Reviewed Journal. I find the authors explanation regarding problems with the cost of experimental material hard to believe.

Whole pork tenderloins at my local retail outlet cost under 6 euro per loin. So under 50 euro for materials. I would expert the authors to have good contacts with pork abattoirs and local suppliers and obtain the meat at wholesale cost or even free.

10 times the current number of samples would give a reasonable distribution to base confidence limits on and cost under 500 euro.

- Firstly, thank you for your response. Considering previous Peer-Reviewed papers about ultrasound inspection in meat products (de Prados et al. 2015 DOI - https://doi.org/10.1016/j.jfoodeng.2014.12.024; Fariñas et al. 2021 DOI - https://doi.org/10.1016/j.jfoodeng.2021.110481; Niñoles et al. 2011 DOI - https://doi.org/10.1016/j.meatsci.2011.04.014; González-Mohino et al. 2019 DOI - https://doi.org/10.3813/aaa.919375), and in other food matrices (Crespo et al. 2022 DOI - https://doi.org/10.1016/j.foodcont.2021.108405; González-Mohino et al. 2021 DOI - https://doi.org/10.1016/j.lwt.2021.110882; González-Mohino et al. 2019 DOI - https://doi.org/10.1016/j.ultras.2019.02.010), the sample size is enough for a robust statistical analysis. Regarding the price of the Iberian pork loin, our comment about the cost was only a note not a justification, our apologies for the misunderstanding. We have based on these previous works to determine the sample size required; thus, we have considered this sample size for the present study. Likewise, we would like to give more information about the costs of the raw material used. The prices of these kinds of products can vary between regions. The purchased samples were close to 40 cm in length, where each piece loin of ‘Cebo de Campo Ibérico’ (CCI) cost 20€, while those of ‘Bellota 50% Ibérico’ (BI) the cost was 31.70€. Likewise, prior to the final ultrasound inspection measurements, the set-up was carried out with one pork loin of each type. Therefore, the total cost was 258.50€, considering only the raw material. The funding obtained came from a regional project of the Junta de Extremadura with reference IB16089. In addition, thank you for your suggestion, we are always looking for new ways and contacts with the meat industry to reduce research costs, and we will consider it in further works.

Highlights

- Different commercial categories of fresh pork loins were evaluated.
- Physicochemical, textural, and ultrasound inspection analyses were considered.
- Various ultrasound parameters have the capacity to distinguish among samples.
- Acoustic parameters were significantly correlated with several determinations.
- Ultrasound is postulated as being a feasible tool for the prediction of physicochemical parameters.

Ultrasound parameters used to characterize Iberian fresh pork loins of different feeding systems

Alberto González-Mohino[a], Antonio Jiménez[b], Montaña Rufo[b], Jesús M. Paniagua[b], Teresa Antequera[a], Trinidad Perez-Palacios[a]

[a] Department of Food Technology, Research Institute of Meat and Meat Products, University of Extremadura, Avda de la Universidad s/n, 10003 Cáceres, Spain

[b] Department of Applied Physics, School of Technology, Research Institute of Meat and Meat Product, University of Extremadura, Avda de la Universidad s/n, 10003 Cáceres, Spain

*Corresponding author: Alberto González-Mohino (albertogj@unex.es). Tel. +34 927251044. IPROCAR, Avda Ciencia s/n, 10003 Cáceres, Spain.

Abstract

The objective of this work was to characterize different commercial categories of pork loin non-destructively by inspection using low-intensity ultrasound at different frequencies. To this end, such ultrasound parameters as the ultrasound pulse velocity (UPV) and variables related to the attenuation and to the frequency components obtained from the fast Fourier transform (FFT) were considered. The acoustic parameters and those obtained using traditional instrumental analyses (physicochemical and texture) were subjected to a Pearson correlation analysis. Several ultrasound parameters allowed the two categories explored to be distinguished. Also, the acoustic determinations yielded many significant correlations with the rest of the parameters studied. The results show that ultrasound can be postulated as an instrument for characterizing and distinguishing samples of different categories of loin, and that it has a promising predictive character.

Keywords: Ultrasound inspection; Pearson correlation; commercial pork loin; physicochemical analysis; instrumental texture.

1. Introduction

Most of the traditional analytical methods used to characterize meat products alter the meat itself (Xiong et al., 2017). For this reason, in recent years non-destructive methods have been explored that would allow the quality parameters of meat and meat derivatives to be assessed reliably with the ultimate goal being to put them forward as alternatives and/or complements to traditional methods. Examples are near infrared spectroscopy (NIRS) (Cáceres-Nevado et al., 2021; González-Mohino et al., 2018; Pérez-Palacios et al., 2019), hyperspectral imaging (HSI) (Antequera et al., 2021; Barbin et al., 2013; Pu et al., 2014), and computer vision techniques applied to magnetic resonance imaging (MRI) (Ávila et al., 2019; Caballero et al., 2016; Pérez-Palacios et al., 2017). Among the different non-destructive methods, low-intensity ultrasound inspection has been postulated as effective, fast, and cheaper than most modern instrumental techniques (Gallo et al., 2018). Non-destructive ultrasound inspection has proven reliability for pork products, using the wave propagation speed as a fundamental parameter for the prediction of the quality parameters of meat and meat derivatives. The technique's viability has been verified for raw meat mixtures (Benedito et al., 2001), 'sobrasada' (Llull et al., 2002), and hams (Corona Jimenez et al., 2013). Isolated components of meat products such as the fat and fatty acids have also been characterized using ultrasound (Niñoles et al., 2007), and even to predict the salt content (de Prados et al., 2015). Apart from the speed of propagation, another parameter that some studies have considered is attenuation, which has been applied to studying textural properties in hamburgers (Fariñas et al., 2021) and to determining pastiness in ham (Contreras et al., 2020).

Although the calculation of speed and attenuation in the traditional way has been a very efficient method for various works, other information that can be provided by the propagation of ultrasound in the medium has been left unused. The frequency components related to the fast Fourier transform (FFT) and diverse variables related to the attenuation (which are calculated when no echoes are visible in the A-scans obtained in the non-destructive ultrasound inspections) are parameters that have not as yet been considered for the assessment of the quality of meat and meat derivatives. These parameters have, however, been found essential to monitor the curdling process in milk (Jiménez et al., 2017), to characterize dry-cured products (Corona et al., 2013), to control the quality of cheese maturation (Crespo et al., 2020), to distinguish between different varieties of honey (González-Mohino et al., 2019a), and to study the influence of cooking on pork loins (González-Mohino et al., 2019b).

Pork is regarded as one of the most important meats in the world because of both the volume of its consumption and consumer preferences (García-Gudiño et al., 2021). The best valued pork products in Spain are those deriving from the Iberian pig. Specifically, consumers consider Iberian pork hams and loins to be high quality products, mainly because of their exceptional sensorial attributes which depend on the characteristics of the raw material and processing conditions (Ventanas et al., 2007).

Spanish legislation (BOE, 2014) considers different commercial categories of Iberian pork loins based on the genetics and the feeding system. These categories are identified with different coloured labels: 'white label' (at least 50% Iberian breed, fed on concentrates), 'green label' (at least 50% Iberian, fed on natural resources and concentrates), 'red label' (at least 50% Iberian breed, fed exclusively on natural resources), and 'black label' (100% pure Iberian breed, fed exclusively on natural resources). These categories attain different prices on the market. For this reason, a reliable classification system is necessary to discriminate between them. Until now, there have been no studies characterizing each type of product for rapid, reliable, and non-destructive classification.

For this study, on the one hand, physicochemical and instrumental texture analyses were carried out, and on the other, non-destructive ultrasound inspection was performed in which the propagation speed, frequency parameters related to the fast Fourier transform (FFT), and parameters related to the attenuation of the sound waves were determined. It should be emphasized that this work presents for the first time a study designed to characterize and classify categories of Iberian loin based on acoustic parameters.

The main objective of the study was to characterize two commercial categories of fresh pork loins by applying new ultrasound parameters for inspection, specifically, the propagation speed, frequency parameters related to the fast Fourier transform (FFT), and parameters related to the attenuation of the sound waves.

2. Material and Methods

2.1. Samples and experimental design

Two different commercial category pork loins were chosen to carry out the study: 'Cebo de Campo Ibérico' (CCI), derived from 50% Iberian × Duroc cross-bred pigs reared extensively, feeding on natural resources and concentrate, and 'Bellota 50% Ibérico' (BI), derived from 50% Iberian × Duroc cross-bred pigs reared extensively, feeding exclusively on natural resources. Both pork loin categories were purchased from Montesano Extremadura S.A. (Badajoz, Spain).

Four pieces of pork loin were acquired for each batch and were divided into two parts for the subsequent analyses – one part was used for physicochemical and instrumental texture analyses and the other for ultrasound inspection. Thus, sixteen parts corresponding to eight pork loins (four for CCI, and four for BI) were obtained. Figure 1 is a diagram showing the procedure.

The ultrasound tests on each piece were carried out in three orthogonal directions at two inspection frequencies (Figure 2). The different groups of parameters calculated were subjected to a correlation study (acoustic vs destructive methods) as a step prior to studying the feasibility of ultrasound inspection as a predictive tool for physicochemical and textural parameters.

2.2. Physicochemical analyses and instrumental texture

Water activity (a_W) was determined by a water activity measuring instrument (Lab Master-aw, NOVASINA AG, Lachen, Switzerland). Instrumental colour of the pork loins was measured using a Minolta CR-300 colorimeter (Konica Minolta, Osaka, Japan) that was calibrated with a standard white calibration tile. The analysis was carried out according to the principles set out by the Commission International d'Éclairage (CIE) (Billmeyer and Saltzman, 1981). Lightness (L*), redness (a*), and yellowness (b*) were the colour coordinates determined. Moisture content was measured by drying the samples (5 g) at 102°C following the procedure of the official methods of the Association of Official Agricultural Chemists (AOAC International reference method 935.29) (AOAC, 2000). Finally, the fat content was determined according to the method described by Folch et al. (1957) with chloroform:methanol (2:1). All physicochemical determinations were done in triplicate.

Instrumental texture was determined using a TA.XT plus texture analyser (Stable Micro Systems Ltd., Surrey, UK). A texture profile analysis (TPA) was carried out, using for this method a cylindrical probe 5 cm in diameter. For each batch and for each sample, five cubes (1 cm^3) were obtained and analysed. They were axially compressed to 50% of the original height. The parameters calculated were: hardness (g), adhesiveness (g·s), springiness (g), gumminess (g), cohesiveness (dimensionless), chewiness (g), and resilience (J·m−3).

2.3. Ultrasound inspection

2.3.1. Inspection

The ultrasound inspection instruments and procedures basically coincide with those described in previous work (Cerrillo et al., 2014; Collell et al., 2012; Crespo et al., 2020; González-Mohino et al., 2019b, 2019a) with some modifications. For this reason, here we shall limit ourselves to describing them briefly, emphasizing those aspects which are most interesting and/or novel.

The pork loin samples were tested using contact ultrasound techniques in through-transmission (TT) mode. Figure 3 shows the set-up used for the measurements. Two different pairs of transducers were used: Panametrics V318-SU and A114-S, with nominal frequencies of 0.5 MHz and 1 MHz, respectively. The intention with this was to check whether or not the inspection frequency affects the calculated ultrasound parameters. The main characteristics of these two pairs of transducers are listed in Table 1. In addition, the transducers were excited at their resonance frequency with a pulse repetition frequency (PRF) of 100 Hz, and a voltage of 200 V peak-peak.

As mentioned above, in the case of the V318-SU pair, the inspection was carried out on each piece in three orthogonal directions, while for the A114 pair it was carried out only in one direction (Figure 2). The reason for this lies in the models' different values of the near field N (Table 1). In particular, the value of N for the A114-S pair is 5.92 cm. Given that this value is similar to, and in some cases greater than, the distance travelled by the ultrasound waves in the inspections carried out in directions 2 and 3, and taking into account that the ultrasound parameters obtained in inspections at distances shorter than N may be erroneous since they are subject to interference phenomena, we decided not to carry them out with the A114S pair in the aforementioned directions. There is no such problem when using the V318-SU transducers, so these were used to inspect the samples in all three orthogonal directions.

A Panametrics-NDT Model 5077PR pulser-receiver was used for the loin characterizations. This pulser-receiver was connected to an InfiniiVision DSO-X 3032A (KEYSIGHT) oscilloscope. Finally, a coupling gel (Olympus) of fluid consistency was applied to the pork loin surfaces to facilitate the transmission of the waves between them and the transducers. This gel is a non-toxic water-soluble organic substance which is easy to apply and to remove. Ultrasound measurements were carried out inside a temperature-controlled chamber (RIVACOLD RC325-45ED, Italy), maintaining a constant temperature of 7.0±0.2ºC.

2.3.2. Parameters

Once all the equipment and instruments were in place, different ultrasound parameters were obtained from the received signal (A-scan). By way of example, Figure 4 shows a representative

A-scan obtained with the V318 transducers. The ultrasound pulse velocity (UPV) calculation is based on the time lapsed from the signal's emission until its reception (time of flight – TOF). Since the distance is known for each inspection, it is possible to determine the UPV.

The frequency parameters are related to the fast Fourier transform (FFT) of the received ultrasound signals. Figure 5 displays the FFT of the signals received in the inspection shown in Figure 4. As can be seen in the figure, the frequency distributions are not at all close to Gaussian, so that the largest amplitude of the FFT is not a priori a meaningful value with which to characterize the inspected samples. This fact is characteristic for the power spectrum of RF signals (Mamou and Oelze, 2013). Hence, in order to facilitate the subsequent correlation analysis, the frequencies corresponding to the 50th and 99th percentiles of the received signals in the cumulative frequency periodograms of the FFT (FFT50, and FFT99, respectively) were calculated, i.e., if the cumulative frequency corresponding to the 50th percentile is at f Hz for a specific inspection, this means that 50% of the received signals had a frequency of less than f Hz.

Finally, a series of parameters related to ultrasound attenuation were also calculated. These parameters are obtained from the inspection of samples whose A-scan lacks clearly visible reflections or echoes, as is the case of these loin samples (see Figure 4). Then, given that the nature of pork loins makes it impossible to distinguish echoes, the attenuation was determined from the signal's progressive energy loss. In this way, one obtains the mean value of the parameters related to the attenuation as a function of time taken to receive certain energy percentages – specifically, 30%, 50%, and 70% (AT30, AT50, and AT70, respectively), expressed as multiples of TOF ($n \cdot$TOF).

2.4. Data analysis

Significant differences between the CCI and BI samples were studied. The normality of the physicochemical, TPA, and ultrasound parameters were evaluated with the Shapiro-Wilk test. The results of these normality tests were significant ($p < 0.05$), and therefore the data were analysed by an ANOVA using the IBM SPSS v.22 (IBM Co., New York, U.S.A) statistics software package.

The physicochemical, TPA, and ultrasound data were subjected to a principal component analysis (PCA) and a linear correlation analysis based on the Pearson correlation coefficient (*R*) using the XLSTAT software package (Addinsoft Pearson Edition 2014, Addinsoft, Paris, France).

3. Results and Discussion

3.1. Physicochemical and texture analysis

Table 2 lists the physicochemical data determined for CCI and BI. There were differences in a_W, in the colour parameters L* and b*, and in fat content between the two pork loin categories. Based on the labelling, it can be seen that the fat content is an important parameter to discriminate between the categories. This is also the case for lightness (L*) and water activity (a_W), with higher values in the CCI loins. On the contrary, yellowness (b*) presented higher mean values in BI. Although there have been numerous works focused on assessing how different Iberian pig feeding regimes influence the chemical composition and sensory characteristics of ham (Cava et al., 2000; Pérez-Palacios et al., 2011), there has been no previous study analysing loins from batches established as in this study corresponding to the commercial categories established in the Iberian quality standard (BOE, 2014). The significant differences in these physicochemical parameters did not translate into differences in the texture of the products (Table 2) with the TPA parameters showing no differences between CCI and BI samples. As mentioned above, there have been no studies with the new commercial classification legislation. Also, comparisons of pig loins from different rearing regimes are not usually approached from an instrumental rather than a sensorial perspective (Jonsäll et al., 2002; Karpiesiuk et al., 2019). Figure 6 shows a factor score plot of the PCA of the physicochemical and TPA data. The first two principal components accounted for 69.35% of the total variance (38.26% for F1, and 31.09% for F2). These parameters did not achieve a homogeneous distribution that would allow discrimination of the loins in accordance with their commercial category.

3.2. Ultrasound parameters

Table 3 lists the results of the ultrasound inspection of the CCI and BI pieces with the V318 transducer pair. The UPV values for both sample groups are quite similar to those determined in other studies in the literature, with variations motivated by the different measurement conditions (temperature, muscle, inspection thickness, inspection frequency). Measurements made in muscles such as the biceps femoris (de Prados et al., 2015) determined the speed at approximately 1534 ± 4 m/s, while with other measurement conditions and sample types (Niñoles et al., 2011) the speeds determined ranged between 1580 and 1590 m/s, both studies using 1 MHz transducers. De Prados et al. (2015) estimated the UPV in pork loin at 1557 ± 6 m/s, again with a 1 MHz transducer. As mentioned above, these variations in ultrasound speeds in pork muscle are due to the measurement conditions, as can be observed in the study of ultrasound parameters in cooked pork loins (González-Mohino et al., 2019b) which established the UPV at 1582 ± 8 m/s for fresh pork loin using a 100 kHz transducer. With respect to the present results for the parameters related to frequency components and attenuation, they are not comparable with other studies because these parameters were not usually considered or, when they were, the transducers and inspection geometries were of different characteristics (González-Mohino et al., 2019b), preventing comparison with the present results.

We must also highlight the results for FFT50 and FFT99 (Table 3) in that their values in direction 1 are significantly lower than those in directions 2 and 3. The explanation for this must be sought in the greater thickness of the direction 1 measurements compared to those in directions 2 and 3. A greater thickness entails a greater transit length of the ultrasound waves through the sample, and therefore greater attenuation, which is especially intense at high frequencies. For this reason, the frequency components of the measurements made with greater thicknesses are lower. In this same sense, the values of AT30, AT50, and AT70 are significantly greater in direction 1 than in the other two directions. Given that the attenuation parameters are reported as a function of the TOF, this result would indicate that, although the ultrasound waves are attenuated more in direction 1 for the aforementioned reasons of traveling through a greater thickness, the rate of attenuation in directions 2 and 3 is greater than that of direction 1. This result is consistent with the fact that the muscle fibres are oriented longitudinally (Kim et al., 2018), which means that the ultrasound waves have to pass through fewer fibres per unit length than when they do so in directions 2 or 3. Since the signal must be attenuated when passing from one fibre to another, the attenuation per unit length in directions 2 and 3 has to be greater than that in direction 1. Most ultrasound parameters did not differ between the product categories. But, of the different measurement directions tested, the UPV of direction 1 was indeed able to distinguish the samples, with greater mean values for CCI than for BI. This may be due to the differences in their lipid content. The behaviour of the ultrasound propagation speed with the fat content is antagonistic in the sense that, as noted by Koch et al. (2011), the speed of propagation declines with increasing fat content of porcine soft tissues. Benedito et al. (2001), however, found that a product with more adipose tissue presented higher ultrasound speeds, although this was when the measurement temperature was low so that the fat remained in a solid state. This is indicative of the major influence of temperature on the measurement. In this present study, the measurement temperature was 7°C, and therefore the pork fat at this temperature was in a solid state, so that the results can be compared with those of the aforecited workers. In any case, even though the temperature-dependent state of the fat is an influencing factor, the ultrasound parameters, and in particular UPV, are influenced by the feeding regime (Niñoles et al., 2007, 2011). Finally, and generally, the attenuation parameters determined using V318 transducers showed no differences between the pork loins.

Figure 7a shows the PCA score plot for the V318 ultrasound parameter results. The first two principal components accounted for 57.69% of the total variance (33.35% for F1, and 24.34% for

F2). The PCA exploratory study of the data distributes the BI samples mostly in the upper quadrants and the CCI in the lower quadrants, following a behaviour to be expected given the significant results obtained.

Table 4 presents the ultrasound parameters obtained in the ultrasound inspection of the CCI and BI samples using the A114 transducer pair. The velocity values are similar to those obtained with the V318 transducer pair. Also, as expected, the FFT50 and FFT99 frequency components are clearly greater than those obtained with the V318 pair simply because the nominal resonance frequency of the A114 (1 MHz) is higher than that of the V318 (0.5 MHz). And the values of AT30, AT50, and AT70 measured with the A114 transducers are lower than the corresponding V318 values, which is logical in the sense that higher values of these attenuation parameters are indicative of a lower attenuation of the ultrasound waves (Crespo et al., 2020). This must obviously be the case with the waves emitted by the lower frequency transducer which, in the present study, is precisely the V318.

As was the case with the speeds calculated for the V318 transducer, the mean values were consistent and similar to those reported in other studies for fresh muscles (de Prados et al., 2015; González-Mohino et al., 2019b), whereas, for the reasons mentioned above, there are no comparable results in the literature for the frequency components and attenuation.

The UPV and attenuation presented significant differences among samples, while the frequency parameters related to FFT did not. Again, the mean UPV values were significantly greater for CCI than BI pork loins, probably due to the influence of the fat content (Benedito et al., 2001) as was indicated above for the V318s. With regard to the attenuation parameters, each of them showed differences between the two commercial categories, with greater mean values for the BI than the CCI loins. This would indicate that the BIs attenuate the ultrasound waves less than the CCIs, at least in direction 1. This effect was masked in the inspection carried out with the V318 transducers due to their lower emission frequency. Thus, the higher frequencies (in the present case those emitted by the A114) have a shorter wavelength (see Supplementary Material 2), which is why they are more sensitive to the detection of discontinuities or alterations in the medium. These alterations could well have gone unnoticed with the V318, but are now detected with the A114. In light of the data given in Tables 3 and 4, the lipid content is the most important factor differentiating the two categories, being clearly greater in the CCIs. Therefore, the presence of more infiltrated fat in this type of sample attenuates the ultrasound signal more than BI, with its lower fat content. This result is consistent with that reported by Fariñas et al. (2021) for samples of pork burgers, where a greater amount of fat lowers the attenuation values, with this parameter understood as energy loss.

Figure 7b shows the PCA factor score plot of the A114 ultrasound parameter results. The first two principal components accounted for 89.30% of the total variance (75.43% for F1, and 13.87% for F2). The differences between the variances of the V318 and A114 transducers are probably influenced by the number of variables considered. According to the significance results, the PCA showed that the parameters calculated from the A114 transducer measurements discriminate the two commercial categories, with the CCI samples being in the left-hand quadrants and the BI samples in the right-hand quadrants. In addition, samples of the same commercial category were located quite close to each other.

3.3. Correlation study

Table 5 lists the Pearson linear correlation coefficients (R) between the ultrasound parameters determined with the V318 transducers and the physicochemical and TPA results. There were several (positive and negative) significant correlations among the determinations studied.

Particularly interesting are the significant negative correlations between the fat content and the attenuations in direction 2. As mentioned above, this is due to the increased attenuation of the ultrasound waves as the amount of fat increases. Unfortunately, these results are not comparable because attenuation is usually calculated as energy loss.

Significant negative correlation coefficients were obtained between cohesiveness and the attenuations in direction 3. Since the cohesiveness corresponds to elastic deformation of the loin sample, this result would indicate that the samples which experience the greatest deformation are those with the lowest AT30, AT50, and AT70 attenuation coefficients, i.e., those that most attenuate the ultrasound signal. This result coincides with the well-known behaviour that attenuation experiences with the elasticity of a solid medium, in the sense that the more elastic samples (those that suffer less deformation under the same stress) are less attenuating to sound waves (Kinsler et al., 1999).

Additionally, there are other notable relationships between parameters, an example being a_W which is positively correlated with UPV_1 and negatively with $FFT50_2$. Hence, if a pork loin has a high a_W, this implies a greater speed and the passage of lower frequency components during the propagation of the wave through the medium. It is difficult to establish any parallel between a_W and a mechanical explanation for it. Nonetheless, the significant negative correlation of moisture with $FFT99_3$ also seems to reflect the less favourable nature of the presence of water in the sample in letting high frequency waves pass.

With respect to the physicochemical parameters related to colour, only b* presented significant correlations with $AT70_3$. Again, the lack of any mechanical meaning for the parameter b* makes it difficult to find an explanation for or against such a correlation.

Table 6 lists the Pearson linear correlation coefficients (R) between the ultrasound parameters determined with the A114 transducers and the physicochemical and TPA results. In this case, there are the same significant negative correlations that were found between fat content and AT30, AT50, and AT70. Furthermore, fat correlates positively with the speed of propagation and the frequency components of the sound waves, significantly in all cases. With respect to the correlation with the speed, this was entirely expected based on the aforementioned results obtained with the V318 and A114 transducers to differentiate the two commercial categories of the study. Regarding the positive correlations with FFT50 and FFT99, this would indicate a greater presence of high frequency components in the samples with higher fat contents. Given that we had already concluded that the presence of fat favours the attenuation of the waves, this result now shows that the said attenuation, although existing at any frequency, is proportionally lower for higher frequencies. The negative and significant correlation of moisture with FFT99 is also repeated, and this time also with FFT50. These results would again point to the fact that the presence of moisture in the sample does not favour the passage of high frequency waves.

With respect to the colour parameters, L* presented inverse correlations with all the attenuation determinations. In the case of a_W, significant correlations with AT50 were also observed. Although this is the only statistically significant case of correlation between a_W and any attenuation parameter, it is necessary to note that the negative character of the correlation exists for both transducers and for the measurement directions considered. This result would be consistent with that obtained by Lewicky et al. (2004), since the samples with higher aw would be more attenuating (lower ATxx values), which is logical due to these samples are more tender and thus less crisp or brittle.

Lastly, the fact mentioned above that samples undergoing less deformation under the same stress are less attenuating to the sound waves is now reflected in the positive correlations between springiness and the attenuation parameters, especially significant in the case of AT30. In fact, and as expected, there is a positive and significant correlation (R = 0.7803) between the springiness and the cohesiveness of the samples.

As a final discussion, and as mentioned above, most ultrasound inspection research on food has focused exclusively on the determination of the speed, without exploring other parameters related to the frequency components of the FFT, or the attenuation calculated without the observation of echoes, which have proven their reliability as discriminating elements both in the current study and in other scientific contributions. Not performing these types of calculations could be considered to be a loss of information that might be decisive for various studies.

4. Conclusions

In view of the acoustic parameter results, one may conclude that ultrasound determinations have the capacity to characterize these two commercial categories of pork loin, being sensitive to the differences in composition of the two groups of samples. The A114 1000 kHz contact transducers were those which demonstrated the better sensitivity in the inspection of the samples in their single measurement direction, showing more significant differences between CCI and BI as well as several significant correlations of the acoustic parameters with physicochemical and instrumental texture parameters. As expected, the moisture and fat contents were the main determinants differentiating the two categories, resulting in physical and chemical changes that were detected by the various acoustic parameters calculated. Further analyses, such as constructing predictive models, could improve the understanding of the relationships among these parameters. The correlation study shed light on that possibility, in several cases finding statistically significant high correlation coefficients.

Finally, this study shows the feasibility of using ultrasound measurements to differentiate categories of Iberian pork loins, postulating this non-destructive technology as a sensitive and rapid technique to characterize Iberian meat products. This technology could be applied in the production lines, characterizing and monitoring samples and processes, as other technologies (NIRS) have tried. This work has presented new contributions of ultrasound inspection for Iberian meat products that may be of interest to the meat industry, either to assess quality rapidly, efficiently, and non-destructively by detecting the properties that conform the product, or to avoid possible cases of marketing fraud.

Acknowledgements

The authors of the present work gratefully acknowledge the support of the European Regional Development's funds (FEDER) and the Junta de Extremadura to the research group FQM010 trough the aid reference GR18089. Likewise, Alberto González-Mohino acknowledges the Universidad de Extremadura and Banco Santander for the funding of 'Accion III Contratos Puente Para Doctores' of the 'Plan Propio de Iniciación a la Investigación, Desarrollo Tecnológico e Innovación'.

References

Antequera, T., Caballero, D., Grassi, S., Uttaro, B., Perez-Palacios, T., 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/https://doi.org/10.1016/j.meatsci.2020.108340

AOAC, 2000. Association of Official Analytical Chemists. Official methods of analysis the of AOAC International. Washington (USA).

Ávila, M.M., Durán, M.L., Caballero, D., Antequera, T., Palacios-Pérez, T., Cernadas, E., Fernández-Delgado, M., 2019. Magnetic Resonance Imaging, texture analysis and regression techniques to non-destructively predict the quality characteristics of meat pieces. Eng. Appl. Artif. Intell. 82, 110–125.

Barbin, D.F., ElMasry, G., Sun, D.-W., Allen, P., 2013. Non-destructive determination of chemical composition in intact and minced pork using near-infrared hyperspectral imaging. Food Chem. 138, 1162–1171.

Benedito, J., Carcel, J.A., Rossello, C., Mulet, A., 2001. Composition assessment of raw meat mixtures using ultrasonics. Meat Sci. 57, 365–370. https://doi.org/10.1016/S0309-1740(00)00113-3

Billmeyer, F.W., Saltzman, M., 1981. Principles of color technology, 2nd ed. New York (USA).

BOE, 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.

Caballero, D., Antequera, T., Caro, A., Ávila, M. del M., G Rodríguez, P., Perez-Palacios, T., 2016. Non-destructive analysis of sensory traits of dry-cured loins by MRI-computer vision techniques and data mining. J. Sci. Food Agric. https://doi.org/10.1002/jsfa.8132

Cáceres-Nevado, J.M., Garrido-Varo, A., De Pedro-Sanz, E., Tejerina-Barrado, D., Pérez-Marín, D.C., 2021. Non-destructive Near Infrared Spectroscopy for the labelling of frozen Iberian pork loins. Meat Sci. 175, 108440.

Cava, R., Ventanas, J., Ruiz, J., Andrés, A.I., Antequera, T., 2000. Sensory characteristics of Iberian ham: influence of rearing system and muscle location. Food Sci. Technol. Int. 6, 235–242.

Cerrillo, C., Jiménez, A., Rufo, M., Paniagua, J., Pachón, F.T., 2014. New contributions to granite characterization by ultrasonic testing. Ultrasonics 54, 156–167. https://doi.org/10.1016/j.ultras.2013.06.006

Collell, C., Gou, P., Arnau, J., Muñoz, I., Comaposada, J., 2012. NIR technology for on-line determination of superficial aw and moisture content during the drying process of fermented sausages. Food Chem. 135, 1750–1755. https://doi.org/https://doi.org/10.1016/j.foodchem.2012.06.036

Contreras, M., Benedito, J., Quiles, A., Lorenzo, J.M., Fulladosa, E., Gou, P., Garcia-Perez, J.V., 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

Corona, E., Garcia-Perez, J. V., Gomez Alvarez-Arenas, T.E., Watson, N., Povey, M.J.W., Benedito, J., 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

Corona Jimenez, E., García-Pérez, J.V., Ventanas Canillas, S., Benedito Fort, J.J., 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

Crespo, A., Martín, A., Ruiz-Moyano, S., Benito, M.J., Rufo, M., Paniagua, J.M., Jiménez, A., 2020. Application of ultrasound for quality control of Torta del Casar cheese ripening. J. Dairy Sci. https://doi.org/10.3168/jds.2020-18160

de Prados, M., García-Pérez, J. V., Benedito, J., 2015. Non-destructive salt content prediction in brined pork meat using ultrasound technology. J. Food Eng. 154, 39–48. https://doi.org/10.1016/j.jfoodeng.2014.12.024

Fariñas, L., Contreras, M., Sanchez-Jimenez, V., Benedito, J., Garcia-Perez, J. V, 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/https://doi.org/10.1016/j.jfoodeng.2021.110481

Folch, J., Lees, M., Sloane Stanley, G.H., 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.

Gallo, M., Ferrara, L., Naviglio, D., 2018. Application of ultrasound in food science and technology: A perspective. Foods 7. https://doi.org/10.3390/foods7100164

García-Gudiño, J., Blanco-Penedo, I., Gispert, M., Brun, A., Perea, J., Font-i-Furnols, M., 2021. Understanding consumers' perceptions towards Iberian pig production and animal welfare. Meat Sci. 172, 108317. https://doi.org/https://doi.org/10.1016/j.meatsci.2020.108317

González-Mohino, A., Antequera, T., Ventanas, S., Caballero, D., Mir-Bel, J., Pérez-Palacios, T., 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

González-Mohino, A., Jiménez, A., Paniagua, M.J., Perez-Palacios, T., Rufo, M., 2019a. New contributions of ultrasound inspection to the characterization of different varieties of honey. Ultrasonics. https://doi.org/10.1016/j.ultras.2019.02.010

González-Mohino, A., Jiménez, A., Rufo, M., Paniagua, J.M., Nas, S.V., Olegario, L.S., 2019b. 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.

Jiménez, A., Rufo, M., Paniagua, J.M., Crespo, A.T., Guerrero, M.P., Riballo, M.J., 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

Jonsäll, A., Johansson, L., Lundström, K., Andersson, K.H., Nilsen, A.N., Risvik, E., 2002. Effects of genotype and rearing system on sensory characteristics and preference for pork (M. Longissimus dorsi). Food Qual. Prefer. 13, 73–80. https://doi.org/https://doi.org/10.1016/S0950-3293(01)00060-X

Karpiesiuk, K., Kozera, W., Bugnacka, D., Penkowski, A., Falkowski, J., Wozniakowska, A., Jarocka, B., 2019. The effect of a feeding and rearing system on the physicochemical properties of pork. J. Elem. 24.

Kim, G.D., Overholt, M.F., Lowell, J.E., Harsh, B.N., Klehm, B.J., Dilger, A.C., Boler, D.D., 2018. Evaluation of muscle fiber characteristics based on muscle fiber volume in porcine longissimus muscle in relation to pork quality. Meat Muscle Biol. 2.

Kinsler, L.E., Frey, A.R., Coppens, A.B., Sanders, J. V, 1999. Fundamentals of acoustics. John Wiley & Sons.

Koch, T., Lakshmanan, S., Brand, S., Wicke, M., Raum, K., Mörlein, D., 2011. Ultrasound velocity and attenuation of porcine soft tissues with respect to structure and composition: I. Muscle. Meat Sci. 88, 51–58. https://doi.org/10.1016/j.meatsci.2010.12.002

Lewicki, P.P., Jakubczyk, E., Marzec, A., Cabral, M.C., Pereira, P.M., 2004. Effect of water activity on mechanical properties of dry cereal products. Acta Agrophysica 4, 381–391.

Llull, P., Simal, S., Femenia, A., Benedito, J., Rosselló, C., 2002. The use of ultrasound velocity measurement to evaluate the textural properties of sobrassada from Mallorca. J. Food Eng. 52, 323–330. https://doi.org/10.1016/S0260-8774(01)00122-4

Mamou, J., Oelze, M.L., 2013. Quantitative ultrasound in soft tissues. Springer, New York (USA). doi:10.1007/978-94-007-6952-6.

Niñoles, L., Clemente, G., Ventanas, S., Benedito, J., 2007. Quality assessment of Iberian pigs through backfat ultrasound characterization and fatty acid composition. Meat Sci. 76, 102–111. https://doi.org/10.1016/j.meatsci.2006.10.018

Niñoles, L., Mulet, A., Ventanas, S., Benedito, J., 2011. Ultrasonic characterisation of B. femoris from Iberian pigs of different genetics and feeding systems. Meat Sci. 89, 174–180. https://doi.org/10.1016/j.meatsci.2011.04.014

Pérez-Palacios, T., Antequera, T., Durán, M.L., Caro, A., Rodríguez, P.G., Palacios, R., 2011. MRI-based analysis of feeding background effect on fresh Iberian ham. Food Chem. 126, 1366–1372. https://doi.org/10.1016/j.foodchem.2010.11.101

Pérez-Palacios, T., Caballero, D., Antequera, T., Durán, M.L., Ávila, M., Caro, A., 2017. Optimization of MRI acquisition and texture analysis to predict physico-chemical parameters of loins by data mining. Food Bioprocess Technol. 1–9. https://doi.org/10.1007/s11947-016-1853-4

Perez-Palacios, T., Caballero, D., González-Mohíno, A., Mir-Bel, J., Antequera, T., 2019. Near Infrared Reflectance spectroscopy to analyse texture related characteristics of sous vide pork loin. J. Food Eng. 263. https://doi.org/10.1016/j.jfoodeng.2019.07.028

Pu, H., Sun, D.-W., Ma, J., Liu, D., Kamruzzaman, M., 2014. Hierarchical variable selection for predicting chemical constituents in lamb meats using hyperspectral imaging. J. Food Eng. 143, 44–52.

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

Xiong, Z., Sun, D.-W., Pu, H., Gao, W., Dai, Q., 2017. Applications of emerging imaging techniques for meat quality and safety detection and evaluation: A review. Crit. Rev. Food Sci. Nutr. 57, 755–768.

Figure Legends

Figure 1. Scheme of the procedure and data analysis.

UPV = ultrasound pulse velocity; FFT_{50}/FFT_{99} = the 50th and 99th percentiles of the fast Fourier transform; AT_{30}/AT_{50}/AT_{70} = attenuation corresponding to receiving 30%, 50%, and 70% of the energy.

==============

Figure 2. Directions of the three orthogonal axes along which the samples were inspected with the V318-SU and the A114S transducer pairs, and the corresponding thicknesses of measurement (d).

==============

Figure 3. Set-up for the ultrasound measurements (1 = oscilloscope; 2 = pulse-receiver; 3 = custom-designed metal structure; 4 = transmitter transducer; 5 = pork loin sample; 6 = receiver transducer).

==============

Figure 4. A-scan sobtained with the Panametrics V318 transducers for BI (a), and CCI (b) pork loin with direction 1.

==============

Figure 5. FFT of the A-Scan from Fig. 4a (a), and Fig.4b (b).

==============

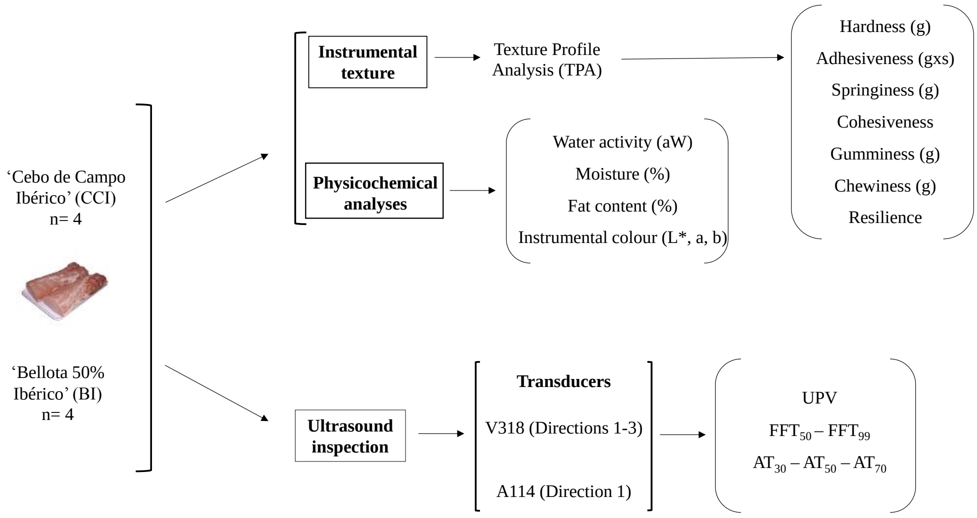
Figure 6. PCA factor score plots of physicochemical and TPA results for two different commercial category pork loins. CCI= Cebo de Campo Ibérico (green label); BI= Bellota 50% Ibérico (red label).

==============

Figure 7. PCA factor score plots for the V318 transducer (a) and A114 transducer (b) parameter results for two different commercial category pork loins. CCI= Cebo de Campo Ibérico (green label); BI= Bellota 50% Ibérico (red label).

==============

Figure 1. Scheme of the procedure and data analysis



UPV= ultrasound pulse velocity, FFT_{50}/ FFT_{99}= Fast Fourier Transform corresponding to the 50th and 99th percentiles, AT_{30}/ AT_{50}/ AT_{70} = attenuation corresponding to reaching 30%, 50%, and 70%, of the energy.

Figure 2. Directions of the three orthogonal axes along which the samples were inspected with the V318-SU and the A114S transducer pairs, and the corresponding thicknesses of measurement (d)

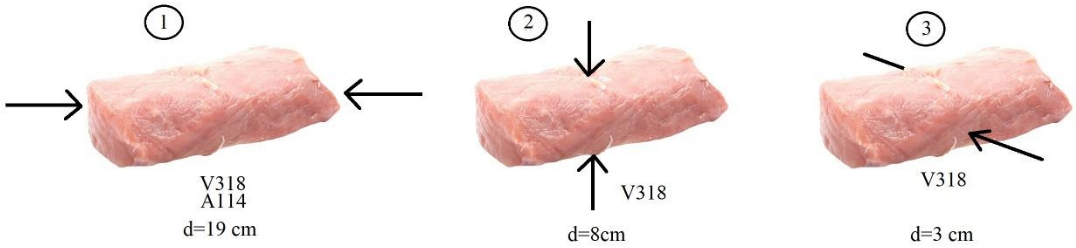


Figure 3. Set-up for the experimental ultrasonic measurements (1= Oscilloscope, 2= Pulse-receiver, 3= Custom-design metal structure, 4= Transmitter transducer, 5= Pork loin sample, 6= Receiver transducer)

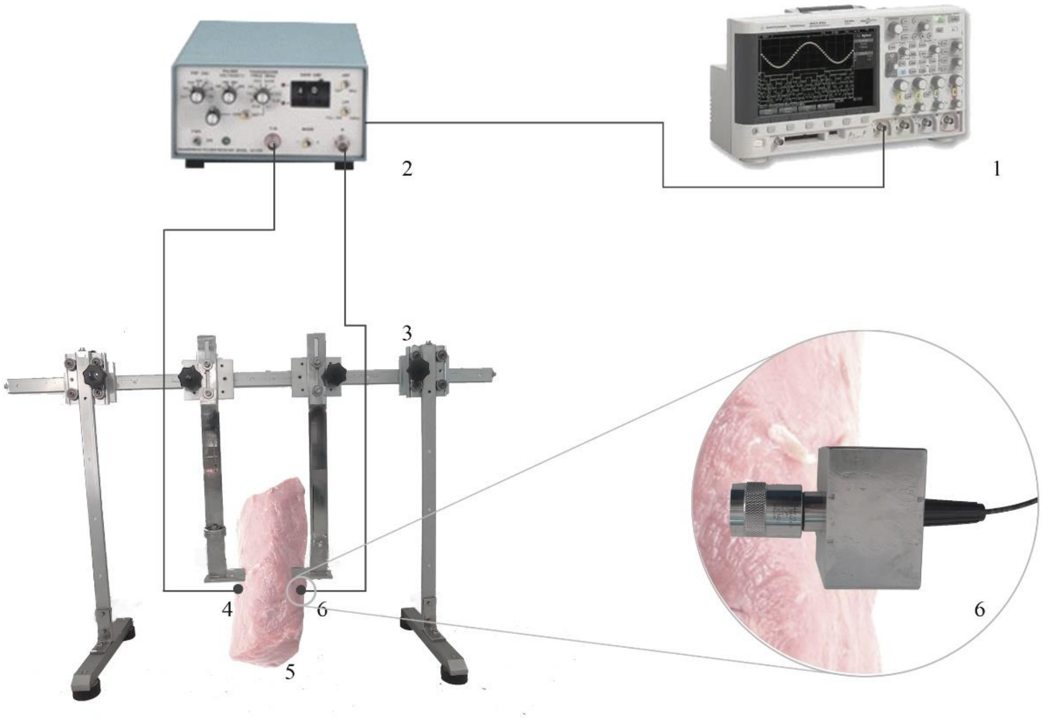
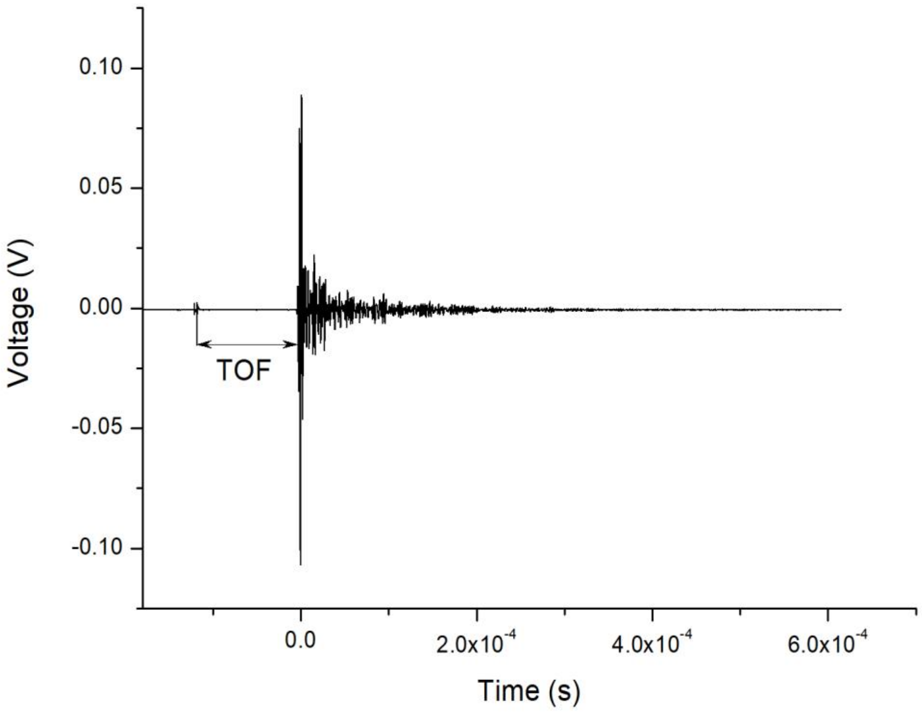


Figure 4: A-scan sobtained with the Panametrics V318 transducers for BI (a), and CCI (b) pork loin with direction 1.

a)



b)

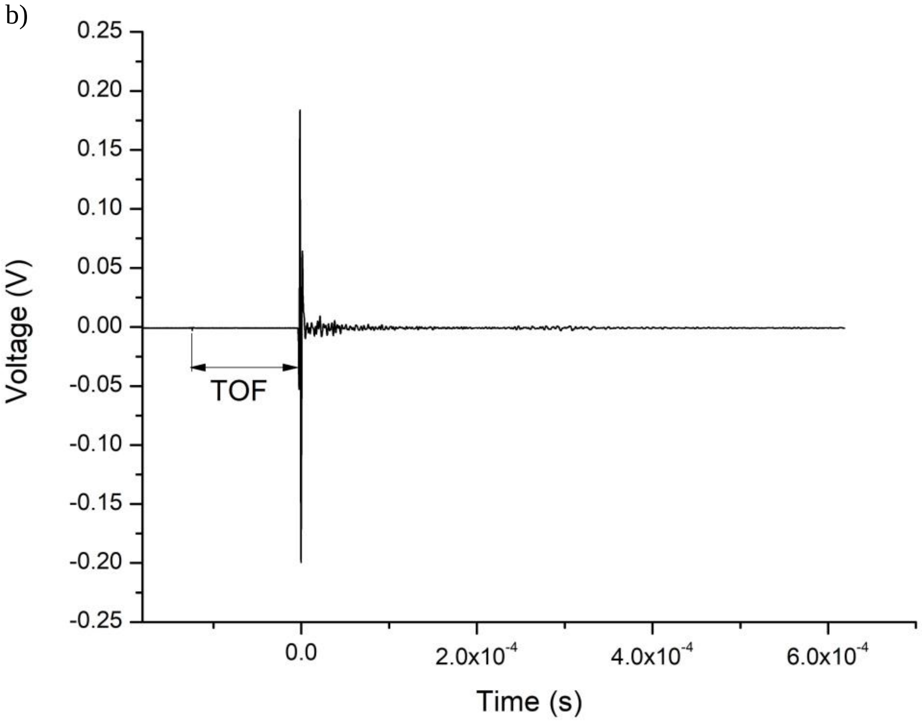
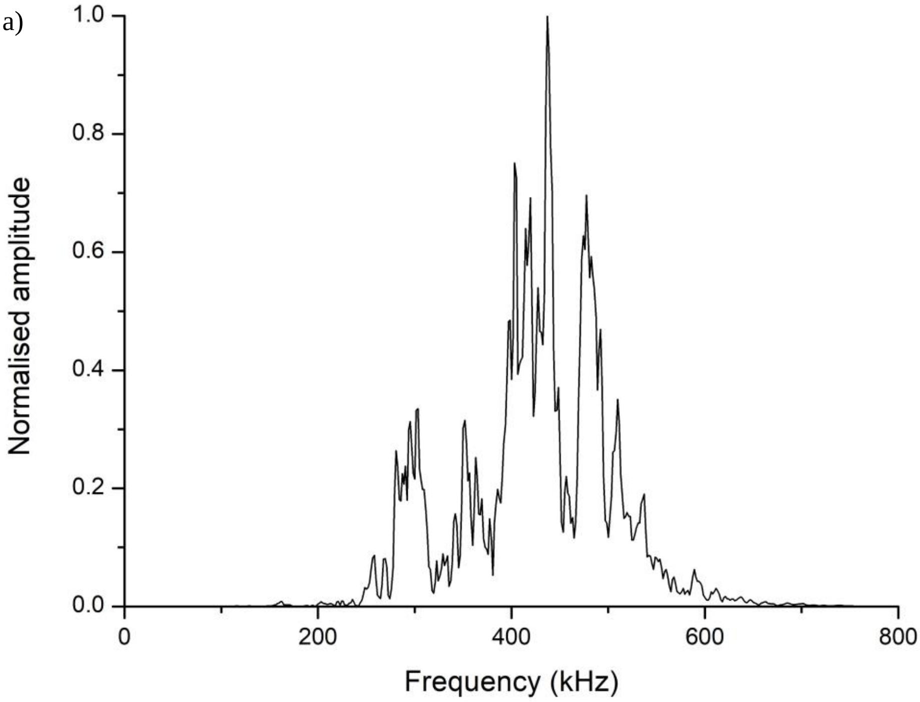


Figure 5. FFT of the A-Scan from Fig. 4a (a), and Fig.4b (b).

a)



b)

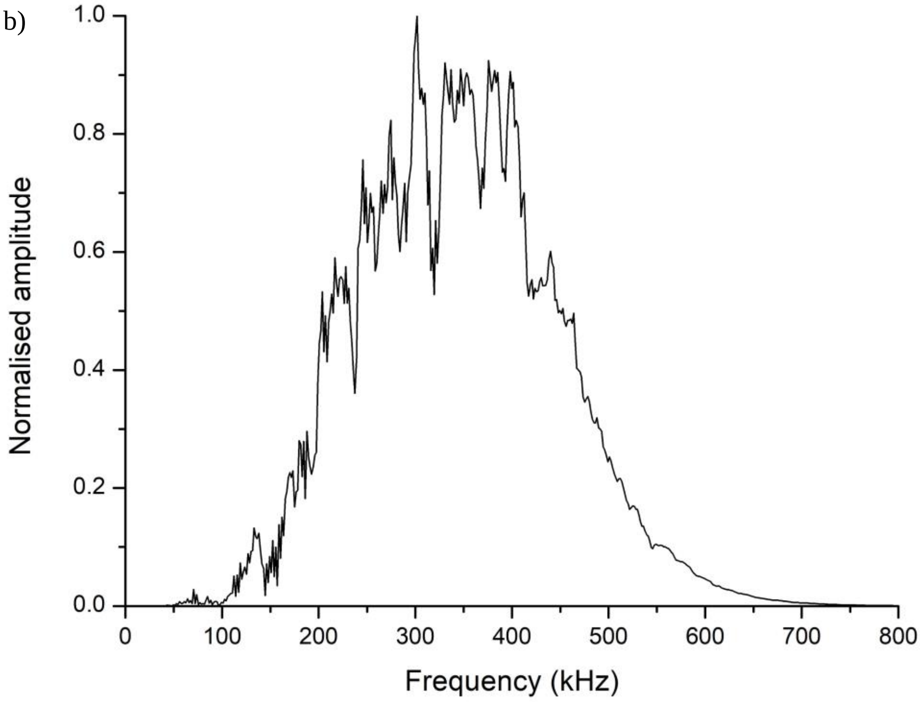


Figure 6. PCA with factor score plots of physicochemical and TPA results, for different commercial category pork loins. CCI= Cebo de Campo Ibérico (green label), BI= Bellota 50% Ibérico (red label).

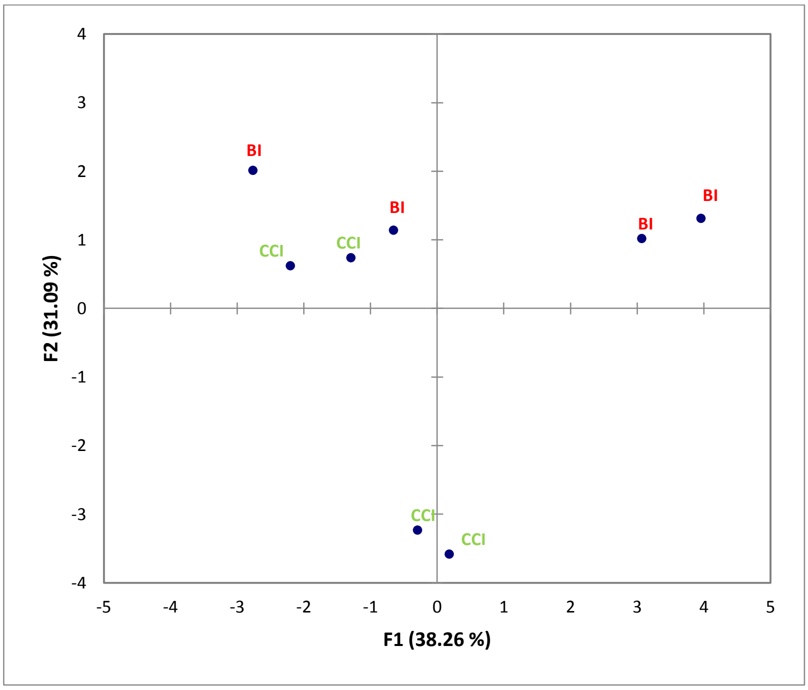


Figure 7. PCA with factor score plots from V318 transducers (a) and A114 transducers (b) parameters results for different commercial category pork loins. CCI= Cebo de Campo Ibérico (green label), BI= Bellota 50% Ibérico (red label).

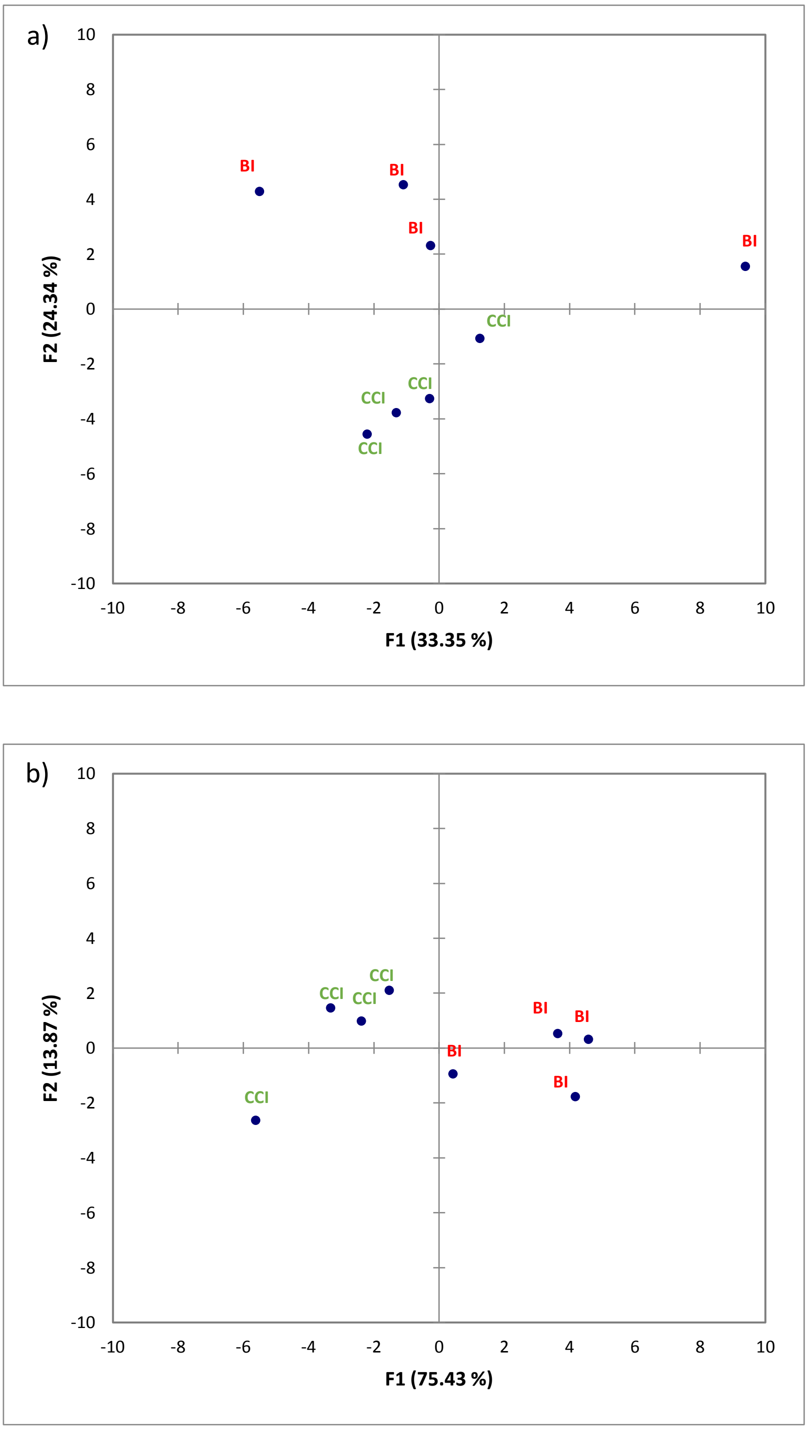


Table 1. Characteristics of the transducer models used.

Model	Diameter (cm)	Frequency (kHz)	Wavelength (mm)	-6 dB bandwidth (%)	N (cm)	φ (°)	Waveform duration (μs)		
							14dB	20 dB	40 dB
Panametrics V318-SU	1.9	500	3.0	61.93	2.96	11.29	3.680	4.888	16.600
Panametrics A114S	1.9	1000	1.5	64.59	5.92	5.62	2.540	2.900	6.079

UPV=1525 m/s was taken for the calculation of wavelength, N, and φ
N= near-field length
φ= beam angle
The bandwidth and waveform direction values were obtained according to the following conditions:
Damping: 500 ohms; Attn: 36 dB; Gain: 40 dB

1

Table 2. Physicochemical and TPA results (mean ± SD), and *p*-values obtained in the statistical analysis comparing the two pork loin categories.

	CCI	BI	*p*
a_W	0.981 ± 0.003	0.977 ± 0.004	0.03
L*	48.41 ± 1.57	45.18 ± 2.24	0.00
a*	9.41 ± 1.56	10.55 ± 1.80	0.06
b*	3.09 ± 1.06	4.27 ± 0.98	0.01
Moisture (%)	67.94 ± 5.17	69.23 ± 2.17	0.44
Lipids g/100 (%)	8.27 ± 1.62	6.08 ± 1.73	0.00
Hardness (g)	1934 ± 771	1612 ± 744	0.19
Adhesiveness (g·s)	-68.70 ± 49.50	-66.48 ± 33.48	0.70
Springiness (g)	0.37 ± 0.08	0.44 ± 0.18	0.55
Cohesiveness	0.37 ± 0.03	0.38 ± 0.07	0.48
Gumminess (g)	723 ± 330	620 ± 349	0.21
Chewiness (g)	274 ± 137	287 ± 205	0.81
Resilience ($J \cdot m^{-3}$)	0.17 ± 0.05	0.18 ± 0.05	0.35

CCI = Cebo de Campo Ibérico; BI= Bellota 50% Ibérico.
a_W= water activity, L*= lightness, a*= redness, b*= yellowness.

Table 3. Ultrasound parameters determined with the V318 transducers (mean values ± SD), and *p*-values obtained in the statistical analysis comparing the two pork loin categories.

V318	CCI	BI	p
UPV_1	1550 ± 12	1491 ± 33	0.02
UPV_2	1546 ± 9	1552 ± 15	0.52
UPV_3	1532 ± 28	1563 ± 8	0.08
$FFT50_1$	403 262 ± 37 820	387 968 ± 39 561	0.60
$FFT99_1$	626 708 ± 11906	636 239 ± 69 140	0.79
$FFT50_2$	427 110 ± 31496	466 763 ± 18 093	0.07
$FFT99_2$	734 458 ± 42054	738 087 ± 32 649	0.90
$FFT50_3$	451 277 ± 10829	451 765 ± 16035	0.96
$FFT99_3$	726 754 ± 10407	750 773 ± 39513	0.28
$AT30_1$	1.092 ± 0.091	1.278 ± 0.211	0.33
$AT50_1$	1.209 ± 0.224	1.409 ± 0.305	0.33
$AT70_1$	1.306 ± 0.316	1.583 ± 0.411	0.48
$AT30_2$	1.043 ± 0.003	1.121 ± 0.100	0.15
$AT50_2$	1.052 ± 0.004	1.193 ± 0.185	0.25
$AT70_2$	1.061 ± 0.002	1.322 ± 0.325	0.07
$AT30_3$	1.104 ± 0.004	1.099 ± 0.018	0.70
$AT50_3$	1.116 ± 0.005	1.113 ± 0.015	0.69
$AT70_3$	1.138 ± 0.003	1.135 ± 0.013	0.76

CCI= Cebo de Campo Ibérico; BI= Bellota 50% Ibérico.

UPV= ultrasound pulse velocity (m/s); FFT50/ FFT99= fast Fourier transform corresponding to the 50th and 99th percentiles; AT30/ AT50/ AT70 = attenuation corresponding to reaching 30%, 50%, and 70% of the energy.

Subscript numbers refer to the directions of the measurements.

3

Table 4. Ultrasound parameters determined with the A114 transducers (mean values ± SD), and *p*-values obtained in the statistical analysis comparing the two pork loin categories.

	CCI	BI	*p*
UPV	1542 ± 11	1513 ± 13	0.01
FFT50	789 362 ± 53 435	728 805 ± 29 234	0.09
FFT99	1 072 887 ± 67 217	1 022 223 ± 42 581	0.25
AT30	1.019 ± 0.005	1.063 ± 0.028	0.02
AT50	1.023 ± 0.005	1.142 ± 0.026	0.02
AT70	1.027 ± 0.004	1.253 ± 0.068	0.02

CCI= Cebo de Campo Ibérico; BI= Bellota 50% Ibérico.

UPV= ultrasound pulse velocity (m/s); FFT50/ FFT99= fast Fourier transform corresponding to the 50th and 99th percentiles; AT30/ AT50/ AT70 = attenuation corresponding to reaching 30%, 50%, and 70% of the energy.

Table 5. Linear correlation coefficients between the V318 transducer ultrasound parameters (UPV= ultrasound pulse velocity; FFT50/ FFT99= fast Fourier transform corresponding to the 50th and 99th percentiles of the received signal; AT30/ AT50/ AT70 = attenuation corresponding to reaching 30%, 50%, and 70% of the energy) and the physicochemical and TPA parameters. Subindices (1, 2, or 3) mean the measurement direction. Boldface numbers mean significant correlations.

	Physicochemical parameters						TPA parameters						
	aw	L*	a*	b*	Moisture	Lipid content	Hardness	Adhesiveness	Springiness	Cohesiveness	Gumminess	Chewiness	Resilience
UPV$_1$	**0.7245**	0.6407	-0.5286	-0.4045	0.0869	0.2974	0.3703	0.0026	-0.3282	0.0752	0.4312	0.1700	0.0093
UPV$_2$	-0.2666	-0.2093	0.1340	0.2673	0.5350	-0.6795	-0.4611	-0.3832	0.2168	0.3491	-0.2670	-0.0559	-0.0386
UPV$_3$	-0.3516	-0.5388	0.6156	0.6121	-0.4226	-0.2227	-0.2518	0.5585	-0.0037	-0.0409	-0.2497	-0.1691	0.1760
FFT50$_1$	0.6239	0.1147	-0.3510	-0.1014	0.1081	-0.1193	0.1634	0.6518	-0.5369	-0.0019	0.2380	-0.0643	0.1393
FFT99$_1$	0.0124	-0.0183	0.0492	0.2011	0.2200	-0.4006	-0.5913	0.0157	-0.2881	0.0328	-0.4454	-0.4525	-0.2523
FFT50$_2$	**-0.7497**	-0.2773	0.4580	0.2796	0.1818	-0.3320	-0.7013	-0.3516	0.2626	0.0070	-0.6473	-0.3473	-0.2639
FFT99$_2$	-0.3333	0.0487	0.6234	0.4419	**-0.8419**	0.4713	-0.1986	-0.0828	0.1294	-0.1565	-0.2917	-0.1861	-0.1147
FFT50$_3$	-0.1067	-0.2743	-0.4009	-0.5567	0.5328	-0.2950	-0.2111	-0.2539	-0.1830	-0.3195	-0.2100	-0.1606	-0.4441
FFT99$_3$	-0.3283	-0.5590	-0.0765	-0.2847	0.1404	-0.2462	-0.5124	0.1680	-0.3881	-0.6125	-0.5917	-0.5642	-0.5592
AT30$_1$	-0.6685	-0.5753	0.1920	-0.1454	0.0060	-0.1335	-0.5313	-0.1684	-0.0230	-0.5305	-0.6449	-0.4438	-0.5337
AT50$_1$	-0.6305	-0.4098	0.0847	-0.2921	0.0961	-0.0519	-0.4832	-0.3551	0.0165	-0.5040	-0.5886	-0.3815	-0.5837
AT70$_1$	-0.3734	0.0467	0.1906	0.1571	0.1770	-0.0698	-0.2620	-0.1878	0.2585	0.1335	-0.2619	-0.1341	0.0132
AT30$_2$	-0.4844	-0.6657	0.3302	0.3065	0.3844	**-0.7457**	-0.1515	-0.1695	0.4287	0.3136	-0.0043	0.3100	0.2020
AT50$_2$	-0.4740	-0.6496	0.3138	0.2909	0.4027	**-0.7478**	-0.1617	-0.1689	0.4124	0.3108	-0.0107	0.2977	0.1907
AT70$_2$	-0.4794	-0.6651	0.3214	0.3013	0.3929	**-0.7568**	-0.1989	-0.1456	0.3826	0.2870	-0.0496	0.2535	0.1674
AT30$_3$	-0.0627	-0.1248	-0.1747	-0.5554	-0.4782	0.5455	-0.1234	-0.0140	-0.4578	**-0.8780**	-0.3528	-0.4384	-0.7020
AT50$_3$	-0.1202	-0.1039	-0.0439	-0.4043	-0.6131	0.6083	-0.1688	0.0275	-0.4170	**-0.8562**	-0.4166	-0.4962	-0.6602
AT70$_3$	-0.0255	-0.2058	-0.3817	**-0.7395**	-0.1169	0.3410	-0.0184	0.0119	-0.4321	**-0.8068**	-0.2175	-0.3059	-0.6214

Table 6. Linear correlation coefficients between the A114 transducer ultrasound parameters (UPV= ultrasound pulse velocity; FFT50/ FFT99= fast Fourier transform corresponding to the 50th and 99th percentiles of the received signal; AT30/ AT50/ AT70 = attenuation corresponding to reaching 30%, 50%, and 70% of the energy) and the physicochemical and TPA parameters. Subindices (1, 2, or 3) mean the measurement direction. Boldface numbers mean significant correlations.

	Physicochemical parameters						TPA parameters						
	aw	L*	a*	b*	Moisture	Lipid content	Hardness	Adhesiveness	Springiness	Cohesiveness	Gumminess	Chewiness	Resilience
UPV	0.4963	0.6752	-0.2981	-0.4652	-0.5331	**0.8902**	0.4254	-0.0007	-0.3146	-0.3133	0.3006	0.0562	-0.1797
FFT50	0.0967	0.5136	0.1368	-0.1414	**-0.7617**	**0.7924**	-0.0679	-0.2873	-0.2220	-0.3696	-0.1506	-0.2050	-0.4452
FFT99	0.0761	0.4079	0.2351	-0.0429	**-0.8661**	**0.8046**	0.0522	-0.0162	-0.2054	-0.3544	-0.0523	-0.1281	-0.2694
AT30	-0.6757	**-0.8061**	0.4851	0.4835	0.4141	**-0.8192**	-0.0207	-0.1851	**0.7415**	0.4927	0.1029	0.5094	0.4571
AT50	**-0.7390**	**-0.8749**	0.5262	0.5080	0.3103	**-0.8121**	-0.4025	0.0211	0.4193	0.2021	-0.3147	0.0257	0.1678
AT70	-0.6710	**-0.7835**	0.5378	0.5911	0.3469	**-0.8597**	-0.4405	0.0410	0.4016	0.3068	-0.3090	0.0125	0.2178

AUTHOR STATEMENT

Authors declare the following:

Alberto González-Mohino: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing.

Antonio Jiménez: Conceptualization, Methodology, Validation, Formal analysis Resources, Data Curation, Investigation, Writing - Original Draft, Writing - Review & Editing, Supervision, Resources, Funding acquisition.

Montaña Rufo: Conceptualization, Formal analysis, Methodology, Data Curation, Writing - Original Draft, Writing - Review & Editing, Validation, Resources, Funding acquisition, Supervision.

Jesús M. Paniagua: Conceptualization, Validation, Data Curation, Writing - Review & Editing, Resources, Funding acquisition.

Terese Antequera: Conceptualization, Methodology, Validation, Writing - Review & Editing, Supervision, Resources, Funding acquisition.

Trinidad Perez-Palacios: Conceptualization, Methodology, Validation, Writing - Review & Editing, Supervision, Resources, Funding acquisition.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: