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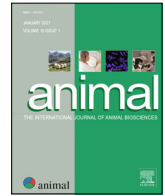


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Review: Pork quality attributes from farm to fork. Part II. Processed pork products

B. Lebret ^{a,*}, M. Čandek-Potokar ^b

^a PEGASE, INRAE, Institut Agro, 35590 Saint-Gilles, France

^b KIS, Agricultural Institute of Slovenia, Hacquetova ulica 17, 1000 Ljubljana, Slovenia

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ABSTRACT

Pork is often consumed in a very wide variety of products, processed from integral cuts or minced meat using different conservation methods (curing, smoking, cooking, drying, fermenting). Quality of pork products results from a combination between the properties of the raw material and the processing conditions to elaborate the final products. The influence of primary production factors, slaughtering and carcass processing on the quality of fresh pork has been reviewed (part 1), considering quality as an integrative combination of various attributes: commercial, organoleptic, nutritional, technological, convenience, and societal image, the latter denotes cultural, ethical (including animal welfare) and environment dimensions related to the way pork is produced, processed, and its geographical origin. This review (part 2) focuses on the influence of primary production factors and processing techniques on the quality of two important and economically significant processed pork products issued from contrasting processing techniques: cooked ham and dry-cured ham. As with fresh pork, many factors influence the quality of processed products, and one factor can affect several attributes. Moreover, in the case of processed products, numerous factors in both animal production and processing steps interact to determine their quality attributes. The quality of cooked ham depends on the properties of the raw material (in particular pH, colour, water holding capacity, presence of destructured meat defect, etc.) which are determined by pig husbandry practices (especially the genotype), pre-, postslaughter and processing conditions including the composition of curing mixture (ingredients, additives), salting, mixing and heat treatment. Processing techniques of cooked ham aim at homogenising the product quality within a given quality category (e.g. 'standard' or 'superior') or brand. Therefore, the variability of raw material is problematic for the cooked ham processing industry, which generally seeks uniformity and homogeneity of fresh hams. Likewise, pig husbandry conditions exert even greater impact on dry-cured ham quality. Indeed, the properties of raw material (including weight of fresh ham, fat thickness, pH, intramuscular fat and antioxidants content, fatty acid profile, etc.) that result from combined effects of primary production factors (genotype, feeding, production system, etc.) interact with processing conditions (salting, drying, ripening conditions and duration, etc.) to elaborate the quality attributes of the final products. Synergies can be sought between the primary production factors and processing techniques leading to specific organoleptic characteristics (texture, taste, aroma, flavour, etc.) that can be valued by quality labels. Quality of products is thus built along the whole chain from farm to fork.

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Implications

Pork processing is characterised by a wide range of products owing to and being determined by the type of raw material (meat cuts) and preservation technique used: cooking, dry-curing, salting, smoking, fermentation, etc. Their quality attributes are thus formed along the whole chain, with relative importance of pig

husbandry factors or processing mode varying according to the product. Promoting synergies between these factors can lead to specific products of high organoleptic quality and typicity which can be recognised by official quality labels.

Introduction

Pork is the first meat consumed in Europe and Asia and the second worldwide just after poultry (IFIP, 2021a). Contrary to meat of

* Corresponding author.

E-mail address: benedicte.lebret@inrae.fr (B. Lebret).

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other species, pork is mainly consumed in the form of various processed products, which accounts for 55–60% of pork consumption in Italy and Poland, around 65% in Spain, 70% in Germany, 75% in France and up to 80% in the United Kingdom (Lécuyer and Legendre, 2015). Historically, the aim was to promote pork preservation, according to procedures and recipes that varied according to region, climatic conditions and cultural habits. This diversity and regional specificities remain. Thus, among diverse “charcuteries” produced in France, the main products are cooked ham and shoulder, various sausages (cooked or dry-cured) and, to a lesser extent, dry-cured pieces (ham, belly) (IFIP, 2021a). Dry-cured pork products are particularly diverse with respect to the preservation techniques used (dry salting or brine salting, smoking or not, long or short ripening time). For example, typical Mediterranean dry-cured ham processing is characterised by dry salting, no smoking and long drying process, while brine salting and smoking are used in continental parts of Europe.

This wide variety of pork products leads to specific requirements regarding the quality of the raw material. For a given product type, the raw material requirements of processors may vary depending on the manufacturing process (recipe) and possibly a quality level of the final product. In addition to the European regulations on the general principles of food safety and consumer protection (EC 178/2002), national rules may also apply for pork products (Lécuyer and Legendre, 2015). For example, the French “Code des usages de la charcuterie”, a compendium of good practices for processed meats established by the professionals of the sector, serves as a reference document for the professionals, control bodies, retailers and consumers. It details the recipes, ingredients and processing techniques for more than 400 pork products (IFIP, 2017). Similarly, other European countries have more or less comprehensive national rules that are covering some of the products (Lécuyer and Legendre, 2015), e.g. the “Real Decreto 474/2014” in Spain (BOE, 2014). Pork products can also be produced according to producer’s specification and/or under official or private quality labels. In Europe, a quality policy was developed to support the collective actions for protection of added value products. In addition to organic production, official European quality labels value the specificity and typicality of the products linked to their geographical origin or tradition, as regards to the pig production, product processing or preparation. Protected Designation of Origin (PDO) and Protected Geographical Indication (PGI) value products for which all (PDO) or only some (PGI) production stages are carried out in a given geographical area and contribute to the product typicality; Traditional Speciality Guaranteed (TSG) values a traditional mode of production or recipe (EU, 1151/2012). In Europe, many pork products benefit from this protection and the eAmbrosia platform (<https://ec.europa.eu/info/food-farming-fisheries/food-safety-and-quality/certification/quality-labels/geographical-indications-register/>) gathers all the specifications of products with quality signs. The specifications, especially for PDO products which need to demonstrate a strong connection with the territory, set also requirements on pig rearing (e.g. breed, feeding), thus combining all stages of production and processing in the development of product quality.

In this context, the objective of our work was to consider the main factors from farm to fork (i.e. animal production and processing conditions) that interact to form the final quality of processed pork products. A first review (part 1) deals with main factors along the production chain affecting the quality attributes of pig carcasses and fresh pork (Lebret and Čandek-Potokar, 2021). Quality has been divided into various attributes - commercial, organoleptic, nutritional, technological, convenience, safety and societal image. The latter corresponds to product’s extrinsic cues, encompassing the credence, ethical, cultural and environmental

dimensions related to the way a food is produced and its geographical origin, all of which playing a role in shaping consumer perceptions, purchase decisions and are promoted in product quality labelling schemes (Prache et al., 2021). Considering the huge diversity of pork products in terms of processing techniques, raw material used and quality attributes (organoleptic, nutritional, societal image, etc.), we focus on two product categories of great economic importance, but differing in processing technique and image to the consumers: cooked and dry-cured products. Within each category, we choose to detail one emblematic cut: cooked ham and dry-cured ham.

Cooked products – Emphasis on cooked ham

Important properties of the raw material for processing into cooked ham

Some physical and biochemical properties of fresh ham are essential for its processing suitability in cooked ham. We describe here their influence on the manufacturing process and their evaluation methods commonly used in the industry. Quality requirements set by the processors in the specifications, i.e. the quality criteria and thresholds for acceptance or rejection, depend on the quality category of the final product (e.g. standard, choice or superior (premium) in France (Code des usages, IFIP, 2017); “prosciutto cotto”, “prosciutto cotto scelto” and “prosciutto cotto di alta qualità” in Italy (Gazzetta Ufficiale, 2005)). The quality criteria of fresh ham generally include i) its weight (for processing into whole cooked hams), ii) the presence of defects (petechiae or haematomas), iii) the thickness of subcutaneous fat, which must be as thin as possible especially for cooked hams without rind, and of white colour, iv) the colour of muscles: should not be too pale or heterogeneous, as it is related to the water holding capacity (WHC) of meat, the lighter the colour the lower the WHC (Prevolnik Povše et al., 2015). Muscle colour depends on numerous factors related to the animal itself, its husbandry during rearing and preslaughter phase, and to the rate and extent of postmortem pH decline (Lebret et al., 2015; Lebret and Čandek-Potokar, 2021). In pork industry, meat colour is usually assessed using the Japanese scale (6 levels), avoiding the lowest (1 and 2: light) and highest (6: dark) scores (Lebret et al., 2015); v) the ultimate pH of meat (pHu) which remains the best predictor of technological yield. For cooked ham, it directly depends on meat WHC, i.e. the capacity of muscle (especially myofibrillar) proteins and structures to bind and entrap the inherent muscle water. WHC depends on pH, ionic strength, oxidation and solubility of proteins and is the lowest at their isoelectric point (pH = 5.1–5.3). WHC is also impaired in the case of fast postmortem pH decline (i.e. low pH1) which, in combination with high muscle temperature, leads to protein denaturation and pale, soft and exudative (PSE) meat (Prevolnik Povše et al., 2015). In industry, pHu measurement (much easier than pH1) is usually performed in the *semimembranosus* muscle (SM); a minimal value of 5.60 is required for processing into superior quality, while lower values can be accepted for choice or standard categories. vi) The presence and extent of the so-called PSE-like or “destructured” meat defect, characterised by a loss of structure and fibrous aspect of muscles which present a soft mass. This defect is macroscopically similar to PSE meat but mainly localised in the deep part of the ham (*adductor* and SM muscles) and therefore not visible before deboning (Minvielle et al., 2001; Theron et al., 2019). In a cooked ham, the defective muscle areas are disintegrated with jelly-like texture, resulting in decreased yields at slicing (especially in the case of high-speed slicing) and leading to significant economic losses in industry. This defect is particularly critical in the case of salt reduction or omission of additives (phosphates) for

processing (IFIP, 2014; Neyrinck et al., 2015). The aetiology of destructured meat is still not well understood but research demonstrates that it is multifactorial and has identified some risk factors: preslaughter conditions, season, genotype, sex and fast growth associated with high carcass lean meat content (Schwob et al., 2018). It has mainly been related to low pH1 and especially low pHu and low WHC (Minvielle et al., 2001; Voutila, 2009). Destructured meat has been associated with decreased protein solubility, changes in postmortem proteolysis and increased oxidative stress and apoptosis in muscle tissues (Hugenschmidt et al., 2009; Theron et al., 2019). However, the hypothesis of altered properties of the intramuscular connective tissue could not be demonstrated (Minvielle et al., 2001; Voutila, 2009). Despite improvements in pig production related to elimination of the RYR1 and RN⁻ mutations, two most important genetic factors affecting the rate and extent of pH decline, respectively (Lebret and Čandek-Potokar, 2021) and a better control of preslaughter (e.g. fasting duration), transport and slaughtering conditions (avoiding stressful pig handling), this defect still affects around 15% of hams in France, but is highly variable (0–30%) (Schwob et al., 2018). Clinquart et al. (2021) recently reported an incidence level of 39% in a field study conducted in Belgium. To the best of our knowledge, no study has yet been conducted to show the impact of recent trends in abandoning male piglet castration on destructured meat, but one hypothesis increased defect occurrence due to leaner carcasses of entire males. In pork industry, this defect is assessed after boning, using subjective evaluation by trained staff on a 4-point scale (IFIP, 2014). Spectral prediction methods are currently being explored, with the aim of upstream ham sorting, or adapting formulations during processing to the quality of the raw material. Near infrared spectroscopy shows good ability (84–90% correct classification) to predict the presence of destructured or PSE defect on deboned ham by scanning SM surface (Vautier et al., 2013; Neyrinck et al., 2015). Detection on bone-in ham, more useful for industry, is also possible; however, the classification accuracy (60–70%) is lower and might be improved by extending the spectrum to the visible region (Neyrinck et al., 2015; Vautier et al., 2017). An imaging system called “JamboFlash” has been recently developed by the French Technical Institute for pig production (IFIP) and the private company CSB system, to detect this defect by digital vision at high speed in industrial environment (IFIP, 2021b). At present, SM pHu remains a good indicator for the destructured meat defect: the risk is multiplied by 3.2 when the pHu decreases by 0.10 unit below 5.60 (and below 5.70 for Nn pigs, i.e. heterozygotes for the defective mutation in the RYR1 gene) (Schwob et al., 2018). The major quality criteria for cooked ham processing described here are determined by various pig production factors related to the animal itself (mainly the genotype, sex, slaughter age/weight), its feeding and rearing conditions, and especially preslaughter handling, slaughtering and carcass refrigeration conditions, as detailed in our companion review (Lebret and Čandek-Potokar, 2021) and summarised in Table 1.

Manufacturing process

Processing into cooked ham involves a series of complex operations to obtain a product of optimal quality (appearance, colour, texture, taste, storage stability, safety, convenience, etc.), while ensuring good economic performance, essentially determined by technological yield, thanks to a good processing control. The main steps of manufacturing process described here are based on Aberle et al. (2012), Arnau Arboix (2014), IFIP (2014) and the French “Code des usages de la charcuterie” (IFIP, 2017) and are summarised in Fig. 1.

Selection of raw material, boning, trimming

The degree of preparation and the properties of fresh ham required by the processor (specifications) depend on the quality category of the final product (standard, choice, superior). Preparation can range from the raw piece with bone and rind, to boneless ham with rind, boneless without rind and trimmed, up to muscle cuts (without intermuscular fat, connective or vascular tissues) for the production of presliced products. The raw material authorised is the “hind leg” of the pig, which may contain the rind and subcutaneous fat; the ham muscles to be used depend on the product category. The required level for quality criteria of raw material is higher for superior than choice or standard products, since the allowed ingredients and additives, and their concentration, decrease with increasing quality category. A high quality of raw material is also necessary for the production of cooked ham to be sold presliced, as there is a higher risk of product damages when slicing at high speed, as practised in the industry.

Curing and tumbling

The curing step of processing is carried out by adding brine, a homogeneous water mixture of functional ingredients to the ham. Brine concentration depends on the product quality category, with the higher quality requiring a more concentrated brine. Injection rate of brine is variable and depends on desired quality level of the finished product. For superior quality, it is below 10%, in most cases, it is between 25 and 50% of raw muscle weight (Moretti et al., 2009; IFIP, 2014) but the injection gain can be even higher, up to 100% (Arnau Arboix, 2014). The ingredients used for meat processing are regulated at international or national levels, as part of the regulation on provision of food information to consumers in Europe (EU, 1169/2011) and by the Food Safety and Inspection Services of the Department of Agriculture and the Food and Drug Administration in the United States, as example. Ingredients can depend on ham quality category; for example, water binders and gelling agents are not allowed under the French regulation for the superior quality category (IFIP, 2014, 2017). Brine ingredients are i) Salt or sodium chloride, the main one; sodium provides the salty taste, and chloride ions enable the solubilisation of muscle proteins and promote their WHC, ensuring good cooking and slicing yields. In France, according to national rules (Code des usages, IFIP, 2017), sodium content depends on the quality category (i.e. maximum in the finished product of 3.0% for standard and 2.0% for superior); allowed substitutes are potassium, calcium and magnesium chloride, and should be labelled as additives. ii) Nitrite salt (of potassium or sodium; additives, respectively, E249 and E250): nitrite is used in meat processing for its preservative role (see Safety attributes section). However, it also contributes to the development of bright red colour with the formation of nitrosomyoglobin before cooking (by combination of nitric oxide resulting from reduction of nitrite and myoglobin) and to the flavour of the product. The ingoing amounts, i.e. maximum use level of nitrites (or exceptionally their residual amounts in the case of some traditionally cured meat products), are regulated by the law (EC 1333/2008 in Europe). Maximum use level is the same for all quality categories of cooked ham, i.e. 150 mg/kg of sodium nitrite in Europe. However, some member states have more restrictive legislations e.g. 120 mg/kg in France (Code des Usages, IFIP, 2017) and 60 mg/kg in Denmark (Decree (BEK) No 542 of 27.05.2013). The use of nitrites for the processing of food products has been debated since the 1970s, due to their involvement in the development of carcinogenic compound nitrosamines (Honikel, 2008; Flores and Toldrá, 2021), the reaction being favoured by high temperatures and acidic conditions. iii) Sugars (dextrose, sucrose, lactose, etc.; considered as ingredients) may be included to impart

Table 1
Major factors from farm to fork affecting the quality of cooked ham.¹

Factors	Quality attributes						
	Commercial ²	Processing suitability	Organoleptic	Nutritional ³	Safety	Convenience	Societal image ⁴
Genotype	+++	+++	++	+	–	–	++
Sex	++	+	++ (flavour)	+	–	–	+++
Age/weight at slaughter	++	–	+	–	–	–	++
Muscle/Muscle cut ⁵	+++	+++	+++	++	–	–	+++
Feeding	++	+	+	++	++	–	+++
Rearing conditions	++	++	+	++	++	–	+++
Preslaughter handling	+++	+++	+++	–	+++	–	++
Slaughtering and carcass refrigeration conditions	+++	+++	+++	–	+++	–	++
Preparation of raw material	+++	+++	++	++	+++	–	+
Curing		+++	+++	+++	+++	–	+++
Tumbling-massaging		+++	+++	+	–	–	–
Heat treatment		+++	+++	+	+++	–	+
Slicing and Packaging		+++	+++	+++	+++	+++	+++

¹ Effect: none (–), weak (+), medium (++), strong (+++).

² Commercial attributes of the raw material before processing.

³ Nutritional characteristics of the final product: salt, sugars, protein, lipids, nitrites and phosphates contents, and fatty acid composition.

⁴ Societal image attributes: preslaughter and slaughtering conditions relate to the perception of pig handling and transport conditions and the size of slaughtering and processing plants. Curing relates to the method (immersion allows the use of label “traditional”) and the brine composition (salt content, addition or not of nitrites or other additives).

⁵ The muscles used differ according to the quality category of cooked ham.

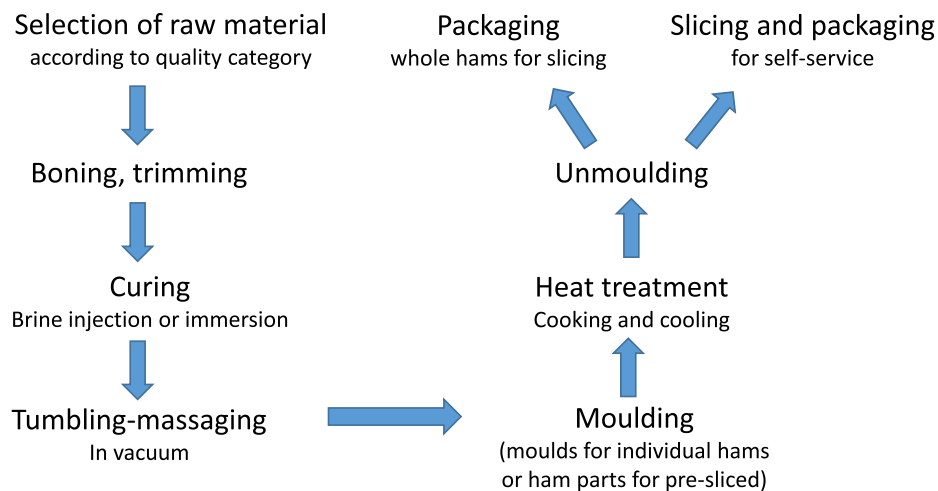


Fig. 1. Diagram of the technological process for the manufacturing of cooked ham (from Aberle et al., 2012; Arnau Arboix, 2014; IFIP, 2014, 2017).

a desired degree of sweetness and to promote colour and flavour; sugar addition level decreases with increasing quality category (3.0–0.5% from standard to superior). iv) Phosphates (additives): their main function is to increase meat WHC by raising the pH away from the isoelectric point of proteins and to reduce meat shrinkage on subsequent heating, thus improving processing yields. They are also able to chelate metal ions that catalyse lipid oxidation, delaying the development of oxidative rancidity. Because they were criticised by consumers for their “chemical product” image and the fact that they artificially increase the water content in the finished products, their use has been drastically decreased in some countries in past 20 years; as example in France, their addition is nowadays allowed in standard (0.5%) and choice (0.2%) but not in superior ham category. v) Reducing agents and antioxidants (additives; e.g. ascorbic or erythorbic acids or their sodium salts): they facilitate the formation of nitrosomyoglobin which is then stabilised by heating, and act as oxygen scavengers to limit oxidation reactions which could impair colour and taste of products during storage. Control of oxidation in cooked products is best achieved by a combination of additives: polyphosphates controlling initiation, nitrites acting as free radical acceptors, and

reducing agents as oxygen scavengers. vi) Spices and aromatics, condiments, flavour enhancers, aromas, etc.: these ingredients give the aromatic specificity to the product, especially in the case of fast processing methods, and contribute to colour. The authorised products and their maximum contents may depend on the product category. An effective flavour potentiator that activates the umami receptor is monosodium glutamate, which potentiates the savoury meat note (its maximum use level is limited). vii) Other authorised ingredients for the processing of standard quality ham include gelatin, pork blood protein and gelling agents (considered as additives). Curing is nowadays, especially in large processing plants, generally carried out by injection of the brine into the muscles using automatic multi-needle injectors, which allows to shorten the curing procedure and to distribute evenly the brine. Muscle tenderising is undertaken for small muscles and superior quality hams to support cooking yield, slice coherency and firmness of the final product. It consists in making small vertical cuts into the muscle using needles or blades (knives) to enlarge its surface and facilitate brine penetration. Immersion of hams into the brine was done traditionally, which lasted several weeks and was difficult to control (hams were not homogenous). Nowadays, it is used

only for superior hams aiming at quality differentiation. After a tempering step to achieve homogeneous temperature of the raw material, brining is undertaken at around 3–8 °C; increasing the temperature promotes salt penetration but reduces the microbiological stability of the brine.

Tumbling-massaging is one of the key steps in cooked ham manufacturing; it provides an intense mechanical action that facilitates the gel forming ability i.e. the extraction of salt-soluble proteins and the formation of “mixing silt” (water, salt, solubilised proteins) which will coagulate and bind the muscles during cooking. Tumbling replaces the maturation phase of “traditional” processing by brine immersion. It is carried out in rotary tanks for many hours (depending also on the brine concentration) with alternating phases of rotation and rest, at 3–6 °C, and in vacuum to avoid foaming (Arнау Arboix, 2014; IFIP, 2014). Tumbling also softens the muscles which facilitates moulding and helps to prevent the formation of holes, and promotes the reactions of nitrite and its derivatives in colour development. Thus, tumbling improves the functionality of brine ingredients and thereby the technological yield and sensory properties of cooked ham. Final result is influenced by massaging time, rotation speed, vacuum, temperature, and tumbler size; all these factors should be adapted to the different types of cooked ham (Arнау Arboix, 2014; IFIP, 2014).

Moulding and heat treatment

The kneaded meat is placed in rigid moulds of variable size and shapes, for either integral hams or ham parts up to 20–25 kg. A polyethylene layer is used to prevent the meat from sticking to the mould, and prevacuum is applied to avoid holes in cooked product due to air locked between muscles. Meat can be also vacuum-packed in thermoshrinkable plastic bag, which can act as a mould (Arнау Arboix, 2014). The heat treatment has several objectives and effects: i) product pasteurisation and its microbiological stabilisation, making heat treatment a critical step in the process, ii) firming of texture due to the gelation of muscle proteins, iii) development and stabilisation of the specific bright pink colour of cooked ham (heat denaturation of myoglobin and transformation of nitrosomyoglobin into nitrosylhemochromogen), and iv) flavour development: heating favours the formation of new compounds that contribute to the specific flavour, which in any case depends mainly on the brining method and duration (traditional immersion brining giving more flavoured products). Moulded hams are cooked with water or steam using constant, increasing, or decreasing temperature (i.e. initial high then reduced cooking temperature). The first cooking method is the most common way, the second is optimal but longer, while the latest is the most rapid but provides lower yields and cohesion of the slices. Smoking can be applied either before (but involves several manipulations) or after cooking (easier but gives a less marked taste). The heating process (time/temperature) depends on the target pasteurisation value and brine composition: the targeted core temperature can be lower for hams without polyphosphates or gelling agents (65–66 °C) than for those containing them (70 °C) (IFIP, 2014). Cooling is also an important phase as it influences the pasteurising effect and the firming of texture and slicing yield, which are favoured by a moderate temperature decrease to about 30 °C, then temperature decrease is faster to avoid microbial growth.

Processing and slicing yields

Major determinants of processing and slicing yields of cooked ham are meat WHC and the absence of destructured defect. These parameters, which are partly associated, are closely related to the kinetics of postmortem pH decline, which in turn depends on many upstream factors. In addition, the manufacturing and slicing yields are influenced by the technological parameters of the curing, tum-

bling and heat treatment steps. The type and content of brine ingredients and additives influence water retention during cooking and processing yield; tumbling is also critical for cooking and slicing yields due to the role of “mixing silt”. Heat treatment (duration/temperature) must be optimised to limit liquid losses, which increases with temperature, while keeping a high level of hygiene (microbial stabilisation) and slice integrity especially for industrial (high speed, thin slices) slicing.

Slicing and packaging

Cooked hams can be marketed sliced or as whole pieces to retailers who will slice them for consumers. After cooking, hams are removed from the moulds and packaging pierced to allow the flow out of cooking juices. Hams are stored at 2–4 °C up to 7 days to stabilise colour and texture and avoid slicing problems. Shelf life of hams marketed sliced depends on the additives used during processing, the packaging method and the product bacteriological status. Packaging should exclude the presence oxygen to preserve the typical colour (it generally contains a mixture of nitrogen and CO₂) and product should be kept at refrigeration temperatures (2–4 °C) until it is supplied to the consumer (Arнау Arboix, 2014; IFIP, 2014).

Quality attributes of cooked ham: Roles of primary production factors and manufacturing processes

The organoleptic (appearance, colour, texture, flavour), nutritional, safety, convenience and societal image attributes of cooked ham result from interactions between the characteristics of the raw material, determined by primary production factors and the manufacturing conditions. The main effects of these different factors on the quality attributes of cooked ham are described here and summarised in Table 1.

Organoleptic attributes

The organoleptic attributes of cooked ham result from interactions and synergies between raw material properties and processing mode, along with the packaging method and storage of the products. Normally, good technological aptitude (high WHC, absence of destructured meat) enables to produce a favourable product appearance and texture for the consumer: typical pink colour, slice integrity and absence of slice defects (holes or pasty zones), appropriately soft texture and perception of meat fibres (IFIP, 2014; Neyrinck et al., 2015). The primary production factors known to influence fresh pork quality parameters such as colour, pH, WHC, etc., namely pig genotype, muscle, feeding, rearing conditions, preslaughter handling, slaughtering and carcass refrigeration conditions (Lebre and Čandek-Potokar, 2021) may also affect the organoleptic properties of cooked ham; however, the effects are less pronounced than on fresh meat (Kowalski et al., 2021). Other influencing factors are related to the fresh ham preparation (size, shape, muscles included), the addition of ingredients and additives according to quality category, the manufacturing parameters related to brine injection, tumbling and their duration, heat treatment and packaging method. The flavour of cooked ham is generally not very intense compared to other pork products and depends on the processing methods, especially the brine composition (presence and concentration of functional ingredients), method (injection or immersion) and duration of brining (Arнау Arboix, 2014; IFIP, 2014). The upstream factors related to pig production play a limited role, and the risk of boar taint (undesirable odour and taste of product from entire male pigs; Lebre and Čandek-Potokar, 2021) is low as cooked ham is purchased already cooked, usually consumed cold, and contains little fat. Indeed, Chevillon et al. (2010) reported high level of consumers acceptability (based on taste, odour, overall appreciation, and intention to re-

consume) for cooked hams from entire males (at high risk for androstenone odour in this study), similar to hams from females or castrated males. Only hams from entire males were noted by consumers to have a less pleasant odour when opening the package. Flavour can be altered by lipid oxidation favoured by non-optimal storage time or conditions, but the risk is low especially for trimmed cooked hams due to their low amount of fat.

Nutritional attributes

The nutritional attributes of cooked ham depend mainly on the composition of the raw material, and of the ingredients and additives used during processing. The nutritional properties of the raw material, such as the content and nature of lipids, vitamins, minerals and antioxidants contained in ham muscles (and in subcutaneous fat in case of hams marketed with rind), are determined by several pig production factors responsible for carcass fatness (genotype, sex, feeding level, etc.), and most importantly by the composition of pig diet with regard to the fatty acid (FA) profile and antioxidant content of tissues (Lebret and Čandek-Potokar, 2021). Possible strategies to increase the n-3 polyunsaturated fatty acid content and n-3:n-6 polyunsaturated fatty acid ratio in pork products to improve their nutritional value are well suited for cooked ham, and well used by the industry as the risk of flavour degradation due to lipid peroxidation is low in this product compared to dry-cured products (Hugo and Roodt, 2007).

The ingredients and additives used for processing, and the prescribed chemical composition and nutritional properties of cooked ham vary greatly depending on the product category. For example, the Italian legislation on “prosciutto cotto” includes a qualitative classification based on the moisture content of the final product corrected for contribution of fat and additives, the lower the value the higher the quality of the cooked ham, with threshold values for each of the three product categories (Gazzetta Ufficiale, 2005). According to French regulation, the maximum contents per 100 g of product are 8.5 and 4% for fat, 3.5 and 1% for sugar, and 3.0 and 2.0% for salt in the standard and superior quality categories, respectively, with these contents being intermediary in the ‘choice’ category (IFIP, 2017). The nutritional objectives to reduce the salt content of food, with processed meats particularly affected, have led to changes in the practices of pork processors who are offering a growing range of cooked hams (generally of superior quality) with reduced salt content. According to European regulation (EC 1924/2006) – 25% is the minimum salt reduction level required for claiming “reduced salt content” in cooked ham. Manufacturing this kind of product requires a raw material of high technological quality and a high control by processors at all processing steps to obtain satisfactory processing yields and high organoleptic and hygienic status of the final product (Desmond and Vasilopoulos, 2019).

Safety attributes

In terms of food safety, a growing concern with cooked ham and processed meat in general is the impact of nitrites on human health and ways to reduce their levels in processed products. Nitrite addition has been used in processed meat for a very long time as preventive measure against pathogenic bacteria including *Clostridium botulinum* (Flores and Toldrá, 2021). This crucial bacteriostatic function is recognised by European legislation which classifies the nitrites as preservative agents. Nitrites also contribute to the development and stabilisation of colour through the formation of nitrosomyoglobin, exert an antioxidant action, and contribute to the flavour of processed products (Honikel, 2008; Flores and Toldrá, 2021). However, residual nitrite, in presence of secondary amines which can be found in processed meats or after fermentation, and in certain conditions (high temperature, low pH, presence of haem iron) can generate N-nitroso compounds, most of which

are carcinogenic (e.g. nitrosamines). Nevertheless, the levels of nitrites used now are much reduced so that N-nitroso compounds are present in meat products at low levels, and contrary to public perception their carcinogenic potential likely to be minor (Higgs and Pratt, 1999). Moreover, recently published studies emphasise that drinking water nitrate can have a significant contribution to the endogenous formation of N-nitroso compounds, independently of the type of meat consumed, although subjects consuming processed red meat had a highest incidence of N-nitroso compounds formation (van Breda et al., 2019; Sinha et al., 2021). This is a complex task as humans do not consume meat products alone, they are part of a diet.

The reduction of nitrites to 40–60 mg/kg in cooked ham and pork products, or even their elimination to reduce the risks of N-nitroso compounds formation in products and during digestion, is a major challenge for processors who must assure microbiological safety, especially the absence of *Clostridium botulinum*, *Bacillus cereus* and *Listeria monocytogenes* in cooked ham. A recent study showed that the addition of sodium nitrites between 30 and 80 mg/kg during cooked ham processing prevented the outgrowth and toxinogenesis of *C. botulinum* Group II, regardless of the sodium chloride concentration (12–19 g/kg), while the complete removal of nitrite allowed the growth and toxin production during product storage (Lebrun et al., 2020). These authors concluded that the maximum use level of nitrite (150 mg/kg) allowed by European legislation could be reduced in cooked ham while ensuring the control of *C. botulinum*, whose outgrowth and toxin production should be evaluated on a case by case basis according to the recipe, manufacturing process and storage conditions. Additional measures should be implemented to guarantee the safety of nitrite-free products such as lower pH, higher sodium chloride concentration, strict cold supply chain and a shorter shelf life (Lebrun et al., 2020).

Cooked hams with “no nitrite salt”, “nitrite-free preservation” or “zero nitrite” claims have been on the market for some years now: no nitrites have been added during their manufacturing and their shelf life is therefore shorter than that of products manufactured with addition of nitrites. This also applies to ‘natural’ and ‘organic’ processed meat in the United States as the regulations of Department of Agriculture do not allow the use of chemical preservatives (nitrites or nitrates) for these claims. However, some recipes include natural sources of nitrite or nitrates, such as vegetable-based ingredients, especially celery, as broths or juices, and nitrate-reducing starter cultures (added lactic acid ferments) that reduce nitrates in the vegetable broths to nitrites (Flores and Toldrá, 2021). These cooked hams are therefore not nitrite-free, and have a characteristic pink colour. The “zero nitrite” products, made with no added nitrites or nitrates (via vegetable broths or juices), have a greyish colour similar to that of cooked pork and a shorter shelf life (about 10 days, compared to 4 weeks when nitrite salt is added). In accordance with consumer protection law, product claims must not be misleading. However, the current regulations do not provide a clear framework for claims on nitrites, in particular regarding their actual content in the products consumed; in this respect, a clarification by the public authorities would be appropriate in the interest of consumers.

Apart from the potential risks for human health associated with the use of nitrites during processing, cooked ham can be source of pathogens, e.g. listeriosis (Hachler et al., 2013). Salt reduction in cooked ham processing increases the rate of this pathogen, and of spoilage flora in general (Duret et al., 2019). The increased risk of *L. monocytogenes* leads processors to use additional control measures such as modified atmosphere or shelf life reduction to ensure the safety of salt-reduced products (Afssa, 2010). Often neglected is the significant role of consumers in the safety of food they consume (Kennedy et al., 2005). A multi-criteria analysis aiming at

evaluating the relationships between energy consumption for cold supply chain (transport, warehouse storage, household refrigerators), food safety (presence of pathogenic bacteria) and food waste (presence of spoilage bacteria) showed that setting household refrigerator thermostat to a precise temperature of 4 °C was the best combination (trade-off) to limit energy consumption while ensuring food safety and reduce food waste (Duret et al., 2019).

Convenience attributes

For the consumers, cooked ham has two key attributes: convenience of use (nothing to prepare!) and shelf life: up to 4 weeks at +4 °C for a product packaged under modified atmosphere. Shelf life highly depends on storage conditions, i.e. light and packaging. Haile et al. (2013) showed that discoloration of cooked ham during storage, estimated by loss of redness (a^*) and nitrosohemochrome, and by increased brightness, was higher for products packaged in clear, gas-permeable film and stored in the light than in similarly packaged products kept in dark. Discoloration depended on photochemical processes rather than on storage duration in dark or packaging. Colour stability was increased in products packaged in a modified atmosphere with little residual oxygen. On the other hand, lipid oxidation was not altered by light exposure, but increased with storage time in the dark, even in the case of short shelf life (Haile et al., 2013). Thus, storage conditions and packaging are key factors in extending the shelf life of cooked ham and convenience for consumers. A lot of research and development studies are undertaken in this regard with increasingly sophisticated (smart) food packaging (Lebret and Čandek-Potokar, 2021). Objectives are now to use thinner packaging and recyclable materials.

Societal image attributes

Regarding the societal image, the evolution in pork product supply, especially cooked ham, shows that pork chain stakeholders are taking into account the growing expectations of consumers concerning the way animals are raised and how products are elaborated (processing techniques). In addition to eating quality, convenience and authenticity associated with processed meat, citizens have recently added new expectations: they declare to pay (much) more attention to their diet, and this increased interest is accompanied by a growing critical thinking and increasing demand and mistrust towards the food industry. They also express the need to regain control over their food and to consume in a “responsible” way (Birlouez, 2019). The growing diversity of cooked ham supply demonstrates the dynamism of chain stakeholders at all levels to respond to image attributes searched by consumers towards pork processed products, with supply of cooked hams with increased n-3 FA, reduced salt content or without added nitrites, or produced from pigs raised without antibiotics (after weaning) or organic pigs. Some products combine claims related to pig production and processing technique. The strong competition between processors stimulates innovation in the sector. Improvements of product societal image also occur in the area of farm to fork product traceability, with for example some ‘integrated’ pork industries covering the whole chain, having set up a blockchain traceability system accessible to consumers via a QR code on the product.

Dry-cured products – Emphasis on dry-cured ham

Dry-curing is one of the oldest methods of meat preservation achieved by dehydration through the addition of salt and drying. Historically, the main objective of dry-curing was to preserve meat for times of scarcity. The development of processing techniques aimed to improve the organoleptic and nutritional product proper-

ties, leading to increased consumer acceptance and demand. Two categories of dry-cured products can be distinguished; products made from whole pieces or cuts (e.g. ham, shoulder, neck, belly) or various sausages consisting of minced meat and fat enclosed in natural or artificial casings. This presentation will focus on hams because they are the most representative. Moreover, in the case of sausages, product characteristics are affected by the action of microflora (which is not the subject of this review); however, the raw material characteristics required and their influencing factors are generally the same for all dry-cured products.

Important properties of the raw material for processing into dry-cured ham

The quality of dry-cured ham is strongly influenced by the properties of the raw material or as often referred to “suitability for processing”. These properties include i) the weight of fresh ham, with a minimum weight generally required (e.g. ≥ 9.0 kg in products with quality label) as the dynamic of salt diffusion depends on ham volume, ii) the subcutaneous fat thickness, also with minimum required (at least 10 mm, generally ≥ 15 mm) to avoid excessive final weight loss or ham defects related to leanness and too much salt intake due to enhanced salt diffusion and, iii) the absence of visual/appearance defects (e.g. skin lesions), iv) the firmness and colour of subcutaneous fat which are linked to its FA composition and especially its polyunsaturated fatty acid content, with aim to avoid excessive lipid peroxidation, and v) the meat physicochemical properties, generally assessed by pHu which should be in the range considered as normal values (5.5–6.2 in SM), or by visual colour assessment (Ramos et al., 2007; Čandek-Potokar and Škrlep, 2012). Recently, Dall’Olio et al. (2020) tried to predict ham weight loss at first salting, a selection criterion in Italian breeding programme for heavy pigs. They confirmed that ‘ham seasoning aptitude’ improves with an increase in backfat and pHu and a decrease in lean cuts. As reviewed by Lebret and Čandek-Potokar (2021), meat and fat qualitative characteristics are determined by rearing factors, in particular the breed (or genetic line), diet and housing (i.e. production system), and by preslaughter and slaughtering conditions regarding meat pH and colour. For dry-cured ham manufacturing, it is extremely important to avoid quality defects associated with pig handling prior to slaughter and carcasses handling on the slaughter line and during refrigeration, since damage inflicted on hams at this stage may render the raw material unacceptable for further processing. Typical defects associated with these stages are traumatic and non-traumatic haematomas, intramuscular petechiae, internal haemorrhages, incisions, veining, tissue separation, PSE appearance and contact spots due to carcasses touching during chilling (Čandek-Potokar and Škrlep, 2012).

Manufacturing process

Unlike cooked ham, dry-cured ham is processed with few additives and little technology, and still relies heavily on the know-how of the producers. Despite important differences in the manufacturing process (e.g. dry or in-brine salting, including smoking or not, different shaping of hams, bone-in or deboned) resulting in various, typical sensory characteristics, they are essentially based on the same principle, namely salting and dehydration. The research has demonstrated that the quality of dry-cured ham depends on the processing method, in particular the salting mixture (use or not of nitrites), conditions and duration of each processing phase, and the quality of the raw material. Various processing techniques for dry-cured ham exist but all of them aim to make a product that is stabilised and can be conserved at room temperature without health risks or product quality changes. Organoleptic attributes,

especially colour, texture and taste, are the most important determinants of consumer appreciation, although nutritional value, price and product convenience are also important (Resano et al., 2011). The processing phases are characterised by three main steps: salting, resting (salt equalisation) and drying with ripening. They are described here based on previous reviews (Čandek-Potokar and Škrlep, 2012; Petrova et al., 2015a and 2015b) and the “Code des usages” (IFIP, 2017) and are summarised in Fig. 2.

Selection of raw material

The quality of the raw material (fresh ham) required by the processors from their suppliers depends on the quality category of the final product e.g. standard, superior, and/or specifications related to quality labels (e.g. PDO, PGI, TSG). In addition to the pig breed/genotype and production system (housing, feeding, age/weight at slaughter, etc.) demanded in some specifications, the major quality criteria are the ham weight and appearance (shape and absence of defects), the thickness of subcutaneous fat and pH of muscles, which all influence the manufacturing process (Čandek-Potokar and Škrlep, 2012).

Salting

Before salting, hams are first trimmed or shaped to the prescribed form (rounded cut) and pressed (usually mechanically) to remove residual blood from the artery and femoral vein. The salting procedures differ with regard to the mixture of salt used and salting method. The ingredients and additives used and/or allowed depend on the category of the final product and specifications in the case of quality brands, and may include i) the salt (in some quality brands of specified origin), ii) sugar (maximum use level of 0.5%): mainly used for dry hams of short processing time (≤ 7 months), it provides a sweet flavour (Gou et al., 2012), iii) spices and aromatic compounds, iv) nitrate of sodium or potassium (additives E251 and E252, respectively; preservative which is transformed into nitrite by the microflora) with maximum dose of use

of 150 mg/kg and maximal residual dose of 250 mg/kg according to European legislation (EC 1333/2008) and in the absence of added nitrite, v) nitrite of sodium or potassium (in association with nitrate), vi) potassium, calcium or magnesium chloride (additive), vii) ascorbate (additive, allowed only for standard cured ham category). The salt mixture is generally slightly moistened to promote its diffusion. It is provided in excess, whether applied to the open muscle masses (with a particularly thick layer of salt around the femur head to prevent putrefying) and called ‘soft’ salting (used for Parma ham for example), or if buried in the salt (technique used in Spain for Serrano and PDO hams from Iberian pig). In any case, salting duration is adapted to the weight of ham. It lasts approximately 1 day per kg for burying salting (Gou et al., 2012) and is longer (between 14 and 21 days) for soft salting, for which open surface of ham is covered with coarse salt and usually applied in two steps. Before salting, which should ideally start within 48 h postmortem, a tempering step is applied to achieve a homogeneous temperature of raw material (1–3 °C). This temperature is maintained during salting to limit microbial growth on the surface of the ham. In case unfrozen meat is used, salting should be shortened to avoid excessive salt uptake. In most cases of European quality labels, ham freezing is not allowed and the acceptable time postmortem before salting is limited. On leaving the salting room, the hams are brushed to remove the residual salt. At the end of salting, the hams lose 3–5% of their weight despite absorbing the salt.

Resting

The hams are then left to “rest” at a low temperature, allowing the absorbed salt to diffuse and equalise in all muscles. In this period, important weight (water) loss occurs (>16%) which stabilises the product. The most important processing innovations in recent history have been associated with the use of cooling chambers in the initial steps of salting and resting phases, which allow the control of temperature and relative humidity in the most critical phase

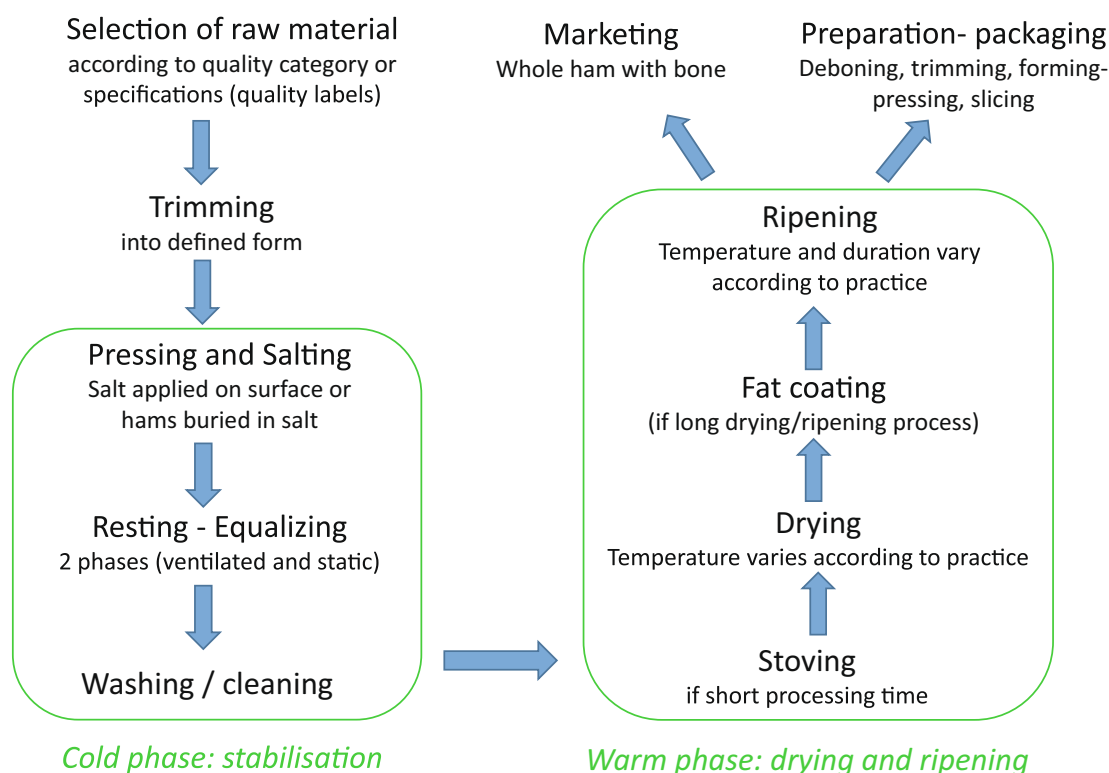


Fig. 2. Diagram of the technological process for the manufacturing of dry-cured ham (from Čandek-Potokar and Škrlep, 2012; Petrova et al., 2015a and 2015b; IFIP, 2017).

of product stabilisation (Gou et al., 2012). Overall, the preservation of dry-cured ham is achieved by means of dehydration, reduced water activity and sufficient salt concentration. During salting phase, the salt penetrates through muscles and skin with subcutaneous fat, but a small amount of salt reaches deep muscles at the end of salting. In the subsequent resting phase, the salt concentration in the entire piece equalises (Vestergaard et al., 2005). The amount of salt absorbed is proportional to the weight loss of ham during processing (Petrova et al., 2015b), which depends on the properties of the raw material (Čandek-Potokar and Škrlep, 2011). During resting, moisture is removed from the product by osmotic dehydration. In a first phase, which lasts about 2 weeks, a high dehydration is achieved thanks to a dynamic ventilation in order to reduce the growth of unfavourable surface microflora. In a second phase, dehydration rate is reduced due to a higher relative humidity and static ventilation; this stage lasts between 5 weeks and up to 3 months or even longer (e.g. in the case of Iberian or Parma hams) depending on the ham weight, inter- and intramuscular fat (IMF) content (which hinders salt diffusion) and the salt content (the lower the salt content, the longer the resting phase) (Petrova et al., 2015b; IFIP, 2017).

Drying - ripening

After the resting period, the hams are washed/cleaned and can enter the drying process which takes place at higher temperatures and is carried out at relative humidity of 65–80% and a moderate air speed to prevent excessive drying on surface (crust formation). During this phase, water is removed from the product by evaporation, driven by a humidity gradient between the air and the product. The final salt content is the result of salt absorption, diffusion, and concentration processes (Petrova et al., 2015b). Different drying techniques/conditions are used; either a short heating to 20–22 °C for several days to accelerate the enzymatic processes on proteins and lipids (described below) and then drying is continued at a temperature of about 15 °C (Italian technique), while in traditional Spanish process, the temperature rise is progressive and can go up to 26 °C or more. When the hams have lost about 25% of their weight, the exposed surface is covered with a layer of fat in order to slow down dehydration, while ripening continues until a predetermined processing loss and maturation period is reached, which depends on the product. During this phase, the product develops its organoleptic characteristics (colour, texture, taste); it may last several weeks or even several months.

Biochemical and physical changes during the process and impacts on product properties

The initial steps of processing are characterised by intense water loss and salt absorption, which, in addition to bacteriostatic function, strongly affect the activity of proteolytic and lipolytic enzymes in the subsequent stages. During the ripening, muscle proteins undergo an intense proteolysis due to the action of endogenous endopeptidases (cathepsins B, D, H and L, and calpains to a lesser extent) and exopeptidases (peptidases and aminopeptidases), resulting in a large amount of small peptides and free amino acids (AAs) (Petrova et al., 2015a). These molecules are further degraded to non-volatile taste precursors and volatile aroma precursors (aldehydes, alcohols) (Toldrá, 1998). Proteolysis also influences the texture, which becomes softer. The intensity of proteolysis and the profile of resulting molecules, which strongly influence the texture and flavour of the final product and thereby its typicity, depend on raw material properties (e.g. a low pH favours proteolysis) and ripening conditions (duration, temperature and salt diffusion) (Virgili and Schivazappa, 2002; Petrova et al., 2015a). However, excessive proteolysis which can result from high activity of cathepsin B due to high water activity and low salt diffusion (Parolari et al., 1994) can be detrimental, leading

to excessive softness and pastiness and unpleasant flavours (Virgili et al., 1995). Control of the proteolysis in dry-cured hams is of great importance, as texture is one of the most important traits that influence consumer acceptance (Morales et al., 2013).

Besides, muscle and fat tissue lipids undergo lipolysis by endogenous and exogenous i.e. bacterial lipases and phospholipases, generating free FA. These are further oxidised, generating a variety of aromatic compounds (alkanes, aldehydes, ketones, alcohols, esters, etc.) which contribute to the formation of fruity flavours of dry-cured ham, but also to rancidity (Toldrá, 1998; Gandemer, 2002). The profile of volatile compounds depends on the tissue FA composition which mainly results from the pig rearing conditions, in particular feed composition (Lebret and Čandek-Potokar, 2021) and on processing conditions including temperature and salt content which can have a pro-oxidant effect (Gandemer, 2002). While lipolysis is principally influenced by the manufacturing temperature, proteolysis is under the influence of salt and water activity (Toldrá et al., 1997).

Overall, the conditions inside the muscle (pH, salt concentration, water content and availability, temperature) combine with the processing conditions, in particular the salting method, duration and temperatures during drying and ripening, to influence the enzymatic activity and consequently the quality of the final product, i.e. the development of texture and flavour characteristics. The 'Spanish' processing technique leads to dry-cured hams with darker red colour, firmer texture, and more or less pronounced oxidation of FA (due to processing temperatures that favour the lipolysis) giving a full-bodied flavour. The 'Italian' technique gives products with a lighter red colour (due to natural red pigments including zinc protoporphyrin, in the absence of nitrates and nitrites (Wakamatsu et al., 2004)), softer texture, less oxidised fat and sweeter taste due to predominance of proteolysis during ripening. These Mediterranean types of dry-cured hams are characterised by dry salting with salt equilibration phase, drying and long ripening, whereas in northern and eastern European countries, the hams are usually smoked and ripening time is much shorter. Thus, the whole manufacturing period can last from few months (e.g. 7 months for the Serrano TSG or Bayonne PGI) to over 2 years for some high added value products (e.g. PDO hams from Iberian pigs).

Product preparation for marketing

The marketing of dry-cured hams is practised in different ways, as a (bone-in) whole ham, as a boneless ham in halves or quarters, or sliced and prepacked. The preparation of boneless products requires boning, trimming, shaping under an automatic press and conditioning during approximately one week to allow the cohesion of muscle masses, before cutting or slicing. The yield of the whole ham with the bone is about 65–70% of the fresh weight used, while it is about 35–50% for a sliced ham.

Quality attributes of dry-cured ham: Roles of primary production factors and manufacturing processes

The main properties of the raw material that are important for dry-cured ham manufacturing, which result from various factors related to the pig production system (genotype, diet, housing) and the conditions before and after slaughter (Čandek-Potokar and Škrlep, 2012; Lebret and Čandek-Potokar, 2021), interact with the processing conditions to elaborate the organoleptic, nutritional, safety, convenience and societal image quality attributes of the final products. These main relationships developed here are summarised in Table 2.

Organoleptic attributes

To achieve appropriate drying intensity and salt uptake during processing, sufficient backfat thickness of fresh ham is necessary,

Table 2
Major factors from farm to fork affecting the quality of dry-cured ham.¹

Factors	Quality attributes						
	Commercial ²	Processing suitability	Organoleptic	Nutritional ³	Safety	Convenience	Societal image ⁴
Genotype	+++	+++	+++	++	–	–	+++
Sex	++	+	+++ (flavour)	+	–	–	+++
Age/weight at slaughter	+++	+++	+++	++	–	–	+++
Muscle/Muscle cut ⁵		+++	+++	+++	–	–	+
Feeding	+++	++	+++	+++	++	–	+++
Rearing conditions	+++	+++	+++	+++	+++	–	+++
Preslaughter handling	+++	+++	+++	–	+++	–	++
Slaughtering and carcass refrigeration conditions	+++	+++	+++	–	+++	–	++
Preparation of raw material	+++	+++	+	–	++	–	+
Processing plant ⁶	+	+++		–	++		
Salting		+++	+++	+++	+++	–	+++
Resting		+++	+++	+++	+++	–	+++
Drying-ripening		+++	+++	++	++	–	+++
Preparation for marketing - Packaging		+++	+++	+	+++	+++	+++

¹ Effect: none (–), weak (+), medium (++), strong (+++).

² Commercial attributes of the raw ham before processing.

³ Nutritional characteristics of the final product: salt, nitrites and lipid contents, fatty acid composition.

⁴ Societal image attributes: preslaughter and slaughtering conditions relate to the perception of pig handling and transport conditions and the size of slaughtering plant. Salting relates to whether or not nitrates, nitrites or other additives are added.

⁵ The whole raw ham is processed into dry-cured ham; however, some qualitative characteristics vary according to the muscle.

⁶ Geographical location (including specific practices and know-how).

especially in the case of products subjected to long ripening. Too rapid drying can lead to surface crusting, which hinders drying and has a negative effect on maturation, in particular proteolysis, and should be prevented. Besides, the beneficial role of IMF on organoleptic characteristics of dry ham is well established and associated with a less firm texture and better flavour due to aromatic compounds resulting from FA oxidation (Gandemer, 2002; Pugliese and Sirtori, 2012). If pigs from the 'conventional' pig production for fresh meat market (i.e. fast-growing lean genotypes) are used, sorting of fresh hams with minimal fat thickness is recommended. The use of heavy pigs or pigs of fat breeds is more suitable for dry-cured ham production. For example, the products protected under the European quality policy (in particular PDO) often require the use of fat pigs from local breeds (Čandek-Potokar and Nieto Linan, 2019) or of heavy pigs (case of Italian "suino pesante" from modern breeds). However, when genetically improved breeds are used, crossing with Duroc breed is often used due to its high IMF content (Bonneau and Lebret, 2010). The superior texture and flavour of dry-cured hams from local breeds compared to genetically improved lean genotypes or their crosses have been clearly established by expert panellists, for example in Iberian and Basque breeds (Carrapiso et al., 2003; Lebret et al., 2013) as well as by consumers (Ventanas et al., 2007a). In the case of typical Italian PDO dry-cured hams, Pagliarini et al. (2016) also showed that specific pig genetic lines or crosses used for heavy pig production give higher organoleptic quality of Parma, San Daniele and Tuscan PDO hams, and a better consumer acceptance of Tuscan ham compared to dry-cured ham from standard commercial crosses. However, these authors also highlighted that the sensory properties and consumer acceptance depended more on the ham brand (i.e. processing conditions) than on the pig genotype. Genotype also determines the morphology of fresh ham and its muscle biochemical properties, including (in interaction with preslaughter and slaughter conditions) the postmortem pH decline and proteolytic potential, which influence texture development. Both a rapid and a high magnitude of pH decline can lead to increased salt uptake but also excessive proteolysis, which negatively affects texture (Virgili and Schivazappa, 2002; Čandek-Potokar and Škrlep, 2012; Petrova et al., 2015a).

Age and weight of pigs at slaughter are also important parameters. Heavy, older pigs, whether of local or "conventional" breeds selected on lean growth efficiency, are generally considered more

suitable for processing into dry-cured ham as they have higher adiposity and muscle pigment content, and lower muscle proteolytic potential which allows to avoid excessive proteolysis and too soft texture (Virgili and Schivazappa, 2002; Čandek-Potokar and Škrlep, 2012). Rearing these animals in extensive (free-range) systems, which combine a large space for freedom of movement and feeding based on local resources (e.g. grass, acorns, chestnuts, etc.) further contributes to the required meat characteristics i.e. a more intense red colour and increased lipid (especially monounsaturated FA) and antioxidant deposition in backfat and muscle tissues (Lebret, 2008; Pugliese and Sirtori, 2012). The combination of raw material properties, resulting from pig genotype and production system and adapted long ripening process, lead to products with specific organoleptic properties and typicality (Flores, 1997; Pugliese and Sirtori, 2012). The most representative examples are the PDO dry-cured hams from pure Iberian pigs, where the last fattening phase, after a period of restricted feeding, is carried out in a silvo-pastoral free-range system with feeding exclusively on acorns and grass (Montanera). Compared to dry-cured hams from Iberian pigs fattened in barns with concentrated feed mixtures, the Montanera system provides hams with better appearance (colour), texture (less firm, fibrous, and juicier), aroma (including fruity aroma) and taste, with less salty taste (Cava et al., 2000). These differences are also perceived by consumers (Ventanas et al., 2007a). Another recent study confirmed the preference of Spanish consumers with regard to odour, texture, taste and overall appearance of hams from 100% Iberian or Iberian × Duroc pigs acorn-fed during finishing, compared to Iberian × Duroc pigs receiving concentrated feed (cereals and legumes) (Diaz-Caro et al., 2019). Thus, feed resources are a way to improve organoleptic attributes of dry-cured ham and depending on the geographical origin (Rentfrow et al., 2012) or pig finishing season (Lebret et al., 2021), leading to flavour variations that can be valorised by quality labels. However, as shown in a study with Basque pigs kept in extensive system with local feedstuffs and concentrates vs indoors and fed with concentrates, sensory differences are smaller when feeding resources are less contrasted (Lebret et al., 2013).

Apart from extensive production systems associated with specific feeding practices, pig nutrition in general, including feed intake and diet composition, exerts a strong influence on carcass fatness and IMF content and composition (Lebret and Čandek-Potokar, 2021) and thereby on fresh ham properties. The FA profile plays

a key role in product flavour, especially in the case of long ripening due to the high sensitivity of polyunsaturated fatty acids to oxidation and the nature of the volatile compounds produced (Toldrá, 1998; Pugliese and Sirtori, 2012). Feed supplementation with antioxidants (α -tocopherol) or grass consumption by pigs in extensive systems is effective in increasing the tissue oxidative stability and the aroma and taste intensities of the final products (Ventanas et al., 2007b).

As described in companion review (Lebret and Čandek-Potokar, 2021), sex of pigs influences carcass fatness and the FA profile of subcutaneous and IMF lipids, the saturated FA content increasing with fatness and being higher in castrated males than females, and the lowest in entire males. Thus, the raw material from castrates is the most suitable and that of entire males the most problematic for dry-cured production due to insufficient subcutaneous fat thickness and IMF content, and high polyunsaturated fatty acid content. With respect to females, studies generally show no significant differences compared to castrates (Banon et al., 2003), however, Tomažin et al. (2020) found that hams originating from gilts were more proteolysed which was associated with differences in texture and colour. Dry-curing also does not mask or reduce the perception of boar taint; moreover, a recent study showed that dry-cured ham from entire males has a significant devaluation of sensory traits other than boar taint, hams from immunocastrated pigs being intermediate (Čandek-Potokar et al., 2020). Quality differences in dry-cured hams from entire and castrated males are also perceived by consumers, especially by women and by regular consumers of this product (Banon et al., 2003). Therefore, the abandonment of castration of male piglets strongly concerns the sector of dry-cured ham production, because of i) the increased risk of boar taint with increasing pig slaughter age and weight (heavy pigs are usually used for dry-cured ham processing), ii) the use of breeds at higher risk such as early maturing and fat local (Čandek-Potokar and Nieto Linan, 2019) or Duroc breeds, and iii) the change in meat technological quality (Lebret and Čandek-Potokar, 2021).

In addition to factors related to the pig and its rearing conditions, preslaughter handling, slaughter and chilling conditions may influence the organoleptic properties of dry-cured hams via their effects on postmortem muscle pH. A rapid pH decline (PSE meat) increases salt absorption and proteolysis, and a high pHu (dark, firm and dry meat) slows down salt diffusion and desiccation, possibly leading to pasty and soft products, and increasing the bacteriological risk (Virgili and Schivazappa, 2002; Čandek-Potokar and Škrlep, 2012).

Nutritional attributes

The nutritional properties of dry-cured ham can be modulated by pig production factors. As detailed, the lipid content of the raw material mainly depends on pig genotype and feeding intensity, while the FA and micronutrients composition (including antioxidants) depend on the diet composition. Supplementing pig diets with n-3 polyunsaturated fatty acids to improve nutritional value is not favourable for a dry-cured product, because of the significant peroxidation of polyunsaturated fatty acids during the process which can be detrimental to the flavour (risk of rancidity) and nutritional properties (formation of toxic compounds) (Hugo and Roodt, 2007). The addition of antioxidants (tocopherols) can limit lipid peroxidation but the dietary antioxidant level must be sufficient. Santos et al. (2008) thus demonstrated that 220 vs 20 mg tocopherol acetate per kg feed with 3% linseed oil was necessary to avoid sensory depreciation of dry-cured hams by consumers. In extensive systems, pig consumption of grass containing n-3 FA but also antioxidants (including α - and γ -tocopherols) increases their tissue content (Ventanas et al., 2007b; Pugliese and Sirtori, 2012), thus limiting the polyunsaturated fatty acid oxidation in pork products.

Healthy eating trends to reduce salt consumption have been the catalyst for the meat industry's efforts to reduce salt content in processed products, here comprised dry-cured hams. Since salt is the essential preservative (the only one allowed in many dry-cured ham specifications), its reduction is a challenge to ensure product safety and desired sensory quality (control of proteolysis and lipid peroxidation) (Andres et al., 2004; Čandek-Potokar and Škrlep, 2012). During processing, salt uptake can be managed and reduction achieved by adding a smaller amount of salt or (more commonly) by shortening the salting time. However, the resting step must be prolonged to reach the water loss and water activity considered as safety thresholds (18–19% and 0.96, respectively) before proceeding to the drying phase (Pinna et al., 2020). Since salt lowers water activity and thus enzyme activities, reducing ham salting increases the risk of excessive proteolysis (Pinna et al., 2020), especially at low pH and in the deep muscles of the ham, to which salt diffusion takes longer. Thus, effects of salt reduction on sensory quality are mainly manifested in deep muscles such as the *biceps femoris*, with reduced salty taste, greater proteolysis, softer texture and less intense flavour (Andres et al., 2004; Tomažin et al., 2020). In summary, reducing the salt content of dry-cured ham to promote nutritional benefits requires a balance between salt reduction and product safety without too much altering the sensory characteristics. This requires adjustments and controls of the raw material and of the salting, drying and ripening phases to avoid undesirable changes in organoleptic properties.

Safety

Dry-cured ham belongs to the group of ready-to-eat shelf-stable processed meat products that can be stored unrefrigerated ($T > 10\text{ }^{\circ}\text{C}$) and are safe to eat without additional preparation (Hui, 2012). The microbiological stability is achieved by the preservation method (i.e. dry-curing) which reduces water content (<60%) and water activity (<0.93). The addition of curing salts sodium chloride, and of potassium and sodium salts of nitrite and nitrate as preservatives contributes to the product safety, but the use of nitrite and nitrate salts represents risks for human health with regards to nitrosamines development. However, in several traditional dry-cured hams of Mediterranean type with long processing duration, sodium chloride is the only preservative used.

Dry-cured safety assurance concern ingoing raw material contamination (Lebret and Čandek-Potokar, 2021) and control measures in the processing steps. In general, the presence of pathogenic bacteria in the processing of dry-cured ham does not pose a major problem, as the process itself is not conducive to their growth and release of toxins, so they occur only when there are errors in the process. Considering the nature of dried meats, *Salmonella* spp., *E. coli* O157:H7, *Staphylococcus aureus* and *Listeria monocytogenes* are of main safety concern (Hui, 2012). During processing, bacterial spoilage can occur before sufficiently low water activity and increased internal salt concentration can stop bacterial proliferation. These bacteria are mainly *Enterobacteriaceae* and *Clostridium* spp. (most commonly *C. perfringens*) (Ockerman et al., 2002; Scolari et al., 2003). They cannot act on the surface due to unfavourable conditions, but can grow inside in case of deficiencies in the processing. Spoilage bacteria enter tissues during cutting manipulations or earlier by bloodstream. Their action leads to profound putrefaction, bloating and the associated repulsive sour, putrid odour and consequent unsuitability of the product for consumption. Putrefaction close to the bone is the most common fault, with *Serratia* spp. and *Proteus* spp. of the *Enterobacteriaceae* family, which can grow at low temperatures and under anaerobic conditions, considered as the main cause of spoilage (Ockerman et al., 2002; Scolari et al., 2003). Once dry-cured ham is dried, only moulds (*Aspergillus* and *Penicillium*) can grow, which can cause

an abnormal flavour and unacceptable appearance, lowering the quality of the product. Moreover, the issue of toxigenic moulds belonging to *Penicillium* and *Aspergillum* genus is of great concern for dry-cured ham safety and is receiving increasing attention (Vipotnik et al., 2017). Spoilage problems have been related to season, with deep muscles being affected more in the cold months, while the superficial parts in the summer. Diagnosis of spoilage is simple - by puncturing with horse's fibula at specific places and sniffing. With past microbiological research establishing salt concentration and water activity levels that inhibit the growth of spoilage bacteria, the incidence of spoilage has decreased significantly. Most processing plants nowadays are equipped to maintain appropriate climatic conditions all over the year. Maintaining low temperatures reduces the incidence of deep muscle spoilage. In contrast, surface defects are less dependent on temperature conditions, and their reduction requires intensive cooling and dry air in the early stage with fast water activity reduction (Parolari, 1996).

The predominant normal microflora that develops on dry-cured ham during drying and ripening is from the *Micrococcaceae* family (Vilar et al., 2000). Among these, the *Staphylococcus* genus largely predominates, followed by the genus *Micrococcus*, whose proliferation is limited by higher salt concentration. They accumulate mainly on ham surface, their halotolerance ensuring their constant presence at all stages of processing. Due to their complex metabolism, *Micrococcaceae* perform technologically very important basic functions: as they consume oxygen, they significantly reduce lipid oxidation and the occurrence of rancidity. They also reduce nitrates to nitrites which exert an inhibitory effect against dangerous microorganisms, including *Clostridia* (Scolari et al., 2003; Vilar et al., 2000). In summary, the hurdles to respect in dry-cured ham production depend on the product and process, with pH and water activity being of primary importance for product safety. Thus, raw material with pH > 6.0 is to be avoided to prevent the microbial growth. For non-fermented cured products like dry-cured ham, the salting and drying steps are critical. Salting step has to be carried at the refrigeration temperatures because the product is not yet stabilised, whereas temperature, time, relative humidity and airspeed must be controlled in drying and ripening stages to prevent incorrect drying and to achieve sufficiently low water activity.

Convenience attributes

Dry-cured ham has two characteristics that are of great interest to consumers: convenience of use, especially when the ham is sold in slices (which nowadays accounts for a large proportion of sales volume), and long shelf life, which is 4 months for slices and many months more for boned pieces that are vacuum-packed and stored at 4 °C. However, shelf life of slices or dry-cured ham pieces depends on product size, ageing time, packaging type (vacuum or protective atmosphere), presence of interleaf (Kilcast and Subramaniam, 2000). New purchasing formats with vacuum or modified atmosphere packaging are more in line with the current consumer habits and trends, and are efficient to protect dry-cured ham from colour changes or lipid peroxidation during storage (Parra et al., 2012). The development of new active and intelligent packaging will further improve the freshness and shelf life through a better control of storage conditions from the point of production to the final consumer (Sohail et al., 2018). Bone-in dry-cured ham can be stored at room temperature or in the cellar for up to 12 months, if previously foreseen by the processing plant (in particular by covering muscle surface with fat during process) to avoid problems and defects due to protracted stay in ripening room. This product therefore fits well with the eating habits and lifestyle of the modern consumer, who values long shelf life of products, ease of meal preparation, multiplication of meals, snacking and nomadic consumption.

Societal image attributes

Societal image, which corresponds to the consumer's perception of the product and its attributes, is particularly important in the case of dry-cured ham, as confirmed by numerous products protected as geographical designations (PDO, PGI) or traditional specialty (TSG) and/or other quality brands in Europe (Spain, Portugal, Italy, France, Germany, Slovenia, Croatia, etc.). Societal image attributes are associated with the tradition, culture and eating habits of a region or country, where a particular product is produced and includes the way in which pigs are raised and the product is processed. There are many varieties of dry-cured hams which differ in terms of origin, pig farming system and resulting raw material quality, processing technique, and of course marketing price for the consumer. We can distinguish between "standard" products, which use raw material from modern lean breeds raised in intensive production systems and represent very large volumes of dry ham production, and high added value dry-cured hams with requirements for the raw material providing the products known for their high quality. Among the latter, the most distinguished are the products originating from traditional local breeds, generally associated with extensive systems and feeding, which mainly represent niche productions (Čandek-Potokar and Nieto Linan, 2019). Within this 'high added value' category, one of the economically most important are Italian PDO dry-cured hams arising from modern breeds but with specific requirements regarding the raw material properties and pig (heavy pig production). Thus, this can generate some confusion for the consumers who may not be well aware of the differences between products related to pig breed and production system used. For example, there are four categories of dry-cured hams with Iberian designation as defined by the Iberian Quality Standard (MAGRAMA, 2014), depending on the pig breed (pure Iberian or crossbred) and production system especially the outdoor access and feed provided (acorn, pastures and/or feed-stuffs), etc. This generates great variability in the final products and sensory differences among ham categories that are perceived by consumers, even though this perception ability greatly varies among consumers (Diaz-Caro et al., 2019). Another misperception, linked to the reputation of Iberian hams, exists between these products and the TSG Serrano whose name may be associated by (non-Spanish) consumers with this geographical origin. However, Serrano specifications are much less binding, focusing only on the processing conditions but not on pig origin, genotype or rearing conditions, allowing much higher production volumes and lower marketing prices than for "Iberian" hams.

Despite the reputation and special quality of some (mainly PDO) dry-cured hams, the research with consumers shows their marked regional or national preferences towards locally produced hams, which can be explained by their familiarity with the product, combined with emotional aspects (Resano et al., 2010; Font-i-Furnols and Guerrero, 2014). Information about product origin contributes strongly to its acceptability but may be perceived differently depending on consumers. A study conducted in Norway showed that one group of consumers preferred high quality dry-cured ham of Spanish origin while the other group preferred Norwegian product (Hersleth et al., 2011). Consumers are also very attentive to information relating to pig breed or production system and ham ripening time when associated with a quality label, which all influence their product perception, as shown in a recent study with PDO Noir de Bigorre dry-cured ham (Vitale et al., 2020).

Conclusions

This review considers the main factors from farm to fork and their interactions on various quality attributes of two pork products of the highest economic importance, cooked ham and dry-cured ham. Moreover, these products are issued from integral

pieces, for which the quality of the raw material and thus primary production factors are of great importance. For cooked ham production, a desired raw material (meat) corresponds to a lean fresh ham with physicochemical quality criteria corresponding to a normal pHu value range and colour, and without destructured meat and visual defects. These traits depend mainly on pig genotype and preslaughter handling, and carcass processing. Among the pig production conditions, diet composition can modulate the nutritional value of cooked ham. The quality of the final product depends also strongly on the processing technique, especially the curing method, brine composition, tumbling, and thermal treatment conditions. However, the reduced use of additives in cooked ham manufacturing and the growing consumer expectations regarding the nutritional and societal image attributes of pork products reinforce the importance of the raw material quality and therefore the way pigs are reared, in the quality of cooked ham. Pig rearing conditions contribute to shaping the quality of the final product even more in the case of dry-cured ham. Their organoleptic, nutritional, technological, safety and societal image attributes depend largely on the properties of the raw material which in turn are determined by a combination of primary production factors. Furthermore, the manufacturing of dry-cured ham is more diversified and the conditions in salting, resting, drying and ripening stages are adapted to raw material, which contributes to the great diversity of dry-cured hams. Optimisations and/or synergies between raw material and processing factors lead to specific products of high quality (luxury) and typicality, which are often recognised by quality labels. With some exceptions (e.g. Mediterranean PDO dry-cured hams), less research has been conducted to establish the link between pig production factors and the final quality of processed pork products, compared to studies on the quality of pork consumed as fresh meat. One reason could be that a major objective of the meat industry is to erase variability of the raw material to adapt better to the manufacturing processes, and that a standardised product of constant quality is assured for the market. Namely, it is difficult to accommodate the processing to the highly variable raw material. However, meat consumption issues related to health and societal image dimensions require more knowledge about the upstream and downstream factors and their interactions and/or synergies that determine the final qualities of meat products.

Ethics approval

Not applicable.

Data and model availability statement

Data used in the review were collected from published scientific literature.

Author ORCIDs

B. Lebret: <https://orcid.org/0000-0001-5435-0389>

M. Čandek-Potokar: <https://orcid.org/0000-0003-0231-126X>

Author contributions

B. Lebret: conceptualization, investigation, writing original draft, review and editing, supervision; **M. Čandek-Potokar:** conceptualization, investigation, writing original draft.

Declaration of interest

None.

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References

- Aberle, E.D., Forrest, J.C., Gerrard, D.E., Mills, E.W., 2012. Principles of meat processing. In Principles of meat science – fifth edition (ed. sine nomine). Kendall Hunt Publishing, Dubuque, IA, USA, pp. 175–212.
- Afssa, 2010. Avis relatif aux conséquences sur les flores microbiennes d'une réduction en taux de sel dans les aliments. Paris, Afssa, Saisine n°2008-SA_0173. Retrieved on 12 April 2021 from <https://www.anses.fr/fr/system/files/MIC2008sa0173.pdf>.
- Andres, A.I., Cava, R., Ventanas, J., Thovar, V., Ruiz, J., 2004. Sensory characteristics of Iberian ham: Influence of salt content and processing conditions. *Meat Science* 68, 45–51.
- Arnau Arboix, J., 2014. Ham Production – Cooked ham. In Encyclopedia of Meat Sciences, Second Edition (ed. Dikeman, M., Devine, C.), Academic Press, London, UK, pp. 82–86. <https://doi.org/10.1016/B978-0-12-384731-7.00226-9>.
- Banon, S., Gil, M.D., Garrido, M.D., 2003. The effects of castration on the eating quality of dry-cured ham. *Meat Science* 65, 1031–1037.
- Birlouez, E., 2019. France, land of «charcuteries». *Cahiers de nutrition et diététique* 54, 5S2–5S4.
- BOE (Boletín Oficial del Estado), 2014. Real Decreto 474/2014, de 13 de junio, por el que se aprueba la norma de calidad de derivados cárnicos. DOE 147, 46058–46078. Retrieved on 5 June 2021 from <https://www.boe.es/eli/es/rd/2014/06/13/474/dof/spa/pdf>.
- Bonneau, M., Lebret, B., 2010. Production systems and influence on eating quality of pork. *Meat Science* 84, 293–300.
- Čandek-Potokar, M., Škrlep, M., 2011. Dry ham ("Kraški pršut") processing losses as affected by raw material properties and manufacturing practice. *Journal of Food Processing and Preservation* 35, 96–111.
- Čandek-Potokar, M., Škrlep, M., 2012. Factors in pig production that impact the quality of dry-cured ham: a review. *Animal* 6, 327–338.
- Čandek-Potokar, M., Nieto Linan, R.M., 2019. European Local Pig Breeds – Diversity and Performance. A study of project TREASURE. IntechOpen, London, UK. <https://doi.org/10.5772/intechopen.83749>.
- Čandek-Potokar, M., Škrlep, M., Kostyra, E., Żakowska-Biemans, S., Poklukar, K., Batorek-Lukač, N., Kress, K., Weiler, U., Stefanski, V., 2020. Quality of Dry-Cured Ham from Entire, Surgically and Immunocastrated Males: Case Study on Kraški Pršut. *Animals* 10, 239.
- Carrapiso, A.I., Bonilla, F., Garcia, C., 2003. Effect of crossbreeding and rearing system on sensory characteristics of Iberian ham. *Meat Science* 65, 623–629.
- Cava, R., Ventanas, J., Ruiz, J., Andres, A.I., Antequera, T., 2000. Sensory characteristics of Iberian ham: Influence of rearing system and muscle location. *Food Science and Technology International* 6, 235–242.
- Chevillon, P., Bonneau, M., Le Strat, P., Guingand, N., Courboulay, V., Quiniou, N., Gault, E., Lhommeau, T., 2010. Consumer acceptability of pork products (sausages, lardons, dry sausages and cooked hams) issued from entire male pigs, compared to products from females or castrated males Retrieved on 12 April 2021 from Journées de la Recherche Porcine 42, 227–228 <http://www.journees-recherche-porcine.com/texte/2010/qual/PQ7.pdf>.
- Clinquart, A., Korsak, N., Harmegnies, N., Vanleyssem, R., Vautier, A., Aluwé, M., Renard, S., 2021. Destructured meat defect: association with carcass, fresh meat and cooked ham characteristics observed during the first study in Belgium (Walloon Region) Retrieved on 12 April 2021 from Journées de la Recherche Porcine 53, 37–42 <http://www.journees-recherche-porcine.com/texte/2021/genetique/g07.pdf>.
- Dall'Olio, S., Aboagye, G., Nanni Costa, L., Gallo, M., Fontanesi, L., 2020. Effects of 17 performance, carcass and raw ham quality parameters on ham weight loss at

- first salting in heavy pigs, a meat quality indicator for the production of high quality dry-cured hams. *Meat Science* 162, 108012.
- Desmond, E., Vasilopoulos, C., 2019. Reducing salt in meat and poultry products. In: Beeren, C., Groves, K., Titoria, P.M. (Eds.), *Reducing Salt in Foods*. second ed. Woodhead Publishing, Duxford, UK, pp. 159–183.
- Díaz-Caro, C., García-Torres, S., Elghannam, A., Tejerina, D., Mesias, F.J., Ortiz, A., 2019. Is production system a relevant attribute in consumers' food preferences? The case of Iberian dry-cured ham in Spain. *Meat Science* 158, 107908.
- Duret, S., Hoang, H.M., Derens-Bertheau, E., Delahaye, A., Laguerre, O., Guillier, L., 2019. Combining Quantitative Risk Assessment of Human Health, Food Waste, and Energy Consumption: The Next Step in the Development of the Food Cold Chain? *Risk Analysis* 39, 906–925.
- EC (European Communities), 2002. Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety. OJ L31 1.2.2002, 1–31. Retrieved on 15 March 2021 from <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32002R0178&from=EN>.
- EC (European Communities), 2006. Regulation (EC) No 1924/2006 of the European Parliament and of the Council of 20 December 2006 on nutrition and health claims made on foods. OJ L 404/9, 30.12.2006. 1–17. Current consolidated version of 13.12.2014. Retrieved on 12 April 2021 from <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006R1924&from=en>.
- EC (European Communities), 2008. Regulation (EC) No 1333/2008 of the European Parliament and of the Council of 16 December 2008 on food additives. OJ L354 31.12.2008, 16–33. Current consolidated version of 23.12.2020. Retrieved on 12 April 2021 from <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02008R1333-20201223&from=EN>.
- EU (European Union), 2011. Regulation (EU) No 1169/2011 of the European Parliament and of the Council of 25 October 2011 on the provision of food information to consumers. Current consolidated version on 01/01/2018. OJ L 304/18, 22.11.2011. 1–46. Retrieved on 12 April 2021 from <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011R1169&from=EN>.
- EU (European Union), 2012. Regulation (EU) No 1151/2012 of the European Parliament and of the Council of 21 November 2012 on quality schemes for agricultural products and foodstuffs. OJ L343 14.12.2012, 1–29. Current consolidated version on 14/12/2019. Retrieved on 8 April 2021 from <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012R1151&from=EN>.
- Flores, J., 1997. Mediterranean vs northern European meat products. *Processing technologies and main differences*. *Food Chemistry* 59, 505–510.
- Flores, M., Toldrá, F., 2021. Chemistry, safety, and regulatory considerations in the use of nitrite and nitrate from natural origin in meat products – Invited review. *Meat Science* 171, 108272.
- Font-i-Furnols, M., Guerrero, L., 2014. Consumer preference, behavior and perception about meat and meat products: an overview. *Meat Science* 98, 361–371.
- Gandemer, G., 2002. Lipids in muscles and adipose tissues, changes during processing and sensory properties of meat products. *Meat Science* 62, 309–321.
- Gazzetta Ufficiale, 2005. Decreto del Ministero delle attività produttive del 21 settembre 2005 sulla produzione e la vendita di alcuni salumi. *Gazzetta Ufficiale della Repubblica Italiana; Serie Generale n.231 del 04-10-2005*. Retrieved on 14 June 2021 from <https://www.gazzettaufficiale.it/eli/id/2005/10/04/05A09366/sg>.
- Gou, P., Arnau, J., Garcia-Gil, N., Fulladosa, E., Serra, X., 2012. Dry cured ham. In: Hui, Y.H. (Ed.), *Handbook of meat processing*. CRC Press, Boca Raton, FL, USA, pp. 673–687.
- Hachler, H., Marti, G., Giannini, P., Lehner, A., Jost, M., Beck, J., Weiss, F., Bally, B., Jermini, M., Stephan, R., Baumgartner, A., 2013. Outbreak of listeriosis due to imported cooked ham, Switzerland 2011. *Eurosurveillance* 18, 7–13.
- Haije, D.M., De Smet, S., Claeys, E., Vossen, E., 2013. Effect of light, packaging condition and dark storage durations on colour and lipid oxidative stability of cooked ham. *Journal of Food Science and Technology* 50, 239–247.
- Hersleth, M., Lengard, V., Verbeke, W., Guerrero, L., Naes, T., 2011. Consumers' acceptance of innovations in dry-cured ham Impact of reduced salt content, prolonged aging time and new origin. *Food Quality and Preference* 22, 31–41.
- Higgs, J., Pratt, J., 1999. Meat, Poultry and meat products. *Nutritional value*. In *Encyclopedia of human nutrition* (ed. Sadler, M.J., Strain, J.J., Caballero, B.). Academic Press, San Diego, CA and London, UK, pp. 1272–1282.
- Honikel, K.O., 2008. The use and control of nitrate and nitrite for the processing of meat products. *Meat Science* 78, 68–76.
- Hugenschmidt, G., Hadorn, R., Guggisberg, D., Silacci, P., Scherrer, D., Haldimann, M., Scheeder, M., Wenk, C., 2009. Destructurations in cooked cured ham. *Fleischwirtschaft International* 2, 55–59.
- Hugo, A., Roodt, E., 2007. Significance of porcine fat quality in meat technology: A review. *Food Reviews International* 23, 175–198.
- Hui, Y.H., 2012. Shelf-stable processed meat products. In *Handbook of meat and meat processing*, second edition (ed. Hui, Y.H.). CRC Press, Boca Raton, FL, USA, pp. 769–789.
- IFIP, 2014. *Mémento viandes et charcuteries*. IFIP-Institut du porc, Paris, France.
- IFIP, 2017. *Code des Usages de la Charcuterie, de la Salaison et des Conserves de Viandes*, Edition 2016, mise à jour 2017. IFIP-Institut du porc, Paris, France.
- IFIP, 2021a. *Porc par les chiffres, édition 2020-2021. La filière porcine en France, dans l'UE et le monde*. IFIP-Institut du porc, Paris, France.
- IFIP, 2021b. CSB JumboFlash: artificial intelligence for raw ham quality control. In *International FoodTec Award 2021*, DLG, Innovation Magazine 2021 pp. 10. Retrieved on 12 April 2021 from https://www.foodtecaward.com/fileadmin/downloads/IFTAnnovationMagazin_2021_IT.pdf.
- Kennedy, J., Jackson, V., Blair, I.S., McDowell, D.A., Cowan, C., Bolton, D.J., 2005. Food safety knowledge of consumers and the microbiological and temperature status of their refrigerators. *Journal of Food Protection* 68, 1421–1430.
- Kilcast, D., Subramaniam, P., 2000. *The stability and shelf-life of food*. Woodhead Publishing Limited, Cambridge, England.
- Kowalski, E., Aluwé, M., Vossen, E., Millet, S., Ample, B., De Smet, S., 2021. Quality characteristics of fresh loin and cooked ham muscles as affected by genetic background of commercial pigs. *Meat Science* 172, 108352.
- Lebret, B., 2008. Effects of feeding and rearing systems on growth, carcass composition and meat quality in pigs. *Animal* 2, 1548–1558.
- Lebret, B., Ecolan, P., Bonhomme, N., Pollet, P.Y., Dourmad, J.Y., 2013. Quality of fresh pork and dry-cured ham: interactive effects of pig breed (Basque or Large White) and production system (conventional, alternative, extensive). *Acta Agriculturae Slovenica (suppl. 4)*, 77–80.
- Lebret, B., Prevolinik Povše, M., Čandek-Potokar M., 2015. Muscle and fat colour. In *A handbook of reference methods for meat quality assessment* (ed. Font-i-Furnols, M., Čandek-Potokar, M., Maltin, C., Prevolinik Povše, M.). *Farm Animal IMaging COST Action FA1102*, pp. 33–44. Retrieved on 12 April 2021 from https://www.researchgate.net/publication/282133283_A_handbook_of_reference_methods_for_meat_quality_assessment.
- Lebret, B., Lenoir, H., Fonseca, A., Riquet, J., Mercat, M.J., 2021. Finishing season and feeding resources influence the quality of products from extensive-system Gascon pigs. Part 2: Muscle traits and sensory quality of dry-cured ham. *Animal* 15, 100305.
- Lebret, B., Čandek-Potokar, M., 2021. Review: Quality attributes of pork from farm to fork. Part I. Carcass and fresh meat. *Animal*, in press, accepted on 7 Oct 2021. <https://doi.org/10.1016/j.animal.2021.100402>.
- Lebrun, S., Van Nieuwenhuysen, T., Crevecoeur, S., Vanleyssem, R., Thimister, J., Denayer, S., Jeuge, S., Daube, G., Clinquant, A., Fremaux, B., 2020. Influence of reduced levels or suppression of sodium nitrite on the outgrowth and toxinogenesis of psychrotrophic *Clostridium botulinum* Group II type B in cooked ham. *International Journal of Food Microbiology* 334, 108853.
- Lécuyer, B., Legendre, V., 2015. Cured meat products in Europe: main characteristics of the different producer countries [La charcuterie-salaison en Europe: principales caractéristiques de différents pays producteurs]. *Les Cahiers de l'IFIP* 2, 1–16.
- MAGRAMA (Ministerio de Agricultura Alimentación y Medio Ambiente), 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. *Boletín Oficial del Estado* núm 10 de 11 de enero de 2014, A-2014-318, pp. 1–16. Retrieved on 7 April 2021 from <https://www.boe.es/buscar/pdf/2014/BOE-A-2014-318-consolidado.pdf>.
- Minville, B., Le Strat, P., Lebret, B., Houix, Y., Boulard, J., Clochefer, N., 2001. Destructured meat: the situation in five slaughterhouses in western France; risk factors and a proposed prediction model; colorimetric, biochemical and histological characterisation Retrieved on 12 April 2021 from *Journées de la Recherche Porcine* 33, 95–101 <http://www.journees-recherche-porcine.com/texte/2001/01txtQualite/V0105.pdf>.
- Morales, R., Guerrero, L., Aguiar, A.P.S., Guardia, M.D., Gou, P., 2013. Factors affecting dry-cured ham consumer acceptability. *Meat Science* 95, 652–657.
- Moretti, V.M., Bellagamba, F., Paleari, M.A., Beretta, G., Busetto, M.L., Caprino, F., 2009. Differentiation of cured cooked hams by physico-chemical properties and chemometrics. *Journal of Food Quality* 32, 125–140.
- Neyrinck, E., De Smet, S., Vermeulen, L., Telleir, D., Lescouhier, S., Paelinck, H., Fraeye, I., Geers, R., Raes, K., 2015. Application of near-infrared spectroscopy for the classification of fresh pork quality in cooked ham production. *Food and Bioprocess Technology* 8, 2383–2391.
- Ockerman, H. W., Basu, L., Crespo, F.L., Cespedes Sanchez, F.J., 2002. Comparison of European and American systems of production and consumption of dry cured hams. *Pork Information Gateway*, American Meat Science Association, Des Moines, IA, USA. Retrieved on 12 April 2021 from <https://porkgateway.org/wp-content/uploads/2015/07/comparison-of-european-american-systems-of-production-and-consumption-of-dry-cured-hams1.pdf>.
- Pagliarini, E., Laureati, M., Dinnella, C., Monteleone, E., Proserpio, C., Piasentier, E., 2016. Influence of pig genetic type on sensory properties and consumer acceptance of Parma, San Daniele and Toscano dry-cured hams. *Journal of the Science of Food and Agriculture* 96, 798–806.
- Parolari, R., Virgili, C., Schivazappa, C., 1994. Relationship between cathepsin B activity and compositional parameters in dry-cured hams of normal and defective texture. *Meat Science* 38, 117–122.
- Parolari, G., 1996. Review: Achievements, needs and perspectives in dry-cured ham technology: the example of Parma ham. *Food Science and Technology International* 2, 69–78.
- Parra, V., Viguera, J., Sánchez, J., Peinado, J., Espárrago, F., Gutierrez, J.I., Andrés, A.I., 2012. Effect of exposure to light on physico-chemical quality attributes of sliced dry-cured Iberian ham under different packaging systems. *Meat Science* 90, 236–243.
- Petrova, I., Aasen, I.M., Rustad, T., Eikevik, T.M., 2015a. Manufacture of dry-cured ham: a review. Part 1. Biochemical changes during the technological process. *European Food Research and Technology* 241, 587–599.
- Petrova, I., Bantle, M., Eikevik, T.M., 2015b. Manufacture of dry-cured ham: a review. Part 2. Drying kinetics, modeling and equipment. *European Food Research and Technology* 241, 447–458.

- Pinna, A., Saccani, G., Schivazappa, C., Simoncini, N., Virgili, R., 2020. Revision of the cold processing phases to obtain a targeted salt reduction in typical Italian dry-cured ham. *Meat Science* 161, 107994.
- Prache, S., Adamiec, C., Astruc, T., Baéza-Campane, E., Bouillot, P.E., Clinquart, A., Feidt, C., Fourat, E., Gautron, J., Girard, A., Guillier, L., Kesse-Guyot, E., Lebret, B., Lefèvre, F., Le Perche, S., Martin, B., Mirade, P.S., Pierre, F., Raullet, M., Rémond, D., Sans, P., Souchon, I., Donnars, C., Santé-Lhoutellier, V., 2021. Review: Quality of animal source foods. *Animal*. in press. Accepted on 01 Sep 2021. <https://doi.org/10.1016/j.animal.2021.100376>.
- Prevolnik Povše, M., Čandek-Potokar, M., Gispert, M., Lebret, B., 2015. pH value and water-holding capacity. In *A handbook of reference methods for meat quality assessment* (ed. Font-i-Furnols, M., Čandek-Potokar, M., Maltin, C., Prevolnik Povše, M.). *Farm Animal IMaging COST Action FA1102*, pp. 22–32. Retrieved on 12 April 2021 from https://www.researchgate.net/publication/282133283_A_handbook_of_reference_methods_for_meat_quality_assessment.
- Pugliese, C., Sirtori, F., 2012. Quality of meat and meat products produced from southern European pig breeds. *Meat Science* 90, 511–518.
- Ramos, A.M., Serenius, T.V., Stalder, K.J., Rothschild, M.F., 2007. Phenotypic correlations among quality traits of fresh and dry-cured hams. *Meat Science* 77, 182–189.
- Rentfrow, G., Chaplin, R., Suman, S.P., 2012. Technology of dry-cured ham production: Science enhancing art. *Animal Frontiers* 2, 26–31.
- Resano, H., Sanjuan, A.I., Cilla, I., Roncales, P., Albisu, L.M., 2010. Sensory attributes that drive consumer acceptability of dry-cured ham and convergence with trained sensory data. *Meat Science* 84, 344–351.
- Resano, H., Perez-Cueto, F.J.A., Sanjuan, A.I., de Barcellos, M.D., Grunert, K.G., Verbeke, W., 2011. Consumer satisfaction with dry-cured ham in five European countries. *Meat Science* 87, 336–343.
- Santos, C., Hoz, L., Cambero, M.I., Cabeza, M.C., Ordonez, J.A., 2008. Enrichment of dry-cured ham with alpha-linolenic acid and alpha-tocopherol by the use of linseed oil and alpha-tocopheryl acetate in pig diets. *Meat Science* 80, 668–674.
- Scolari, G., Sarra, P.G., Baldini, P., 2003. Mikrobiologija suhega mesa. In: Bem, Z., Adami, J., Zlender, B., Smole Mozina, S., Gasperlin, L. (Eds.), *Mikrobiologija živil živalskega izvora*. Biotehniška fakulteta, Odelek za živilstvo, Ljubljana, Slovenia, pp. 351–362.
- Schwob, S., Vautier, A., Lhommeau, T., 2018. Etude génétique du défaut « jambon déstructuré ». *Les Cahiers de l'IFIP* 5, 9–20.
- Sinha, R., Zhao, N., Goedert, J.J., Byrd, D.A., Wan, Y., Hua, X., Hullings, A.G., Knight, R., Breda, S.V., Mathijs, K., de Kok, T.M., Ward, M.H., PHYTOME consortium members, 2021. Effects of processed meat and drinking water nitrate on oral and fecal microbial populations in a controlled feeding study. *Environmental Research* 197, 111084.
- Sohail, M., Sun, D.W., Zhu, Z.W., 2018. Recent developments in intelligent packaging for enhancing food quality and safety. *Critical Reviews in Food Science and Nutrition* 58, 2650–2662.
- Theron, L., Sayd, T., Chambon, C., Venien, A., Viala, D., Astruc, T., Vautier, A., Sante-Lhoutellier, V., 2019. Deciphering PSE-like muscle defect in cooked hams: A signature from the tissue to the molecular scale. *Food Chemistry* 270, 359–366.
- Toldrá, F., Flores, M., Sanz, Y., 1997. Dry-cured ham flavor: enzymatic generation and process influence. *Food Chemistry* 59, 523–530.
- Toldrá, F., 1998. Proteolysis and lipolysis in flavour development of dry-cured meat products. *Meat Science* 49, S101–S110.
- Tomažin, U., Škrlep, M., Prevolnik Povše, M., Batorek Lukač, N., Karolyi, D., Červek, M., Čandek-Potokar, M., 2020. The effect of salting time and sex on chemical and textural properties of dry cured ham. *Meat Science* 161, 107990.
- Van Breda, S.G., Mathijs, K., Sági-Kiss, V., Kuhnle, G.G., Van Der Veer, B., Jones, R.R., Shina, R., Ward, M.H., de Kok, T.M., 2019. Impact of high drinking water nitrate levels on the endogenous formation of apparent N-nitroso compounds in combination with meat intake in healthy volunteers. *Environmental Health* 18, 87.
- Vautier, A., Lhommeau, T., Daumas, G., 2013. A feasibility study for the prediction of the technological quality of ham with NIR spectroscopy. Book of abstracts of the 64th annual meeting of the European Association for Animal Production, 26–30 August 2013, Nantes, France, p. 108.
- Vautier, A., Pieper, T., Lhommeau, T., Petersen, H., Christensen, M., 2017. NIR and VIS-NIR spectroscopy to predict PSE-like zones. Proceedings of the 63rd International Congress of Meat Science and Technology, 13–18 August 2017, Cork, Ireland, 2 p. Retrieved on 12 April 2021 from http://icomst-proceedings.helsinki.fi/papers/2017_03_54.pdf.
- Ventanas, S., Ruiz, J., Garcia, C., Ventanas, J., 2007a. Preference and juiciness of Iberian dry-cured loin as affected by intramuscular fat content, crossbreeding and rearing system. *Meat Science* 77, 324–330.
- Ventanas, S., Ventanas, J., Tovar, J., Garcia, C., Estevez, M., 2007b. Extensive feeding versus oleic acid and tocopherol enriched mixed diets for the production of Iberian dry-cured hams: Effect on chemical composition, oxidative status and sensory traits. *Meat Science* 77, 246–256.
- Vestergaard, C., Erbou, S.G., Thauland, T., Adler-Nissen, J., Berg, P., 2005. Salt distribution in dry-cured ham measured by computed tomography and image analysis. *Meat Science* 69, 9–15.
- Vilar, I., Garcia Fontan, M.C., Prieto, B., Tornadizo, M.E., Carballo, J., 2000. A survey on the microbiological changes during the manufacture of dry-cured lacon, a Spanish traditional meat product. *Journal of Applied Microbiology* 89, 1018–1026.
- Vipotnik, Z., Rodríguez, A., Rodrigues, P., 2017. Aspergillus westerdijkiae as a major ochratoxin A risk in dry-cured ham based-media. *International Journal of Food Microbiology* 241, 244–251.
- Virgili, R., Parolari, G., Schivazappa, C., Soresi-Bordini, C., Borri, M., 1995. Sensory and texture quality of dry-cured ham as affected by endogenous cathepsin B activity and muscle composition. *Journal of Food Science* 60, 1183–1186.
- Virgili, R., Schivazappa, C., 2002. Muscle traits for long matured dried meats. *Meat Science* 62, 331–343.
- Vitale, M., Kallas, Z., Rivera-Toapanta, E., Karolyi, D., Cerjak, M., Lebret, B., Lenoir, H., Pugliese, C., Aquilani, C., Čandek-Potokar, M., Gil, M., Oliver, M.A., 2020. Consumers' expectations and liking of traditional and innovative pork products from European local pig breeds. *Meat Science* 168, 108179.
- Voutila, L., 2009. Properties of intramuscular connective tissue in pork and poultry with reference to weakening of structure. PhD thesis, University of Helsinki, Helsinki, Finland. Retrieved on 12 April 2021 from <https://core.ac.uk/download/pdf/14916349.pdf>.
- Wakamatsu, J., Nishimura, T., Hattori, A., 2004. A Zn-porphyrin complex contributes to bright red color in Parma ham. *Meat Science* 67, 95–100.