Application of non-invasive technologies in dry-cured ham: An overview

Cristina Pérez-Santaescolástica^a, Ilse Fraeye^b, Francisco J. Barba^c,
Belen Gómez^a, Igor Tomasevic^d, Alberto Romero^e, Andrés Moreno^f, Fidel
Toldrá^g and Jose M. Lorenzo^{a*}

^a Centro Tecnológico de la Carne de Galicia, rúa Galicia nº 4, Parque Tecnológico
de Galicia, San Cibrao das Viñas, 32900 Ourense

^b KU Leuven Technology Campus Ghent, Leuven Food Science and Nutrition
Research Centre (LForCe), Research Group for Technology and Quality of Animal
Products, Gebroeders De Smetstraat 1, BE-9000 Gent, Belgium

^c Nutrition and Food Science Area, Preventive Medicine and Public Health, Food
Sciences, Toxicology and Forensic Medicine Department, Faculty of Pharmacy,
Universitat de València, Avda. Vicent Andrés Estellés, s/n, 46100 Burjassot, València,
Spain

^d Department of Animal Source Food Technology, University of Belgrade, Faculty
of Agriculture, Nemanjina 6, 11080 Belgrade, Serbia

^e Departamento de Ingeniería Química, Universidad de Sevilla, Facultad de Física,
Sevilla, 41012, Spain

^f University of Castilla-La Mancha, Faculty of Chemical Sciences and Technologies
(San Alberto Magno Building), Department of Organic Chemistry, Av. Camilo José Cela,
10, Ciudad Real, 13071, Spain

^g Instituto de Agroquímica y Tecnología de Alimentos (CSIC), Avenue Agustín
Escardino 7, 46980 Paterna (Valencia), Spain

*Corresponding author:

Email address: jmlorenzo@ceteca.net. Tel: +34 988548277

Abstract

Background: Dry-cured ham is one of the most valued food products by Mediterranean consumers. In this sense, the appropriate development of its different production stages is essential to ensure the quality requirements. For this reason, non-invasive technologies have gained popularity and have been reported as useful not only to ensure the food safety of different products, but also to monitor fundamental stages in the production process, such as the salting stage, to analyze the content of different compounds without sample losses, and to correct possible defects in the final product.

Scope and approach: This work has been focused on summarizing the studies that describe and have successfully applied these techniques, as well as on mentioning other technologies with potential use in dry-cured ham manufacture which have not been studied enough. Finally, the potential next steps to improve and optimize the process, as well as the suitability of creating new products with added value based on the new quality standards, have also been evaluated.

Key findings and conclusions: Innovative non-invasive technologies such as high pressure (HP), ultrasound (US), pulsed electric fields (PEF), microwaves, irradiation, etc. can be used as promising tools to effectively control salting and curing stages as well as for checking defects of the final product and/or ensuring food safety. HP and US are useful tools for the determination of salt and fat content, and for monitoring the salting process. Moreover, HP enhances salty taste perception, which makes it a useful tool to reduce salt addition. Both, HP and US, can correct texture defects. In addition, NIRS allows predicting the state of the meat to remove those pieces that could result in defective products. Moreover, RAMAN or MRI are able to detect anomalous textures at the end of the process. Microwaves could be useful for the online estimation of salt, water and fat contents easily with portable equipment. Finally, data mining, that allows to make

54 predictions based on an immense data file, is the most promising discovery in recent years
55 for detecting defects or classifying products according to sensory attributes.

56

57 **Keywords:** dry-cured ham, non-invasive technologies, high pressure, ultrasound,
58 infrared spectroscopy, magnetic resonance, pulse electric fields, time domain
59 reflectometry microwave, data mining, laser backscattering imaging

1. Introduction

Dry-cured ham is a highly consumed product around the world, whose organoleptic characteristics are strongly valued by consumers. Its production process consists of salting the entire back leg of the pig in order to stabilize the raw meat by reducing water availability, followed by a dry-curing process which includes post-salting, pre-drying and lengthy dry-ageing stages (Harkouss *et al.*, 2018). Throughout the process, many lipid and protein conversion reactions take place in the raw meat, giving rise to the particular flavour of dry-cured ham (**Fig. 1**). In this context, in order to get a tasty and safe product, a good control of all process stages is absolutely necessary. For example, manufacturing temperature greatly affects lipolysis reactions (Ripollés *et al.*, 2011), and salt content and water activity (a_w) play an important role in proteolysis reactions and microbial spoilage (Bermúdez *et al.*, 2014; Purriños *et al.*, 2013). In addition, salt is involved in textural functions, organoleptic characteristics and water holding capacity (WHC) (Taormina, 2010). The salting stage is one of the longest steps in dry-cured ham production, due to the high resistance of cell membranes to mass transfer (Janositz, 2011), extending the process time. While the use of salt is fundamental from a technological point of view, the high amount that is incorporated turns dry-cured ham into a high salt content product. It is well known that high salt intake is related with hypertension, stroke risk, different types of cancers and osteoporosis owing to a high level of calcium excretion (Karppanen and Mervaala, 2006). As a result, during the last years, new consumer requirements are being established, increasing the need to improve processing techniques and to create new products with added value based on the new quality standards.

Regarding lifestyle changes, one of the manufacturing strategies is the development of ready-to-eat (RTE) foods. In this regard, slices of dry-cured ham are commercialized in RTE-vacuum packages (Jin *et al.*, 2012). Despite the great ease for consumers, this

product format involves more handling, increasing the microbial contamination risks (Jin *et al.*, 2012; Sánchez Molinero *et al.*, 2010). Furthermore, since products with low sodium content are increasingly attractive to consumers and demanded for healthy reasons (Lorenzo *et al.*, 2015a, 2015b), many studies in dry-cured ham have focused on reduction of NaCl content and its substitution by other salts (Armenteros *et al.*, 2011). However, NaCl reduction implies a longer post-salting time to reduce water activity levels, assuring microbial stability (Harkouss *et al.*, 2018). On the other hand, evaluation of physicochemical characteristics along the entire process is mostly done through traditional methods. These methods are often lengthy, arduous and, above all, in many cases cause product losses (Pérez-Palacios *et al.*, 2014).

To solve the current drawbacks in dry-cured ham production, and to be able to optimize analytical procedures, non-invasive technologies have been the object of several studies. In this way, the monitoring and characterization of ham during the salting stage facilitate the salt reduction (Fulladosa *et al.*, 2015a). Likewise, a_w monitoring allows to assess the final product safety (Santos-Garcés *et al.*, 2010). Furthermore, non-invasive technologies such as near infrared or microwave spectroscopy can be used to determine textural characteristics of the product (Fulladosa *et al.*, 2018; Damez and Clerjon, 2013; Rubio-Celorio *et al.*, 2016; Ortiz *et al.*, 2006; García Rey *et al.*, 2005). The objective of the present work is to summarise and update on the use of non-invasive technologies, and their potential applications, in the processing of dry-cured ham.

2. New technologies

There are some non-destructive techniques that have been evaluated widely with regard to their implementation in the dry-cured ham manufacture, while very little research has been performed on others. The techniques that are discussed in this work are

summarised in **Table 1** along with their respective working principles, current subtypes and the main potential applications.

2.1. Irradiation technologies

Irradiation technologies commonly refer to ionising radiation in food processing and are based on attenuation variations which are caused by radiation passing through different materials influenced by energy (Farkas, 2006).

Even though high efficacy on microorganism control was shown (Kong *et al.*, 2017; Jin *et al.*, 2012), consumers associate irradiated products with quality reductions (Lee *et al.*, 2004). However, irradiated food is permitted in a wide range of countries (Jin *et al.*, 2012) because it is declared completely reliable and, in meat products, this technique has been considered as one of the most effective preservation procedures (Kong *et al.* 2017; Alfaia *et al.*, 2007). The purpose of its application is based on the absorbed radiation dose (Farkas 2006). In this regard, while doses below 1 kGy are used to delay ripening, inhibit germination and kill insects, doses between 1 and 10 kGy are applied for spoilage reduction and microbial control in fresh products.

Among the irradiation techniques, gamma irradiation, electron beam generators and X-Ray accelerators are the most commonly investigated. The interest of researchers for these techniques began a long time ago. The first evidence was in 1895 when a German Physics Professor, called Wilhelm Conrad, discovered X-Rays. Initially, the interest in this technique related mainly to medical purposes. After that, the number of studies focusing on the application of these promising technologies increased and later on, the first implementations in food manufacture were established: grain disinfestation in 1980 in the Soviet Union, poultry meat decontamination in 1991 in France, fish products sterilization in Belgium and France, fermented sausage sanitisation in Thailand, space foods sterilization in the USA and frozen meals in South Africa (Farkas, 2006).

In spite of the great potential and the wide range of research about the use of gamma and energy electron beams irradiation, very few studies focused on their application to dry-cured ham. Only two publications were found in the literature (**Table 2**). Jin *et al.* (2012) evaluated the effects on the physicochemical and sensory characteristics of absorbed doses of gamma irradiations between 2.5 and 10 kGy, since the effectiveness of 10 kGy and lower doses were previously probed for microbial reductions (FSIS, 1999). The study confirmed its potential use and reported that doses below 5 kGy could maintain the sensorial properties intact, while higher doses result in color changes, lipid oxidation and the increase of off-flavours.

Regarding electron beam irradiation, although there is little information available, it is important to note that Kong *et al.* (2017) demonstrated that this irradiation maintains sensory properties better than gamma irradiation. It is well known that lipid oxidation is the major consequence of irradiation and its effects on nutritional value and sensory characteristics are meat color fading and off-odor production (Alfaia *et al.*, 2007). In this regard, Kong *et al.* (2017) carried out an evaluation of both technologies focusing on their effects on volatile compounds and, in contrast to previous evidence in meat products, no differences were shown in aldehyde and ketone contents between control and both irradiated hams. Therefore, the main odour modifications were not considered to be originated from lipid oxidation.

On the other hand, while electron accelerating equipment produces high energy electron beams, X-Ray technology turns electron energy into electromagnetic X-Rays (Farkas, 2006). This latest technology uses single or dual absorptiometry to analyze the composition of dry-cured ham samples (De Prados *et al.*, 2015; Fulladosa *et al.*, 2015a, 2015b). In addition, it uses multi energy sensor for predicting salt contents (Fulladosa *et al.*, 2016) or making textural measures (Fulladosa *et al.*, 2018). Unfortunately, composition

159 identifications are bound to error due to the fact that X-Ray technology is influenced by the
160 density of the object. In this sense, dense objects produce more attenuation, but also
161 variations in thickness can result in different attenuations (Fulladosa *et al.*, 2015b).
162 Moreover, increments in attenuation has been observed in the presence of salt, since Na⁺
163 and Cl⁻ ions are denser than the inorganic substances present in the medium (Fulladosa *et*
164 *al.*, 2010; Håseth *et al.*, 2008). These attenuation increments were mainly observed at low
165 energy radiations (Kalender, 2000). For that, Fulladosa *et al.* (2015b) concluded that the
166 salt content could only be predicted by using 50 kV. However, variations in part of the
167 obtained data were shown, which could be caused by the fact that the water content
168 influences sample densities to a large extent. The same energy was tested as effective
169 method to predict fat contents (**Table 2**), and it is possible to improve the resulting
170 predictions by adding the information obtained using 70 kV. In this regard, De Prados *et*
171 *al.* (2015) considered the best positively correlated conditions at 90 kV and 4mA ($R^2= 0.57$)
172 and at 70 kV and 8 mA ($R^2= 0.53$). Lower attenuations were shown at 80, 110 and 140 kV
173 in samples in which proteolysis induction times were extended (Fulladosa *et al.*, 2018). The
174 reason for that could be the protein degradation and the associated induction of changes in
175 cell structure, originating from modifications in the X-Ray scattering (Fulladosa *et al.*,
176 2018; Fulladosa *et al.*, 2017; Hoban *et al.*, 2016).

177 On the other hand, computed tomography (CT) also employs X-Ray for
178 irradiations. The scanning parameters (voltage, energy, slice thickness, etc.) affect the
179 quality of images, for example noise or low resolution can be reduced by the use of a
180 higher radiation dose (Goldman, 2007). CT equipment loses part of the X-Ray energy
181 when the body tissues interact with them, depending on differences in the tissue densities
182 and was thus mainly used to predict pigs body composition and to evaluate the content
183 and distribution of salt in meat (Vestergaard *et al.*, 2005; Frøystein *et al.*, 1989; Sørheim

and Berg, 1987). The first studies in dry-cured ham were performed by Sørheim and Berg (1987) who demonstrated the viability of CT for studying the salting process, and Frøystein *et al.* (1989) who reported the effect of freezing on salt penetration. As in previous cases, because of the high costs and the low technical development, the technique began to be studied in depth only a few years ago (Vestergaard *et al.*, 2005). Finally, CT was declared useful in curing processes, mainly to monitor the salting and post-salting steps, considering that the addition of NaCl, due to its high density, increases X-Ray attenuation, facilitating salt monitoring (Fulladosa *et al.*, 2010; Håseth *et al.*, 2008). The first published calibration model for predicting salt contents in ham was developed by Håseth *et al.* (2007). The obtained prediction error at 130 kV was 0.8% NaCl; this precision was improved one year later by optimizing the tube voltage (Håseth *et al.*, 2008) concluding that the most useful voltage to predict salt content, according to later studies (Fulladosa *et al.*, 2010), was 80 kV, or even better, a combination of 80 and 120 kV. In addition, it was shown that a voltage of 120 kV is also the best option for the prediction of water content. Furthermore, it was observed that both fat and water content had a great influence on the model precisions (Fulladosa *et al.*, 2010). Thus, the models could be unfeasible when there are areas with fat contents above 30% on dry matter of dry-cured ham or when the measurement is made at the end of the process (Santos-Garcés *et al.*, 2010; Fulladosa *et al.*, 2010).

CT imaging applications have been extended, through the generation of models for salt and water contents in different stages along the process, for characterizing and optimizing the dry-cured ham process (Santos-Garcés *et al.*, 2011; Håseth *et al.*, 2012). Additionally, it has been demonstrated that CT scanning can be used for detecting unsuitable practices in the dry-cured ham manufacture process by determining the relationship between the salt distribution and the physical characteristics of the product

(Vestegaard *et al.*, 2005). Moreover, Harkouss *et al.* (2018) indicated that CT models can be used to monitor the post-salting stage in dry-cured hams with reduced salt content in order to evaluate the time required to obtain the same characteristics in the final product.

2.2. Magnetic resonance imaging

Magnetic resonance imaging (MRI) is based on the knowledge that certain atomic nuclei absorb energy when subjected to a magnetic field and stimulated by radio waves with appropriate frequency. The atomic nuclei release the absorbed energy (resonance signal) when the magnetic field ceases. This energy is received and analyzed and, in this sense, MRI allows to observe the composition inside bodies and this is why medical science frequently uses it for diagnoses. In the case of food science, the use of this technique is not so extended even though some reviews on its possibilities published in the 1990s. There was some research about food morphology characterisation to identify defects (Ciampa *et al.*, 2010) and some related to optimised treatments in food processing (Bouhrara *et al.*, 2011). In the case of meat products, the application of MRI was evaluated as a method to analyze the lipid distribution (Beavallet and Renou, 1992), to characterize muscle structure (Bonny *et al.*, 2001) and to quantify muscle and subcutaneous and intermuscular fat contents (Monziols *et al.*, 2006). Furthermore, MRI is used to check the water distribution along meat processing steps such as a freeze-thawing (Guiheneuf *et al.*, 1997) or drying (Ruiz- Cabrera *et al.*, 2004), and to quantify changes in the moisture and structure of cooked chicken meat (Shaarani *et al.*, 2006). Furthermore, this technology, in combination with computer vision recognition techniques, could be useful for the evaluation of quality characteristics in pig products, for instance, for a classification based on feed (Perez-Palacios *et al.*, 2009), on intramuscular fat content, on sensory properties (Antequera, *et al.*, 2003) or on the type of muscle (Antequera *et al.*, 2007; Caro *et al.*, 2003). The use of MRI to determine the

content and distribution of intramuscular fat is very important to improve the dry-cured ham process, since penetration of salt and water loss are very influenced by the fat content (Ripollés *et al.*, 2011). As shown in **Table 3**, water content and salt diffusion are the most studied properties among the MRI applications. Fantazzini *et al.* (2005) observed a good correlation between the experimental salt-to-moisture ratio (S/M) and the ratio obtained by MRI, allowing the non-invasive control of microbial populations during the process. Texture analysis based on MRI confirmed the advantage of applying MRI technology in dry-cured hams in order to differentiate between pigs fed diets based on acorn and grass and diets based on concentrates of oleic acid (Perez-Palacios *et al.*, 2011; Perez-Palacios *et al.*, 2010b). As a result of these studies, it was noted that the biggest difference in texture characteristics was shown in *semimembranosus* (SM) muscles due to their higher sensibility to the ripening process. In this regard, Antequera *et al.* (2007) used MRI combined with an Active Contour to observe and identify changes in muscle volumes during ripening. These results showed high correlations between the information from joint MRI and Active Contour and, on the other hand, weight and water content, obtaining better results for *biceps femoris* (BF) muscle than SM, since this muscle is an internal muscle and its extraction is more difficult, generating more variability in the data.

Additionally, a_w , soluble solids and salt contents were characterized by MRI to monitor the process not only in SM and BF muscles, but also in *semitendinosus* (ST) and *rectus femoris* (RF), finding a similar correlation as the one observed in BF (Manzocco *et al.*, 2013). Besides that, Perez-Palacios *et al.* (2011) focused on the prediction of sensory properties by fat and texture features characterisation through MRI and they reported that fatty acids could participate in the hardness of the fat and lean, flavour intensity, brightness and juiciness, while texture features can define the marbling, the intensity of the odour and flavour and the redness resulting at the end of the curing

process. On the other hand, the use of ^{23}Na isotope for MRI analysis was investigated since it is able to measure the molecular nuclei directly instead of through attenuation differences. Measurements can be performed by either one- or two-dimensional profile maps. While two-dimensional analyses give information about the sodium position, namely information of sample structural features, one-dimensional profiles provide information about the water proton mobility, thus the concentration can be calculated as a distance function (Vestergaard *et al.*, 2005). They have been applied in some foods to quantify salt contents: paste from fermented soy, vinegar cucumbers, plums, crabs and meat (Nagata *et al.*, 2000). However, only one publication was found on dry-cured ham, whose conclusions reported that both application types were viable to investigate salt contents, although they have some limitations. The main limitation is related to the salt contents of the samples. Good results were obtained in ^{23}Na -MRI from two-dimensions when samples had more than 2.5 g NaCl/ 100 g and in ^{23}Na -MRI from one dimension at concentrations above of 0.9 g NaCl/ 100 g. (Vestergaard *et al.*, 2005). In conclusion, ^1H -MRI is considered a good method for dynamical monitoring of moisture losses (Antequera *et al.*, 2007), while ^{23}Na -MRI is capable to observe the dynamic tracking of salt content into the ham (Vestergaard *et al.*, 2005)

2.3. Infrared spectroscopy

Infrared spectroscopy (IS) techniques are based on the absorption of infrared light due to the changes in the vibrational states of organic molecules. Due to the opacity of certain samples, their use is limited (Rinnan *et al.*, 2009), although the viability of IS to quantify and to characterize different components in meat and fish products has been evaluated (Ziadi *et al.*, 2012). Moreover, the ability of IS based techniques for the identification of different meat species, allowing the detection of food fraud, has been reported (Damez and Clerjon, 2013; Kamruzzaman *et al.*, 2012). Nevertheless, it should be

noted that the different existing techniques have a variety of bandwidths and optical parameters, such as transmission, reflection or scattering, among others, which may need to be adjusted to get better results (Damez and Clerjon, 2013).

Among the different existing techniques, Near Infrared reflectance spectroscopy (NIRS) is the measurement of the wavelength and intensity of near infrared light absorption (700 nm - 2500 nm). When the light hits a sample, part of the photons can be transmitted through it, and the rest is absorbed by some covalent bonds that act as oscillating springs, coupled with the exact frequency or wavelength of the light radiation (Cajarville *et al.*, 2003). By absorbing energy, the bonds of the molecules vibrate in two fundamental ways: they extend, increasing the interatomic distance along the axis between two atoms (which occurs at higher frequencies or shorter wavelengths), or they bend (at lower frequencies or greater wavelength) by changing the bond angle between two atoms (Alomar and Fuchslocher, 1998). Absorption is selective and depends on the molecular groups involved. Therefore, it is estimated by the difference between incident light and reflected or transmitted light.

Some researchers have reviewed its applications in meat technology (Prieto *et al.*, 2009) and many others have used NIR for studying quality parameters (Berzaghi *et al.*, 2005; Garcia-Rey *et al.*, 2005), sensory attributes (Liu *et al.*, 2011) and for predicting a_w , moisture, fat, protein and NaCl contents (Collell *et al.*, 2010). Unfortunately, in the case of dry-cured hams, the available literature about the potential use of NIR is scarce. There are only few studies, as reported in **Table 4**, focused on predicting the content of diverse compounds, monitoring processes and classifying according to different characteristics.

Regarding the classification studies, Garcia-Rey *et al.* (2005) showed the viability of NIR to classify dry-cured hams based on different levels of pastiness and anomalous colours. To illustrate this point, using the content predictions obtained by the NIRS

analysis, the main result consisted of an overall accuracy of 88.5% for the pastiness classification, and 79.7% for colour defects. However, the authors observed in the Principal Component Analysis (PCA) a high number of factors to explain the variance for pastiness predictions, which were attributed to the numerous elements that influence the NIR measurements. For the quantification of compounds, Collell *et al.* (2010; 2011) developed models to predict the a_w content in different meat products, obtaining better results in sausage samples than in dry-cured hams, probably due to the differences in the homogeneity between samples. In the same study, the NaCl content was also predicted, but the obtained RMSECV was not very successful. Additionally, the use of wavelength in the visible range (visible-NIRS) was also examined. Garcia-Rey *et al.* (2005) concluded that it is a potential method for predicting sensory attributes such as texture and colour, and Ortiz *et al.* (2006) also assayed its suitability in dry-cured hams classification according to other sensory parameters, such as pastiness, crusting or marbling.

On the other hand, Geesink *et al.* (2003) indicated that use of NIR allows to classify raw meat according to the WHC (superior or inferior) and, consequently, this fact allows the early detection of meat that could result in anomalous products at the end of the process (Garcia-Rey *et al.*, 2005), reducing associated economic losses.

The combination of classical computer vision and spectroscopy gives rise to the hyperspectral technique, which combines the strengths of both providing spectral and spatial information. Although this technique was used initially for geological purposes, there are some studies about its application to evaluate the quality of different meat products (Måge *et al.*, 2013; Barbin *et al.*, 2012; ElMasry *et al.*, 2011).

ElMasry *et al.* (2011) applied hyperspectral imaging to investigate the effect of different processes in cooked hams from turkeys, while Talens *et al.* (2013) tested the

feasibility of this technology to predict compounds, like fat, water and protein content, and to classify cooked hams from pig meats based on different qualities using the information from fat, water and protein predictions. However, only a few publications have been found related to dry-cured hams. As shown in **Table 4**, three studies focused on moisture and salt predictions. Liu *et al.* (2013) obtained a good coefficient of determination for both water and salt content, although Gou *et al.* (2013) showed better values reducing the wavelength interval. In addition to water and salt content, Gou *et al.* (2013) also predicted the fat content, obtaining a Root Mean Squared Error (RMSE) of 1.36%.

In the range of middle IS, it is worth highlighting the Raman spectroscopy, a high-resolution photonic technique that provides in a few seconds chemical and structural information of almost any organic or inorganic material or compound, allowing its identification. To obtain molecular information, the characteristic vibrational energy levels of the atoms of the bond, its conformation and its environment are analyzed. These levels have characteristic resonance frequencies, which are a function of the mass of the molecules and the strength of their bonds. Unlike other IS technologies, which require a change in the dipole moment of the molecule, Raman spectroscopy requires a change in polarizability, which allows obtaining complementary spectral information on homonuclear molecules. Moreover, its main advantage is the minimal influence of water in the samples (Damez and Clerjon, 2013). Raman spectroscopy proved that it was possible to determine the unsaturation degree of animal fats (Olsen *et al.*, 2007) in pork meat. In this sense, in pork loins, it was shown that Raman spectroscopy was able not only to predict the texture, tenderness (Beattie *et al.*, 2004), juiciness and chewiness of pork loins (Wang *et al.*, 2012), but also to evaluate the effect of thermal treatments and salt addition (Herrero *et al.*, 2008). Additionally, there is a recent advance in this technology; Sowoidnich *et al.* (2012) developed a portable Raman device allowing a

quick identification of pork meat spoilage. Therefore, Raman could be considered useful in dry-cured ham processing, due to evidence suggesting its potential application for detecting microbial population, characterizing textural attributes and even for monitoring the drying process. However, there are no studies in dry-cured ham yet so that its application potential to this particular product is still unknown.

2.4. High pressure

The use of high-pressure technology is one of the most investigated techniques across time. In 1899, Bert Hite designed a prototype HP system, which was used to pasteurize some foods, but in this time its viability in food industry was limited due to the high cost involved. It was not until 1993 that the HP technology was introduced in food manufacture with stabilizing purposes (Rivalain *et al.*, 2010). The mechanism of action of HP units resides in a chamber in which the food, previously packed, is positioned. After closing the vessel, the chamber is filled with a medium capable of transmitting the pressure.

The traditional main purpose of HP treatments has been the microbial reduction in order to extend shelf life (Duranton *et al.*, 2015). In this sense, Bajovic *et al.* (2012) observed that pressures around 10 or 50 MPa had an effect on microbial growth, even though higher pressures are needed for the inactivation of microorganisms.

On the other hand, it has been observed that in dry-cured loins there is an increase in autolytic activity when a pressure of 300 MPa was applied, however at 500 MPa the activity of aminopeptidases was decreased (Campus *et al.*, 2008). HP application implies modifications in the final products and the food could undergo physical, chemical, organoleptic, technical and functional alterations or all at once (Rivalain *et al.*, 2010; Liu *et al.*, 2008). However, these changes are not necessarily negative. In this regard, dry-cured products showed an increase in saltiness perception caused by HP (Fulladosa *et al.*,

2012; Clariana *et al.*, 2011, 2012; Rubio *et al.*, 2007), which is interesting with regard to reduced salt product elaborations.

In relation to dry-cured ham, **Table 5** shows the studies carried out in last years. Likewise, the initial purpose of HP use has also been microbial inactivation (Rubio-Celorio *et al.*, 2016; Clariana *et al.*, 2011; Garriga *et al.*, 2004). Since dry-cured ham is a highly salted product, and so the water activity level is low, thus the main spoilage presented corresponds to Gram-positive bacteria and yeast, which are mainly located at the surface of the product. It has been proved that HP treatments at 600 MPa keep the microbial load at low levels during storage with a remarkable effect on psychrotrophs, resulting in an extension of the shelf life up to 4 months (Garriga *et al.*, 2004). Furthermore, moulds require pressures between 200 and 300 MPa for their inactivation, while their spores need 400 MPa (Aymerich *et al.*, 2008). There was a study focused on purine and pyrimidine content, which are compounds declared as indicators of microbial spoilage, in which no differences were observed between untreated samples and samples treated at 600 and 900 MPa, maybe due to the water and salt contents, since a low a_w preserves the cells from pressure effects (Clariana *et al.*, 2011). Moreover, diverse studies showed that the HP application at 100 MPa causes lysosomal membranes destruction and reversible protein denaturation, and the protein denaturation at pressures beyond 200 MPa becomes irreversible (dos Santos *et al.*, 2018; Qi *et al.*, 2015) facilitating proteolytic reactions. These structural protein modifications also cause higher water losses. Therefore, higher pressures result in higher water losses (García-Gil *et al.*, 2014; Picouet *et al.*, 2012; Fulladosa *et al.*, 2009; Serra *et al.*, 2007a). In this regard, Rubio-Celorio *et al.* (2016) observed a 0.43% increase in water loss for every pressure increment of 100 MPa, while Picouet *et al.* (2012), observed even higher losses up to 0.82%. In addition to this, the pressure could induce physicochemical changes, such as reductions in water

holding capacity with treatments between 300 and 600 MPa (Picouet *et al.*, 2012; Fulladosa *et al.*, 2009). Previously, Serra *et al.* (2007a) showed a 24% increase in salting weight losses in samples treated before the salting process at 600 MPa compared to samples treated at 400 MPa and both HP-treated samples showed lower NaCl content than control samples. This fact is attributed to an increase in protein denaturation caused by pressurization, in turn increasing salting weight losses (Serra *et al.*, 2007a). Due to this lower NaCl content, significantly higher levels of a_w were observed in pressured samples from BF muscle, whereas no differences were found in SM muscle, may be due to the large variability in the composition values of this muscle (Virgili and Schivazappa, 2002).

Moreover, there are some studies about the effects of pressure treatments on enzymatic activity. These studies concluded that most of enzyme activities is generally unaffected at 200 MPa and below (Masson *et al.*, 2001), but inactivation begins to occur as the pressure increases, with differences depending on the enzyme (Rivalain *et al.*, 2010). In this sense, it has been shown that pressures of 600 MPa reduce glutathione peroxidase (GSHPx), superoxide dismutase (SOD) and catalase (CAT) activity. Moreover, at 400 MPa, the inactivation percentage of CAT increases. Based on this evidence, Serra *et al.* (2007a) concluded that the ageing conditions and the dry-curing process would have a greater effect on the enzymatic activity than the pressure application. However, modifications in protein links, protein solubility losses and decreases in cathepsin B, D and L activity have been observed in HP-treatments above 400 MPa (Campus *et al.*, 2008). The provided effect of HP on both enzyme activity and protein denaturation, which are widely associated with the final texture, have caused an increasing interest in its potential use in meat tenderization (Ichinoseki *et al.*, 2006; Jung, *et al.*, 2000). In spite of previous evidence in meat showing significantly higher shear force values in HP-treated salted pork meat (Duranton *et al.*, 2012) and in cooked beef

meat (Jung *et al.*, 2000), the textural effect on dry-cured hams has not been thoroughly studied. To date, only a few studies have been published about it, reporting higher hardness values in pressurized samples (Rubio-Celorio *et al.*, 2016; Fuentes *et al.*, 2010; Fulladosa *et al.*, 2009). Fuentes *et al.* (2010) reported greater hardness and chewiness in pressurized samples, and they observed that the treated samples were less juicy and doughy than the controls.

On the other hand, colour parameters can also be affected by the application of pressure, as increments in reflectance and lightness (L^*) and lower redness (a^*) values have been reported (Rubio-Celorio *et al.*, 2016; Hughes *et al.*, 2014; Fulladosa *et al.*, 2009; Andres *et al.*, 2004), modifications which could be explained by the fact that HP promotes changes in protein structural conformations, which could have an undesirable impact on the organoleptic characteristics of final products (Serra *et al.*, 2007b). The increase in salty taste is another organoleptic change observed after pressure treatments. Picouet *et al.* (2012) explained this observation by the increment of the amount of sodium ions released due to differences in salt and protein interactions after the application of pressure.

Since the final aroma is influenced by all the reactions occurring during the dry-curing process, such as proteolysis and lipid oxidation reactions, several researchers have focused on investigating the volatile profile changes due to pressure application to determine the organoleptic impact (Lorido *et al.*, 2015; Clariana *et al.*, 2011). In this sense, since pressure promotes lipolysis reactions (Fuentes *et al.*, 2014; Fuentes *et al.*, 2010), mainly at pressures around 600 MPa (Fuentes *et al.*, 2010; Andrés *et al.*, 2004), the amount of some lipolysis derived volatiles increases in HP-treated samples. Martinez Onandi (2018; 2017; 2016a; 2016b) evaluated the changes in the volatile profile of dry-cured ham slices treated at 600 MPa and its evolution after 5 months of refrigerated

storage. They observed higher levels of 12 volatile compounds in the treated samples, whereas, after the storage period, only 9 of the total volatile compounds were enhanced. On the other hand, at 400 MPa, Rivas-Cañedo *et al.* (2009) also observed increased amounts in volatile compounds, whereas, at treatments between 200 and 600 MPa, Andres *et al.*, (2004) reported an important increase in hexanal which is considered the main compound derived from lipid oxidation and it contributes to the fatty distinctive matured ham flavour. Its amount was even more pronounced at 800 MPa. Similarly, Fuentes *et al.* (2010) noticed higher levels in 5 aldehydes after treatment at 600 MPa, which caused an increment of the rancid odor perception while differences in rancid flavour were not shown. However, enhanced saltiness, bitterness and cured flavour were obtained in the HP-treated samples.

Likewise, HP treatments could reduce the levels of some volatile compounds due to enzyme inactivation or matrix structure modifications (Garcia-Gil *et al.*, 2014; Picouet *et al.*, 2012). Thus, Martinez-Onandi *et al.* (2018) established reductions in 23 volatile compounds, as performed by Rivas-Cañedo *et al.* (2009) and, Martinez-Onandi *et al.* (2016b) in 6 volatile compounds and by Martinez-Onandi *et al.* (2017) in 31 volatile compounds.

In summary, the effects of HP treatments depend on the pressure level, although the influence of factors such as the measuring conditions of the HP treatment, packaging material or storage cannot be ignored (Martinez-Onandi *et al.*, 2017).

2.5. Ultrasound

Ultrasound technology (US) is based on pressure fluctuations caused by sound waves that increase temperature and pressure leading to cavitation phenomena which could accelerate mass transfer (Jambrak *et al.*, 2010). As shown in **Table 6**, the interest about the potential uses of US has increased significantly in the last years. However, it is

difficult to compare the different results obtained due to the high variability among studies, including the many parameters that could influence the outcomes (Berlan and Mason, 1992). Regarding the intensity applied, US is classified into low-intensity, (frequencies above 100 kHz and intensities below 1 W.cm⁻²) and high-intensity ultrasound (frequencies from 18 to 100 kHz and intensities above 1 W.cm⁻²) (McClements, 1995). The first one can be considered as non-invasive due to the lower level of intensity. For this reason, it is useful for characterization purposes within food processing (Chandrapala *et al.*, 2012; Koch *et al.*, 2011a, 2011b). On the contrary, high-intensity ultrasound could induce physical, chemical and/or mechanical modifications (Jayasooriya *et al.* 2004) and this is why its traditional use in food manufacture has been for generating emulsions (Dolatowski *et al.*, 2007).

As far as characterization uses are concerned, salt, fat and water content have been the most studied constituents in dry-cured hams. In this sense, salt analyses are performed in both pre and post-salting process stages (De Prados *et al.*, 2016; De Prados *et al.*, 2015). The importance of post-salting research consists of the process optimization since US allows the classification according to different levels of salt content with the aim of the development of the following stages (De Prados *et al.*, 2017).

Since ultrasonic velocity depends on the aggregation states of the matter, the use of this technology to measure fat content is strongly affected by the temperature of the sample. In this sense, fat is solid at low temperatures so that ultrasound velocity is enhanced and the differentiation between fatty and lean tissues is clearly possible. Conversely, at high temperatures, fat becomes liquid and the velocity of ultrasonic waves is reduced, approaching that in lean tissue. In this regard, De Prados *et al.* (2015) concluded that temperatures around 2°C are suitable for fat determinations due to the remarkable difference in both velocities. In contrast, Fulladosa *et al.* (2015b) showed that

at 2°C the velocity in fatty tissues is similar to that in the protein matrix and they suggested to calculate the velocity variation between 2 and 15°C, showing great fat and protein identification at 15°C. In spite of this result, they concluded that the US feasibility to create models for fat and protein contents is not very disheartening, since they showed other factors, like water content, which influence US to a greater extent than lipid and protein matrices. However, it has been proved that ultrasonic models provide a better percentage of hams correctly classified into different fat levels compared to other non-invasive technologies like X-Ray (88.5% vs 65.4%, respectively) (De Prados *et al.*, 2015). In addition, US implementation in the ham manufacture is cheaper and easier than, for instance, MNR or X-Ray techniques (Corona *et al.*, 2013). Despite of the commented advantages, some production system adaptations are required for its effective incorporation (Corona *et al.*, 2013).

Until now, commented results are obtained using the through-transmission mode, namely a method in which two transducers are connected directly at both sides of the sample (De Prados *et al.*, 2017). That is the reason why it can be very difficult to introduce this mode of application in certain stages of the dry-cured ham process. However, the pulse-echo mode allows to simplify its implementation in the process, considering that only one transducer is positioned in the sample, working as emitter and transducer at the same time (Awad *et al.*, 2012). Traditionally, this mode has been applied for the detection of defects in metallic materials, although its use for the characterization of components in food has been recently investigated (De Prados *et al.*, 2017). By measuring the Time of Flight variation (Δ TOF) of the pulse-echo mode it is possible to monitor the salting process in hams with a mean thickness of 15.7 cm (De Prados *et al.*, 2017), showing a high Δ TOF reduction at few hours after the beginning of the salting (De Prados *et al.*,

2016). Additionally, the salt prediction model could be improved by the addition of fat and water gain information (De Prados *et al.*, 2017).

In addition, it was shown that the US applications around 64 or 51 W cm⁻² could accelerate the transport of water and salt due to the changes caused by cavitation phenomena (Cárcel *et al.*, 2007). Nevertheless, in recent studies, Siró *et al.* (2009) defined 2–4 W cm⁻² as the intensity in which the diffusion of salt is strongly enhanced, while McDonnell *et al.* (2014a) obtained the highest increment with the application of for 25 min at 19 W cm⁻². Additionally, McDonnell *et al.* (2014a) also established treatments for 10 or 25 min at intensities of 19 W cm⁻² as a good method to increase the water gain. Despite of previous studies in meat which have not shown any effect on texture after US application, McDonnell *et al.* (2014a) found lower cohesiveness and gumminess values in treated hams. Moreover, hardness was found to increase upon treatments with high intensity US, which could be due to the induced heating the treated samples (Contreras *et al.*, 2018). Pérez-Santaescolastica *et al.* (2018) found a drop in adhesiveness values, although the treated samples presented modifications in the volatile compounds profile and enhanced the sweet, acid, bitter and aged tastes compared to the untreated samples.

Finally, there are alternative techniques based on ultrasonic waves that have not been studied yet even though could be useful for improving the dry-cured ham process. For instance, air-coupled ultrasound has been used for foreign body detection (Pallav *et al.*, 2009), as well as to identify modifications in physicochemical properties of liquids (Meyer *et al.*, 2006) and to find anomalies in starchy solid consistency (Gan *et al.*, 2002). Corona *et al.* (2013) suggested that the use of air-coupled ultrasound could lead to an important reduction in the time and manipulations throughout the process. In addition, they commented that scanning acoustic microscopy (SAM), which is a potential technique to analyze the distribution of different tissues, should be investigated.

3. Other emerging technologies

In the early 90's, food manufacture started to use electricity to process foods, particularly in milk pasteurization, although other potential uses were also investigated (Chauhan and Unni, 2015). In this context, in 1960, Doevenspeck patented the pulse electric fields (PEF) technique and in 1967, Sale and Hamilton probed its effectiveness in reducing the bacterial population and inactivating enzymes (Chauhan and Unni, 2015). However, the PEF treatment in dry-cured hams has been poorly studied (**Table 7**).

This technology is based on the application of pulses during short times, usually 1-100 μ s every 0.001-1 ms, which can expand the cell membrane pores or, even generate new ones (Chauhan and Unni, 2015). These pores increase the permeability of the membrane causing cell content losses or the entry of external substances, with both situations resulting in cell death (Rodrigo *et al.*, 2010). Depending on the applied intensity the process can be reversible or irreversible. In addition to microbial inactivation, the process can result in the modification of some food properties, such as texture or water holding capacity (WHC) (Gudmundsson and Hafsteinsson, 2001). Different factors are involved in the effectiveness of the process, and these factors could be technological, such as the intensity, time or temperature of the application, or derived from the matrix in which they are applied, e.g. conductivity, pH or fat content (McDonnell *et al.*, 2014b).

It was shown that PEF application allows the reduction in the curing time since mass transfer is improved (Chauhan and Unni, 2015). Previously, Toepfl and Heinz (2007) observed improvements in salt diffusion after applying PEF in dry-cured products. This fact could be explained by myofibril fragmentation, caused by the treatment, which would break the structure of the muscle (O'Dowd *et al.*, 2013). Consequently, this results in increases in weight loss. Moreover, the weight loss is influenced by the frequency of the treatment, as shown by McDonnell *et al.* (2014b), who observed a higher water content in samples treated

at 100 Hz than in the ones treated at 200 Hz, whereas the latter frequency resulted in higher WHC values compared to the first one. In the same study, it was also proved that treatments at 100 Hz combined with 300 pulses enhanced the NaCl content and the samples tended to be harder and chewier. This study was the only one found in literature about the potential PEF applications in dry-cured hams.

Likewise, electrical impedance scanning (EIS) has also been poorly studied. This technique is based on the application of a potential signal to an electrode and the measurement of its current response at different frequencies, obtaining an impedance spectrum. The first research in which the EIS treatment was applied in hams as a classification method based on different ranges of pH and fat in raw meat (Oliver et al., 2001). The early identification of potential pale, soft and exudative (PSE) hams could help to prevent textural and flavour anomalies in the final product, thus improving the process. As a result, 88.46% of hams with pH above 6.1 were well-classified, while hams with pH under 5.95 were classified with an accuracy of 92.31%.

On the other hand, electromagnetic waves have been widely used in meat products for investigating quality attributes, like sensory and nutritional characteristics, chemical and physicochemical properties, and safety (Damez and Clerjon, 2013). An electromagnetic technique worth highlighting is microwave spectroscopy, whose main advantages include energy efficiency and food safety (Han *et al.*, 2018). Nevertheless, nowadays its use in meat manufacture is not enough investigated and no studies were found in relation to dry-cured hams. The available publications related to meat address structural and compositional measures (Nelson and Trabelsi, 2012; 2008) and foreign body detection Damez and Clerjon, 2013. Another example of microwave spectroscopy technology is the namely Time Domain Reflectometry (TDR), which is based on the determination of the propagation speed of an electromagnetic wave after being reflected. It is characterized for a faster

response, being easier to use and providing a portable equipment (Miura *et al.*, 2003). This new technology has been considered capable of water and salt estimations in dry-cured hams, with a RMSEV of 1.67% and 0.22% respectively, and for fat content estimation with lower precision (RMSEV=2.81%) (Fulladosa *et al.*, 2013). Moreover, Rubio *et al.* (2013) observed its potential for classifying slices based on different pastiness levels, with 93% probability of correct classification.

Meanwhile, Magnetic induction (MI) is the process by which magnetic fields generate electric fields in a conductive material. The use of MI has been investigated recently in food technology, having the great advantage that electrodes are not needed for its application (Schivazappa *et al.*, 2017). There are several studies in which the spectra of agricultural products have been analyzed using multi-frequency MI (Barai *et al.*, 2012) and single-frequency MI (Euring *et al.*, 2011). Regarding hams, Schivazappa *et al.* (2017) obtained a higher signal in salted hams than in fresh ones, and they developed a model for salt prediction in which the RMSEC was 0.18%. There is little difference between this RMSEC and the one obtained by using other technologies previously cited. This fact demonstrated the feasibility of MI to predict the salt content in dry-cured products although more studies should be carried out to extend its use in the food industry.

Another satisfactory technology for process monitoring is Laser backscattering imaging (LBI), since it is an inexpensive technology in which the sample microstructure affects the light scattering, offering information about the changes that can take place in the physical properties and in the component distributions (Fulladosa *et al.*, 2017). In general, this technology was successfully developed for quality evaluation of different products (Adebayo *et al.*, 2016; Mollazade *et al.*, 2012; 2013; Qing *et al.*, 2007; 2008), for detecting damages in bananas (Hashim *et al.*, 2013), for detecting citrus decomposition (Lorente *et al.*, 2013), and for monitoring drying processes in fruits and vegetables (Udomkun *et al.*,

2014; Romano *et al.*, 2011). In meat products, one research was found in which the freshness of pork was analysed (Li *et al.*, 2016). In hams, there is a recent publication by Fulladosa *et al.* (2017), whose results confirmed that the proteolysis caused by drying and the water content variations influence the response of the light backscattering and then, the estimation of texture properties is not possible using only LBI technique. However, they suggest that the combination with others technologies could be feasible for these purposes.

Finally, one of the techniques that have aroused most interest in recent years is data mining. This new technology consists in exploring and analyzing many data sets in order to predict and describe new data (Witten *et al.*, 2016). Some studies have applied it on food (Wu *et al.*, 2012; Holmes *et al.*, 2012. Liu *et al.* (2013) used data mining to predict water activity and NaCl content in pork meat, but it was in 2010 when it was first applied in hams and considered useful for classifying them as a function of the pig feeding (Perez-Palacios *et al.*, 2010a; 2011b). After that, Perez-Palacios *et al.* (2014) investigated the ability of data mining to estimate quality traits. Finally, Caballero *et al.* (2016) used the Waikato Environment for Knowledge Analysis (WEKA) free software and proved its feasibility for classifying dry-cured hams according to the post-salting time and muscle type.

4. Conclusions and future trends

The most important aspect in the dry-cured ham process is to maintain a rigorous control of the salting and curing stages, since all the reactions that give rise to the typical sensory properties of the product take place at these stages. The control of the salt distribution in the muscle is essential for an appropriate development of the process. This has been and continues to be the most widespread study object among the research carried out with new technologies. However, it is not the only application for which emerging non-invasive technologies can be useful, since detecting defects of the final product or

ensuring food safety are examples of applications that can help to optimize and improve the process.

As has been shown, there is a wide variety of technologies that are potentially applicable in ham, although further research is needed for a number of them to determine their application potential. Regarding techniques based on irradiation, they can ensure commercial sterility. However, some of them, such as gamma radiation, promote lipid oxidations causing color changes and off-flavors, and they are not widely accepted by consumers; therefore, their use is limited. Among the most studied techniques are HP and US, which have demonstrated their potential use as texture defect correctives, but for US implementation, despite being a cheaper technique, production line adjustments are needed. However, HP was shown to be practical in order to reduce the salt content since the salty taste is enhanced with HP treatments. On the other hand, NIRS can be used to classify based on WHC at the beginning of the process, allowing for the early detection and disposal of meat that could result in defective products in the following process stages, while RAMAN or MRI are able to detect anomalous textures at the end of the process.

A less studied technology is that based on microwaves, which is characterized by its energy efficiency. It could be useful to online estimate salt, water and fat contents in an easy way due to the availability of portable equipment. Like PEF and EIS, it could be a good choice for further research since their multiple uses have been proved in other foods. Finally, data mining, which allows to make predictions based on an immense data file archive, is the most promising discovery in recent years for detecting defects or for classifying products according to sensory attributes.

To sum up, there is still much to explore in the use of these technologies in dry-cured ham and there are many alternatives and potential applications across the dry-cured ham manufacture which could provide great advantages.

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1187 **Figure captions**

1188 **Fig. 1.** Dry cured ham elaboration process, characteristics of the product and

1189 possible alterations

1190

Figure 1

Table 1. Summary of non-invasive technologies used in dry-cured hams sorted by their fundament and their potential applications

TECHNOLOGY	WORKING PRINCIPLE	ALTERNATIVES	PRODUCT APPLICATION	USEFULNESS
Irradiation techniques	Technology based on the application of sources, like alpha, beta, gamma rays or X-rays that have enough energy to ionize the matter, extracting electrons which are linked to the atom.	X-Ray simple X-Ray multi energy detector Gamma irradiation Electron Bean Irradiated	To sterilize	Processing
		Computed Tomography (CT)	To monitor process To model and to estimate components	Analytical
Magnetic Resonance Imaging (MRI)	Absorption spectroscopy based in the absorption of energy (radio frequencies) by a magnetically active nucleus, which is oriented within a magnetic field, changing its orientation as a result of that energy.	Proton-based magnetic resonance imaging (1H-MRI) Sodium-based magnetic resonance imaging (23Na-MRI) by one or two dimensional analysis	To monitor process To predict salt and fat content To predict muscle volumes To identify feeding backgrounds	Analytical
Infrared spectroscopy	Absorption of infrared radiation by molecules in vibration, which begin to vibrate in a certain way thanks to the energy supplied by infrared light.	Near infrared imaging (NIRS) Near infrared hyperspectral imaging (hyperspectral -NIRS) Visible-Near infrared imaging (Visible -NIRS) RAMAN	To predict sensory attributes and components To model and to monitor process	Analytical
High Pressure (HP)	Application of instantaneous and uniform high pressure	High Pressure (HP)	To reduce microbial population To correct sensory attributes	Processing
Ultrasound	It is based on the difference of speed of an ultrasonic wave when crossing different materials.	Through-transmission ultrasound Pulse-echo mode Air-coupled ultrasound Scanning acoustic microscopy	To sterilize To monitor process To predict water, fat and salt contents To correct texture defects	Processing Analytical

Pulse electric fields (PEF)	Application of high voltage pulses for short periods of time to a food, which is placed in an electrolytic solution, between two electrodes.	Pulse electric fields (PEF)	To accelerate salting	Processing
Electromagnetic waves	Based on the electrical properties of a flow of photons when go through a medium	Microwave spectrometry Time Domain Reflectometry Magnetic Induction	To predict components	Analytical
Laser Backscattering Imaging	Based on the obtaining of absorption, transmission and reflectance by the passage of light at different wavelengths through the product	Laser Backscattering Imaging	To predict sensory attributes and components To monitor process To detect defects	Analytical
Data mining	Based on exploring and analyzing a high range of data sets	Data mining	To predict components To classify in function of sensorial traits	Analytical

Table 2. Gamma, electron beam and X-Ray irradiation-based technologies and their applications across the dry-cured ham process sorted by method parameters

TECHNOLOGY	MEASURE CONDITION			PURPOSE OF THE RESEARCH	REFERENCES
Gamma irradiation	0, 2.5, 5.0, 7.5, and 10 kGy			To determine the effects on physicochemical and sensory properties	Jin et al. (2012)
Gamma irradiation	3 and 6 kGy			To eliminate pathogens and extend shelf life	Kong et al. (2017)
Electron beam irradiation	3 and 6 kGy			To eliminate pathogens and extend shelf life	Kong et al. (2017)
	Voltage	Intensity	Sample thickness		
X-Ray	90 kV	4 mA	Whole piece	To predict salt content in bone-in hams after salting	Fulladosa et al. (2015a)
	70 kV	8 mA	76.3 ± 3.5 mm	To predict salt and fat content	Fulladosa et al. (2015b)
	50 kV	15 mA	Whole piece	To predict fat content for industrial classification purposes	de Prados et al. (2015)
X-Ray multi energy detector	50 keV	1.5 mA	Variable (between 1.2 and 9 mm)	To determine changes of the energy spectra, energy bands and ratios due to salt addition	Fulladosa et al. (2016)
	80 keV	1.7 mA			
	140 kV	1 mA	20 mm	To characterize and classification commercial samples according to their proteolysis index or defective texture level	Fulladosa et al. (2018)
	110 kV	1.5 mA			
Computed tomography (CT)	80 kV	2.8 mA			
	130 kV		10 mm	To monitor salt penetration	Vestegaard et al. (2005a)
	80 kV	106 mA	5 mm	To determine salt content	Haseth et al. (2007)
	110 kV		2 mm	To determine effects of CT scanner parameters on CT values variations	Haseth et al. (2008)
	130 kV		10 mm	To determine optimal tube voltage settings and modeling conditions for NaCl prediction at different production stages	
	80 kV	250 mA	10 mm	To predict water and salt transfers.	Fulladosa et al. (2010)
	120 kV			To predict water and salt transfers.	Santos-Garcés et al. (2010)
	140 kV			To estimate the effect of freezing and thawing treatment, before salting, on the apparent NaCl diffusion	Picouet et al. (2013)
	140 kV	145 mA	10 mm	To estimate lean content for further drying processing	Picouet et al. (2010)
	3 GHz		Unknown	To predict water and salt transfers, water activity and proteolysis during the early stages of the process	Harkouss et al. (2018)

Table 3. Magnetic resonance imaging technology applications across the dry-cured ham process sorted by method parameters

TECHNOLOGY	MEASURE CONDITION*				PURPOSE OF THE RESEARCH	REFERENCE
	FOV	ET	TR	SECTION		
Non specified-Magnetic resonance imaging (MRI)	120 x 85 mm	20 ms	500 ms	2.0 mm	To predict lipid content, sensory traits and pigs fed.	Pérez-Palacios et al. (2010a)
					To discriminate different feeding backgrounds	Pérez-Palacios et al. (2010b)
						Pérez-Palacios et al. (2011)
		Unknown	Unknown	2.0 mm	To characterize fat content and distribution	Caro et al. (2003)
Proton-based magnetic resonance imaging (¹ H-MRI)	390 x 390 mm	22ms 134 ms	567 ms 7520ms	4.0 mm	To estimate salt content in different stages	Manzocco et al. (2013)
	120 x 85 mm	20 ms	500 ms	2.0 mm	To determine BF and SM volume during the ripening process	Antequera et al. (2007)
	180 x 180 mm	10, 14, 20, 50, 80, 130, 210, 350, 550, 750 ms	3000 ms	100 mm	To monitoring changes during processing,	Fantazzini et al. (2009)
					To predict salt-to-moisture ratio	Fantazzini et al. (2005)
Sodium-based magnetic resonance imaging (²³ Na-MRI)	64 x 64 mm	2.7 ms	250 ms	20 mm	To quantify salt diffusion	Vestergaard et al. (2005)

*FOV= Field Of View; ET=Echo Time; TR= Repetition Time

Table 4. Infrared spectroscopy based technologies and their applications across the dry-cured ham process sorted by method parameters

TECHNOLOGY	PROCESSING CONDITION	PURPOSE OF THE RESEARCH	REFERENCE
Near infrared spectroscopy (NIRS)	Intervals: 2nm Wavelength range: 400 to 2200 nm	To classify dry cured hams as a function of their texture and colour evaluation	García-Rey et al. (2005)
	32 scans Resolution: 8cm ⁻¹	To predict moisture, water activity and NaCl content and to determine the optimum number of spectra per sample.	Collell et al. (2011)
	0.7 x 0.8 mm ² Intervals: 3.15nm Wavelength range: 900-1700 nm	To construct models for predicting NaCl and moisture contents	Garrido-Novell et al. (2015)
Near infrared hyperspectral imaging (hyperspectral -NIRS)	Resolution: 20nm	To analyze water, fat and salt contents	Gou et al. (2013)
	Wavelength range: 400–1000 nm	To predict moisture and salt content at different stages in the salting process	Liu et al. (2013)
Visible-Near infrared spectroscopy (Visible-NIRS)	Intervals: 2 nm Wavelength range: 400 -2500 nm	To predict sensory quality	Ortiz et al. (2006)

Table 5. High pressure technology applications across the dry-cured ham process sorted by method parameters

MEASURE CONDITION			Sample type	PURPOSE OF THE RESEARCH	REFERENCE
Pressure	Time	Temperature			
200 MPa 400 MPa 600 MPa	5 min	20°C	Sliced vacuum-packed dry-cured ham	To reduce intrinsic water population	Rubio-Celorio et al. (2016)
600 MPa 900 MPa	6 min 5 min	Variable	Sliced, skin vacuum-packed dry-cured ham	To reduce intrinsic microbial population	Clariana et al. (2011)
600 MPa	6 min	31 °C	Sliced, skin vacuum-packed dry-cured ham	To inactivate microbial population	Garriga et al. (2004)
400 MPa 600 MPa	10 min	Variable	Frozen vacuum packed ham	To evaluate the effects on physicochemical parameters and on antioxidant and proteolytic enzyme activities at different stages of ham elaboration and on the final product characteristics	Serra et al. (2007a) Serra et al. (2007b)
600 MPa	6 min	12 °C	Sliced vacuum-packed dry-cured ham	To examine lipid and protein oxidation and sensory properties	Fuentes et al. (2010)
300 MPa 600 MPa 900 MPa	5 min	12 °C	Sliced vacuum-packed dry-cured ham	To examine structural and molecular changes affecting sodium and water dynamics	Picouet et al. (2012)
500 MPa	3 min	3°C	Sliced, skin vacuum-packed dry-cured ham	To evaluate textural changes	García-Gil et al. (2014)
400 MPa	10 min	12°C	Sliced vacuum-packed dry-cured ham	To investigate changes in the volatile fraction influenced by packaging material.	Rivas-Cañedo et al. (2009)
600 MPa	6 min	21 °C	Sliced, skin vacuum-packed dry-cured ham	To evaluate the influence on the volatile fraction	Martinez-Onandi (2017) Martinez-Onandi (2018)

Table 6. Ultrasound technology applications across the dry-cured ham process sorted by method parameters

TECHNOLOGY	MEASURE CONDITION		PURPOSE OF THE RESEARCH	REFERENCE
	INTENSITY	TEMPERATURE (°C)		
Ultrasound (US) Through-transmission	1 MHz	2 °C	To predict the fat content in dry-cured hams for industrial classification	De Prados et al. (2015)
			To monitor dry salting	De Prados et al. (2016)
		2 °C and 15 °C	To predict salt and fat contents	Fulladosa et al. (2015b)
		0, 2, 4, 6, 8, 10, 12, 14, 20, 22 and 24 °C	To characterize the melting properties of subcutaneous fat	Niñoles et al. (2010)
	50 W	40, 45 and 50°C	To shorten the hot air mild thermal treatment applied to correct the texture	Contreras et al. (2018)
	4.2, 11 and 19 W cm ⁻²	Below 21°C	To accelerate the curing stage	McDonnell et al. (2014)
Ultrasound (US) Pulse-echo mode	600 W	50 °C	To correct texture defects	Pérez-Santaescolástica et al. (2018)
	1 MHz	2 °C	To monitor dry salting and to predict the final salt content	De Prados et al. (2017)
	0.75 MHz	6 °C	To characterize	Corona et al. (2013b)
Scanning acoustic microscopy	10 MHz	6 °C	To characterize	

Table 7. Other non-invasive technologies with potential use in the dry-cured ham process sorted by measure conditions

TECHNOLOGY	MEASURE CONDITIONS	PURPOSE OF THE RESEARCH	REFERENCE
PULSE ELECTRIC FIELDS (PEF)	VOLTAGE 25 kV PULSE WIDTH 4-32 μ s FREQUENCY 1000Hz	To accelerate salting	McDonnell et al. (2014)
ELECTRICAL IMPEDANCE SPECTROSCOPY (EIS)	ELECTRICAL IMPEDANCE From 8 kHz to 1 MHz	To classify based on quality characteristics	Oliver et al. (2001)
	ELECTRICAL IMPEDANCE From 8 kHz to 1 MHz	To predict salt content and texture	Guerrero et al. (2004)
TIME DOMAIN REFLECTOMETRY (TDR)	FREQUENCY 20 MHz-5 GHz	To predict salt, water and fat contents	Fulladosa et al. (2013)
	TIME-BASE RESOLUTION 10 ps	To predict salt content, texture and a_w	
	FREQUENCY up to 5x10 ⁹ Hz TIME-BASE RESOLUTION 0-2.56 ns	To classify according to the pastiness level	Rubio et al. (2013)
MAGNETIC INDUCTION (MI)	INTENSITY 1 μ T INSPECTION VOLUME 45 cm width, 27 cm height, and 60 cm length	To predict salt content in whole hams after salting	Schivazappa et al. (2017)
LASER BACKSCATTERING IMAGING (LBI)	RESOLUTION IMAGEN 1280 x 960 pixels with WAVELENGTHS RANGE 400-750 nm.	To determine composition and textural characteristics	Fulladosa et al. (2017)