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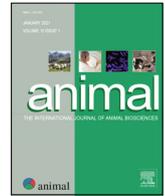


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Review: Pork quality attributes from farm to fork. Part I. Carcass and fresh meat

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ABSTRACT

This work considers all factors along the production chain from farm to fork influencing the quality of fresh pork and processed products. Pork quality is multidimensional and comprises various attributes: commercial value of carcasses, meat organoleptic, nutritional, technological (i.e. suitability for processing and storage) properties, convenience, and societal image. The latter denotes cultural, ethical (including animal welfare) and environmental dimensions related to pork production, including geographical origin, all of which influence societal perceptions for pork. This review covers the impact of production factors, slaughter methods, carcass processing, and *post mortem* ageing on fresh meat quality. The impact on pork quality from some of these factors are now well documented and clearly established (e.g. genetics and pork technological attributes; diet and lipid profile; preslaughter and slaughter conditions and pork technological or organoleptic attributes...). Gaps in scientific knowledge are also identified, including the need for a better understanding of regulatory pathways for oxidative stress *in vivo* and *post mortem* that can contribute to optimise pork organoleptic and nutritional attributes and its suitability for processing and storage. This review highlights the strong interactions between primary production factors on pork quality attributes. Interactions are particularly marked in alternative production systems, in which synergies between factors can lead to specific quality characteristics that can be used to market pork at a premium as branded products. There are also antagonisms between quality attributes, namely between carcass commercial value and pork technological and organoleptic properties, between nutritional attributes and processing and storage suitability of fat tissues, between societal image and pork technological attributes in outdoor production systems, and between societal image (better welfare) and organoleptic attributes (risk for boar taint) in entire male production. Further research is needed to better understand the effects of some specific production factors and their interactions on quality attributes. A holistic approach with the use of multicriteria analyses can help to work out the trade-offs between pork quality attributes and between stakeholders (farmer, slaughterhouse or processing plant, consumers, citizens...) whose priorities may differ.

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Implications

Pork quality comprises a variety of attributes related to the characteristics of the product itself and the conditions under which pigs/pork are produced. Each of these attributes is influenced by various individual factors, ranging from pig genetics to pork preparation for consumption, and their interactions. Pork quality is built along the whole food chain, with synergies and antagonisms between quality attributes. Moreover, the priority attributes depend on chain stakeholders, from the farmer to consumer. Dif-

ferent production and processing methods from farm to fork are identified to improve pork quality according to the priorities and trade-offs between attributes and stakeholders.

Introduction

The global pig industry is responsible for pork production that accounts for 33% of total meat consumption, with large differences in consumption levels from one continent to another (OECD, 2021). Pork is the most consumed meat in Asia and in Europe, with an average of 41 kg carcass equivalent per inhabitant in 2019 but with large differences among countries (from 24 kg in the United Kingdom up to 56 kg in Spain and 76 kg carcass equivalent/year in Den-

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mark; [IFIP, 2021](#)). Approximately 56% of the world's pork production (112.5 million tonnes carcass equivalent in 2018) is produced in Asia (48% in China), although Asian pork production has fallen sharply since 2019 due to African Swine Fever. North America (USA and Canada) and the European Union (EU, 28) account for 12 and 21% of the world's pork production, respectively, with Germany, Spain and France being the main European producers. Self-sufficiency levels (117% at EU level) vary greatly among countries, from 30% in Greece to more than 400% in Denmark ([IFIP, 2021](#)). Some countries import carcass cuts from EU countries for processing into specific products (e.g. hams for the production of dry-cured hams in Italy). In fact, pork is consumed in Europe mainly (up to 75% in some countries) in the form of a variety of processed products, either dried, cured, cooked (and consumed hot or cold), as whole pieces (e.g. dry-cured or cooked hams) or minced (sausages, 'pâtés'...) products ([IFIP, 2021](#)). This wide variety of pork products leads to different and specific quality expectations depending on the product and the respective stakeholders for the sector: producers, packing plants/abattoirs, processors, distributors, consumers ([Lebret and Čandek-Potokar, 2021](#)).

Despite the wide variety of processed products, most of the world's pigs are produced using conventional 'intensive' systems where animals are kept confined in buildings on slatted floors, to achieve the lowest feeding/pig production costs. Use of alternative production systems with bedding of straw (or sawdust), with access to an outdoor yard, or under extensive conditions are limited and are often used to produce specific premium, branded products (organic, geographical origin...) for value adding pork/pork products to compensate for higher production costs. Over the last 20 years, pork consumption per capita has been nearly constant in some western regions such as the EU, but slightly and constantly decreasing in some countries. Recently, there has been a large increase in the volumes of fresh pork and pork products sold with official quality labels or trademarks, as well as the number of pigs produced in alternative production systems. These changes attest for an increasing diversification of both pork products and pig production systems ([IFIP, 2021](#)). For example, European organic pig production increased by 50% from 2015 to 2018 and continues to grow steadily, even though it represents only a small proportion of pig production (0.9% in 2018) ([Agence Bio, 2020](#)). There are also changes in pig husbandry practices in response to the evolution of consumer and public expectations and/or legislation, such as the reduction (ban in some countries) of surgical castration for male piglets without pain treatment or anaesthesia ([Bee et al., 2015](#)).

Overall, the wide variety of pork products which creates specific quality expectations for the 'raw' material used for processing, combined with the growing expectations of citizens for more sustainable pig production systems, makes pork quality a complex and multidimensional issue. According to the International Organisation for Standardisation, product quality is defined by a set of attributes that can satisfy the stated or implicit end-user needs. In this review, pork quality is based on various quality attributes: carcass commercial value, meat organoleptic, nutritional, technological (i.e. suitability for processing and storage) properties, convenience, and societal image. The latter corresponds to the product's extrinsic cues, encompassing the credibility, ethical, cultural and environmental dimensions related to the way a food is produced, as well as its geographical origin. Societal image includes many objective (animal welfare, environmental impacts, origin) and subjective dimensions, which all play a role in shaping consumer perceptions and purchase decisions, and are promoted in product quality labelling schemes ([Prache et al., 2021a](#)). The objective of this review is to present how carcass and fresh pork quality attributes are impacted by production factors along the production chain ([Table 1](#)). A complementary review focuses on farm to fork production and processing factors influencing quality

attributes for processed pork products ([Lebret and Čandek-Potokar, 2021](#)). This manuscript is largely based on reviews and meta-analyses published in the field, supplemented by results from primary scientific articles to illustrate specific points.

Carcass commercial attributes

In the EU, a SEURO classification system for pig carcasses was implemented in the 1980s to harmonise the assessment of carcass composition and value within and among member states and to provide the basis for objective payment to producers. The system is based on the prediction of the lean meat percentage (LMP) for the carcass using different devices to measure fat and muscle tissue at one or more anatomical sites, and develop prediction equations that are approved for a defined range of carcass weights. The methods and equipment used in different member states vary, with the most recent ones based on using a video camera and image analyser ([Pomar et al., 2009](#)). However, all methods must meet the conditions regarding method accuracy according to European regulation ([EU, 2017](#)). Prediction equations were established based on carcass composition determined from carcass dissection or computerised tomography ([EC, 2008](#)). In practice, the commercial value of the carcass is determined on the basis of payment schemes developed for national sectors; the EU requests monitoring and reporting of carcass prices on a standardised basis, and monitoring of the operators performing the classification. For the most part, the intrinsic pork attributes (technological, sensory or nutritional) are not taken into account in payment systems. For producers, the commercial value of pigs directly depends on slaughter weight, carcass dressing ($\approx 78\%$ in pigs depending on genetic, sex and BW) and body composition (lean-to-fat ratio). Increasing slaughter weight and age decreases LMP ([Trefan et al., 2013](#)). Therefore, payment schemes are designed by stakeholders to find an optimum in the case of standard pig production. The exceptions are specific chains and adapted classification and payment scales, such as the case of Italian heavy pig production.

Genotype

Pig genotype is one of the main factors determining carcass composition and value. Despite the rather large number of pig breeds, most of the commercial pork industry primarily uses a limited number of breeds in cross-breeding to benefit from the effects of heterosis on important economic traits ([Mote and Rothschild, 2020](#)). Genetic selection for growth rate, feed efficiency and leanness has been very effective, leading to a 12 point increase in carcass LMP since 1970 ([Bidanel et al., 2020](#)) with 92% of carcasses yielding LMP of at least 55% in 2020 ([EU Dashboard, 2020](#)). The increase in carcass leanness has contributed to a marked increase in meat production volumes in the last decades and is valued by pork industry stakeholders due to consumer demand for lean products. The detrimental effect of the well-described mutation (n allele) in the **RYR1** (halothane) gene on technological and organoleptic pork quality (detailed below) has led many breeding companies to eliminate it from their pig populations. However, the favourable impact of the RYR1 gene on carcass LMP has been retained in some genetic lines to increase carcass LMP from heterozygous pigs ([Davoli and Braglia, 2007](#)). In addition to RYR1, other gene polymorphisms have been associated to significantly affect carcass traits, e.g. **IGF2** (insulin-like growth factor 2) and **MC4R** (melanocortin-4 receptor) ([Ciobanu et al., 2011](#); [Mote and Rothschild, 2020](#)). Branded pork products (either private trademarks or official quality labels) have been developed in specific geographical regions using local pig breeds that have not been

Table 1
Major factors affecting the quality of pig carcasses and meat (lean tissue).¹

Factors	Quality attributes					
	Commercial ²	Organoleptic	Nutritional	Technological	Convenience ³	Societal image ⁴
Genotype	+++	+++	++	+++	–	+++
Sex	++	+++	++	+	–	+++
Age/weight at slaughter	++	+	+	–	–	+++
Muscle/Meat cut		+++	+++	++	+++	+++
Diet	++	++	+++	++	–	+++
Rearing conditions	++	++	++	++	–	+++
Preslaughter handling	++	+++	–/+	+++	–	++
Slaughter and carcass refrigeration conditions	++	+++	–	+++	–	++
Meat ageing/storage conditions and duration		+++	++	+++	+++	+++
Cooking mode		+++	+++	+++	+++	+++

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

² Commercial attributes: estimated effects on carcass value according to genotype, sex, age/weight at slaughter, diet, and rearing conditions factors, and on value of primary cuts (especially ham) for preslaughter and slaughter/refrigeration conditions.

³ Convenience attributes: the effect of muscle or meat cut refers to the method of preparation or processing (cooked, raw, matured, smoked ...) and therefore to the convenience of use.

⁴ Societal image attributes: the effect of the muscle/muscle cut refers to the nutritional perception of the product; the effects of preslaughter and slaughter/processing conditions refer to the perception of the handling/transport conditions for animals and the size of slaughter and processing plants.

selected for growth efficiency and carcass leanness (Bonneau and Lebret, 2010; Supplementary Table S1).

Sex

Among the animal-related factors determining carcass commercial value, sex plays an important role. It is well established that entire males (EM) are the leanest followed by females (FE) and castrated males (CM) (Pauly et al., 2012; Trefan et al., 2013). Total production costs are also lower feeding EM than CM or FE, due to their greater feed efficiency and protein retention (Bee et al., 2015). Surgical castration of male piglets is now an animal welfare issue in many parts of the world. While production of EM is now being promoted, there is a real risk for undesirable flavour (boar taint) in meat cuts from EM, which are then strongly devalued (Bee et al., 2015). A meta-analysis showed that immunocastration (IC) of EM represent an alternative solution to surgical castration, with a double benefit for boar taint prevention and carcass LMP which is intermediate between that of CM and EM (Batorek et al., 2012). Despite the scientifically proven advantages of IC, there has been limited implementation due to concerns about consumer acceptance (Aluwé et al., 2020; Supplementary Table S2).

Diet

Diet is a major production factor for modulating body composition and thus directly affecting pig carcass value. During pig growth, feed intake restriction reduces body fatness and is commonly used during the finishing phase to improve carcass value, since fat deposition increases faster than lean deposition with increasing BW (Lebret, 2008). Besides feeding level, dietary nutrient composition, especially protein-to-energy ratio (or lysine, the most limiting amino acid (AA) for pig growth) affects carcass composition. A protein-deficient diet offered ad libitum increases fatness while a gradual reduction in the lysine-to-energy ratio during growth can be used for precision feeding to meet the animal's nutrient requirements and control carcass LMP (Lebret, 2008).

Pig housing conditions or production system

The environment of pigs during rearing can influence the commercial value of the carcass, due to variation in lean-to-fat deposition according to various factors. Ambient temperature plays an

important role with greater carcass LMP in cold conditions (below pig's thermoneutral zone) especially if greater pig energy requirements are not met (Lebret, 2008; Faure et al., 2013a). Heat exposure (≥ 30 °C) can also lead to higher carcass LMP due to a reduction in spontaneous feed intake (Lebret, 2008). Compared to slatted floors, housing on straw is usually associated with greater available surface area per pig and lower ambient temperature, often leading to fatter carcasses from pigs fed ad libitum (Millet et al., 2005). The influence of 'alternative' production systems with outdoor access to courtyards or rangelands on carcass composition and value results from the interactive effects of climatic conditions, and pig's physical activity and dietary intake. Due to fluctuating rearing conditions, a greater variability in the carcass commercial value can occur with alternative production systems than in conventional indoor systems. In organic pig production, the ban on synthetic AA use in the diet together with the limited availability of organic protein resources makes it difficult to satisfy pig's nutritional requirements and optimise carcass composition (Prunier and Lebret, 2009). Moreover, pig nutrition interacts with housing conditions to affect carcass composition (Supplementary Table S3), even though producer returns for carcasses from organic pigs, and other branded quality labels, are based on specific payment scales and/or premiums.

Organoleptic attributes

Organoleptic or sensory properties of pork include the attributes that consumers perceive with their senses, including appearance (colour, marbling), texture (tenderness, juiciness), and flavour (aroma and taste). These properties are the result of complex interaction of factors related to the animal itself and its rearing conditions, peri-mortem handling (transport, slaughter), meat refrigeration and ageing conditions and meat preparation/cooking mode.

Genotype

This is one of the key factors determining muscle tissue characteristics and consequently, the organoleptic properties of pork. The major genes which are well known to impair meat quality are the halothane gene (causative mutation recognised as the R615C substitution in the RYR1 gene) and the RN gene (also referred to as R200Q substitution in PRKAG3 gene) (Ciobanu et al., 2011). Both affect *post mortem* muscle glycolysis (rate or extent of pH decline),

lowering water-holding capacity and technological quality and increasing meat toughness. The unfavourable allele in the halothane gene has been gradually eliminated in most lines of affected pig breeds (e.g. Pietrain, Belgian Landrace). The unfavourable RN⁻ allele in the PRKAG3 gene has been mostly eliminated from the Hampshire breed, whereas a favourable 199I mutation is reported to be at high frequency in the Berkshire breed (Ciobanu et al., 2011). Other polymorphisms such as in the CAST (calpastatin) gene influence pork organoleptic quality, in particular tenderness (Mote and Rothschild, 2020). The use of the Duroc breed is recognised for improving pork sensory quality, especially tenderness due to high intramuscular fat content, even though intramuscular fat content also varies among Duroc lines (Schwob et al., 2020). Local or autochthonous breeds are also well reputed for their meat sensory qualities: redder meat, lower exudate, greater tenderness and juiciness ratings as compared to selected breeds (Bonneau and Lebret, 2010). These breed differences are likely a result of interactive effects of genetics and production factors, i.e. older age and heavier weights at slaughter and specific rearing conditions (e.g. management favouring a phase of compensatory growth and intramuscular fat deposition in some cases; extensive rearing conditions improving colour and modifying muscle properties) (Lebret et al., 2015) (Supplementary Table S1). For this reason, claims for superior sensory properties or use in specific sectors or niche markets are often associated with the use of Duroc or local breeds.

Sex

Sex has a moderate effect on pork sensory quality, except for boar taint, an unpleasant meat off-flavour and aroma for pork from uncastrated males. Tainted meat develops an off-flavour when heated, aversive to most consumers, which is mainly ascribed to androstenone and skatole that accumulate in adipose tissue. Androstenone is principally related to sexual development which is largely under genetic influence, whereas skatole level depends on husbandry factors (nutrition, hygiene and health), but these two substances have interrelated metabolism (Zamaratskaia and Squires, 2009). For the use of meat from uncastrated males, it is important to take into account consumers' sensitivity (which is overall greater for skatole than androstenone but with extensive individual variation), level of boar taint (i.e. concentrations of androstenone and skatole and their synergistic effects), as well as the product's fat content and method of preparation/consumption (Bee et al., 2015). Thus, processing using a dilution or masking (aromas, spices, smoke) effect helps to alleviate the perception of boar taint which is also more easily perceived in high fat content products and/or when the product is eaten warm (Bonneau et al., 2018). Pork production from EM is complex at both the production (due to sexual behaviours) and processing stage (boar taint risk) and needs whole system adaptations. In the context of standard pig production, the prevalence of boar taint is relatively low but highly variable (5–25%) due to detection method and production factors (i.e. pig genotype, age at slaughter, diet, health; Aluwé et al., 2020) and requires screening and sorting of carcasses on the slaughter line. Currently, the subjective method, so-called "human nose" scoring, is mainly used. Extensive research has been conducted to develop rapid online methods to identify tainted carcasses. An expensive mass spectrometry method with automated sampling and sample pretreatment has been recently proposed (Borggaard et al., 2017) which is fast and robust, and measures both androstenone and skatole levels. Besides boar taint risk, meat from EM can be less tender (higher shear force) than meat from CM or FE, which may be related to the lower intramuscular fat content in EM (Pauly et al., 2012); however, these pork texture differences are not always found (Trefan et al., 2013). Pork from EM may also

be more prone to lipid oxidation due to more unsaturated lipids in the carcass due to lower endogenous lipid synthesis (Supplementary Table S2).

Age and weight of pigs at slaughter

Simultaneous increases in age and slaughter weight ('heavy' pigs) are associated with greater carcass adiposity and intramuscular fat content which is a priori favourable for improved sensory quality. However, a specific increase in age at slaughter due to restricted feeding may counteract the effect on intramuscular fat content, as feed restriction reduces fat deposition at both carcass and muscle levels (Lebret, 2008). The reported effects of increased slaughter weight and age on organoleptic properties are not consistent which may be attributed to other confounding factors including weight/age difference when pigs are marketed, feeding and husbandry practices, or cooking method (Ngapo and Garipey, 2008).

Anatomical location

Muscle anatomical location is related to its physiological role, resulting in muscle-specific contractile and metabolic properties. For example, loin and some hind leg muscles have a more glycolytic metabolism, whereas foreleg, abdominal and neck muscles have more oxidative metabolism (so-called white or red muscles, respectively), causing differences in appearance (colour, exudation, amount and distribution of fat) and biochemical composition, resulting in sensory quality differences (Listrat et al., 2016). For example, red muscles have smaller muscle fibres, often more intramuscular fat, greater water-holding capacity, more phospholipids and certain free AA. A consumer study (Channon et al., 2016) found that consumers preferred more red coloured muscles (shoulder) over paler, white muscles (loin; biceps femoris), and highlighted predominant effects of anatomical location over meat ageing duration, cooking method or temperature.

Diet

Diet can influence meat organoleptic properties through different pathways; according to Ngapo and Garipey (2008) by way of (a) a direct transfer of aroma/flavour compounds (e.g. feeding fish oil) into muscle/fat tissues, (b) absorption of aroma-active microbial metabolites in the gastrointestinal tract (e.g. fermented liquid feed), fatty acid composition (e.g. high amounts of dietary polyunsaturated fatty acids), (c) nutrient balance in the diet (e.g. AA deficiency), (d) feeding strategy (ad libitum, restriction, compensatory growth). Thus, increased pork tenderness has been reported for low-protein but not energy-restricted diets, which increases intramuscular fat content (Lebret, 2008). A diet high in polyunsaturated fatty acid may lead to reduced oxidative stability and cause flavour defects in both lean and adipose tissues, the extent of which depending on tissue polyunsaturated fatty acid composition, iron content and pH of the meat (Amaral et al., 2018). Supplementing antioxidants i.e. vitamin E or microelements (Se, Zn; cofactors for antioxidant enzymes) along with the presence of natural antioxidants in the diet (which contain phenolic compounds to limit development or spread of free radicals) can limit oxidation of lipids (Falowo et al., 2014) but also of proteins during storage, with the latter possibly influencing meat texture (Bao and Ertbjerg, 2019). Dietary supplementation with methionine (precursor of cysteine which forms an important cellular antioxidant glutathione) two weeks prior to slaughter reduced meat discoloration and the risk of lipid oxidation during storage along with providing higher glutathione concentrations in muscle tissue at slaughter (Lebret et al., 2018).

Pig housing conditions or production system

Environmental (housing) conditions for rearing pigs have been indirectly linked to the organoleptic attributes of pork, through the combined effects of physical activity, environmental temperature, and diet on muscle tissue characteristics (Lebret, 2008). Free-range rearing or access to the outdoors has led to redder meat (Bee et al., 2004). Rearing pigs on straw-based floors improved bacon taste and texture (Maw et al., 2001) and pork juiciness when pigs had access outdoors (Lebret et al., 2011). However, many other studies found no significant effect of housing conditions or production system on meat sensory quality from 'conventional' pig genotypes (Millet et al., 2005) or even opposite effects, e.g. decreased tenderness and juiciness for meat from outdoor raised pigs during winter which was associated with lower intramuscular fat content and muscle pH (Lebret, 2008).

Organic production

The aforementioned difficulty in organic pig production to meet nutrient requirements, especially AA intakes, may have a positive effect on intramuscular fat content (Sundrum et al., 2000) and hence on sensory quality. However, the need for roughage in organic pig production limits "concentrate" feeding, which may reduce energy and protein intakes, growth rate and intramuscular fat content, with negative effects on tenderness (Hansen et al., 2006). The organoleptic properties of organic pork are affected by the combination of practices used to meet organic production regulations, including diet (nutritional composition, feeding management), housing (ambient temperature, space availability), and pig genotype. The application of various production practices is responsible for a wide variability of sensory properties observed within organic pork (Prunier and Lebret, 2009; Prache et al., 2021b; Supplementary Table S3).

Extensive rearing of local breeds of pigs

Extensive production systems can cover a variety of housing conditions (i.e. outdoor access, free-range), specific feeding management programmes, marketing at older ages and heavier weights at slaughter, and use of local breeds to increase organoleptic quality. This includes greater intramuscular fat content, a more favourable fatty acid composition, a more reddish colour and increased tenderness and juiciness, as compared to using 'conventional' pigs and conventional rearing conditions for pork production (Bonneau and Lebret, 2010) (Supplementary Table S1). Extensive rearing stimulates physical activity and integrates the influence of ambient temperatures, which may affect the biochemical, metabolic and contractile properties of muscles (Fazarinc et al., 2020; Lefaucheur and Lebret, 2020) and further differentiate organoleptic attributes of pork from local breeds as compared to indoor or semi-outdoor housing (i.e. breed × environmental interactions; Lebret et al., 2015).

Preslaughter and slaughter conditions

Pig handling during loading and unloading from the truck, during transport and in the slaughterhouse (lairage, stunning), can impact pork quality (Rosenvold and Andersen, 2003; Aguilar-Guggenbuhl, 2012). Any stress factor that occurs during this phase may affect *post mortem* physicochemical changes in the conversion of muscle to meat and subsequently pork quality (Foury et al., 2011; Terlouw et al., 2021). The stunning and exsanguination phases are particularly critical to avoid problems with undesirable meat appearance (ecchymosis, petechiae). The effects on other organoleptic attributes especially texture are indirect (mainly linked to pH and water-holding capacity) and thus discussed within the section on technological attributes.

Meat refrigeration and ageing

The refrigeration conditions for carcasses or meat cuts and the duration of *post mortem* meat ageing are particularly important for pork tenderness, but also to flavour. If the muscle is cooled to a low temperature before it reaches its final pH, calcium storage in the sarcoplasmic reticulum is destabilised, leading to myofiber contraction. A very rapid refrigeration, particularly in conjunction with lean carcasses and hot deboning can therefore lead to muscle contraction and meat toughening (Monin, 2004). This phenomenon cannot be remedied by ageing, which normally tenderises the meat due to myofibrillar proteolysis (Warner et al., 2017). *Post mortem* ageing of pork from 2 to 7 days improves sensory quality, as perceived by a panel of experts and consumers (Channon et al., 2003). Meat ageing for 10 days may have a greater effect on tenderness than genotype (Duroc versus Large White), along with improving flavour as released peptides and AA interfere with other volatile compounds during cooking (Wood et al., 1996). While new technologies (high pressure, ultrasound, etc.) can improve hygienic quality and meat tenderness, the improvements are much smaller for pork than beef or lamb, probably due to the lower initial shear force for pork (Warner et al., 2017).

Freezing

Freezing is a common method for preserving pork and an important economic lever for the industry to facilitate meat trade. Freezing must preserve meat original properties as much as possible, which requires control over temperature decline and water crystallisation, frozen storage and thawing (Lawrie and Ledward, 2006). During freezing, most water in meat solidifies into pure ice crystals, accompanied by a separation of dissolved solids. Fast freezing leads to small ice crystals that mainly remain within the muscle and preserves its microstructure. During thawing, exudate is released and bound by proteins; if the freezing is rapid and the thawing slow, moisture loss is minimal. Freezing affects organoleptic properties, especially colour, tenderness and flavour. Leygonie et al. (2012) noted ice crystals grow and destroy muscle cells during frozen storage, resulting in release of enzymes promoting protein and lipid oxidation, which may lead to flavour deterioration and discoloration. The effect of freezing /thawing on texture seems controversial. According to Ngapo and Gariepy (2008), previously frozen pork may be easier to chew, while no effects on texture were found by Duma et al. (2015).

Cooking

While meat cooking is a basic procedure to obtain a tasty and safe product, cooking method has a major impact on sensory characteristics. The difficulty with understanding cooking effects is that it takes place immediately before consumption and is under the sole control of the consumer. Thus, a communication campaign was recently launched in Australia to inform consumers about how overcooking pork deteriorates its sensory properties (Warner et al., 2017). Bajerholm and Aaslyng (2004) noted the changes in meat during cooking involve shrinkage of myofibrils, loss of water, denaturation of proteins (which occurs at different temperatures according to muscle protein components: collagen, myosin, actin...), melting of fat and consequently changes in texture and flavour. The important factors in thermal treatment of meat are (a) surface temperature, (b) temperature profile through the meat, and (c) mode of heat transfer (Bajerholm and Aaslyng, 2004). In general, an increase in internal meat temperature reduces tenderness but increases pork flavour intensity. Optimal tenderness and juiciness are achieved with low to moderate temperatures (60 to 80 °C) regardless of cooking method used (Warner

et al., 2017); however, the effect is also muscle dependent. Heat-induced changes produce different flavours (odours and tastes) derived from AA, carbohydrates and fat. High temperatures (≥ 110 °C) favour production of Maillard reaction (between AA and sugars) compounds that impact flavour determination, especially in grilled pork (240–250 °C) (Aaslyng and Meinert, 2017). Optimising pork organoleptic quality consists of finding a balance between flavour and texture (tenderness and juiciness) that are conversely affected by cooking temperature. The cooking method used, in conjunction with muscle type, determines the final sensory quality perceived by the consumer.

Nutritional attributes

The nutritional value of pork refers to its nutrient composition, i.e. nature and quantity of nutrients with particular health benefits. There are five major classes of nutrients: protein with essential AA, fats with essential fatty acid, vitamins and minerals and other health-promoting compounds (e.g. antioxidants). Pork is rich in essential minerals and vitamins (Fe, Zn, Se, vitamins D, B1, B2, B6, B12) with high bioavailability (Higgs and Pratt, 1998). While the protein content (18–22% of fresh muscle weight) and its AA composition are stable and balanced for human needs, there are extensive differences in fat content and fatty acid composition, due to muscle type and/or edible part of the carcass and from differences in carcass composition between animals. In terms of fat composition, constituent fatty acids include saturated, monounsaturated and poly-unsaturated fatty acid, within which n-6 or ω -6 poly-unsaturated fatty acid and n-3 or ω -3 poly-unsaturated fatty acid are distinguished. Dietary recommendations in human nutrition target lower amounts of saturated fatty acid and greater amounts of n-3 poly-unsaturated fatty acid (especially linolenic acid) (Mourot, 2009). In pigs, intramuscular fat content varies between 1 and 10% of fresh muscle weight (depending on the muscle) and these lipids are composed of triglycerides (reserve lipids, 0.5 to over 5%), phospholipids (structural lipids, between 0.5 and 1%) and cholesterol (0.05–0.1%) (Schwob et al., 2020). Phospholipid content is greater in oxidative (red) than glycolytic (white) muscles. Triglyceride content and fatty acid profile are highly variable and depend on muscle and husbandry factors: genotype, sex, but mainly on pig diet especially regarding fatty acid composition (Lebret, 2008; Wood et al., 2008). With regard to fatty acid profile, saturated fatty acids account for 35–45 % of total fatty acids, while monounsaturated fatty acids are predominant in pig muscles and backfat where they account for 42–52% of total fatty acid, and close to 60% in certain fatty breeds (Mourot, 2009; Poklukur et al., 2020). Oleic acid C18:1 is the main tissue fatty acid (over 40% of total fatty acid). The proportion of poly-unsaturated fatty acid is lower and the most variable (5–20% of total) depending on factors related to carcass adiposity (breed, sex) and rearing (especially diet). The proportion of n-3 poly-unsaturated fatty acid is generally much lower than that of n-6 poly-unsaturated fatty acid (0.8–1.5% versus 5–18% of total fatty acid), resulting in a n-6:n-3 ratio of about 15, much greater than the recommendation for human diets (<5) with the ratio of linoleic (C18:2 n-6) to linolenic (C18:3 n-3) acid ranging between 15 and 30 for conventional pork (Mourot, 2009).

Factors related to the animal: genotype, sex, tissue anatomical location, age/weight at slaughter

Any factor that affects carcass fatness will also affect the fatty acid profile in fat depots (Nurnberg et al., 1998). The influence of pig genotype and sex on lipid content and composition of pork is directly related to their effects on body fatness. Modern pig breeds selected for leanness have less saturated and monounsaturated

fats than fat pigs because of their lower endogenous lipogenesis, which produces only saturated fatty acid and monounsaturated fatty acid in pigs (poly-unsaturated fatty acids are strictly from exogenous origin, i.e. diet in pigs). Entire males are the leanest sex with the greatest amount of unsaturated fat, castrates have the most saturated fat, while females are intermediate (Schwob et al., 2020). A concomitant increase in age and weight (with growth) is also associated with increased endogenous synthesis and deposition of saturated fatty acid and monounsaturated fatty acid. The anatomical location of the fat depot also influences its fatty acid composition and therefore its nutritional value. For example, subcutaneous backfat has fewer lipids and more water and protein than perirenal fat. Even within subcutaneous backfat, the outer layer contains more water and fewer lipids than the inner layer due to differences in lipogenic activity (Poklukur et al., 2020). Compared to perirenal fat, subcutaneous backfat contains less saturated fatty acid and more monounsaturated fatty acid and poly-unsaturated fatty acid, especially in the outer layer, since fatty acid from endogenous origin is preferentially localised in the inner adipose tissue (Mourot, 2009). Intramuscular fat generally has lower saturated fatty acid and poly-unsaturated fatty acid, and higher monounsaturated fatty acid proportions than subcutaneous backfat, with muscle differences related to total lipid content (affecting both fatty acid and fat-soluble vitamins) and muscle type; oxidative muscles are often richer in phospholipids and poly-unsaturated fatty acid than white muscles (Wood et al., 2008).

Diet, housing conditions and production system

Diet is a key factor for modulating fatty acid composition by which the ratio of n-6:n-3 poly-unsaturated fatty acid in pork can be controlled and better adapted to a healthy human diet. The source of dietary lipids determines fatty acid composition of pork, since dietary poly-unsaturated fatty acids are directly incorporated in pig tissues without biochemical modification (Nurnberg et al., 1998). Because the tissue “response” is rapid, feeding n-3 fatty acid rich ingredients (e.g. flax, rapeseed canola, or hemp) shortly before slaughter can better align pork fatty acid composition with nutritional recommendations. The efficiency depends on the n-3 fatty acid source used, level and form of inclusion with extruded flax appearing to be most beneficial (Mourot, 2009), and with similar efficacy for deposition in meat and subcutaneous backfat (Wood et al., 2008). Antioxidant supplementation of the pig diet is strongly recommended in association with dietary enrichment with n-3 poly-unsaturated fatty acid to prevent lipid peroxidation that can alter flavour (see above) and pork nutritional value by the degradation of essential linoleic and linolenic fatty acid and the formation of toxic compounds during storage (Amaral et al., 2018). However, the strategy is not recommended for products subjected to long ripening (e.g. dry-cured ham) due to increased risks for lipid peroxidation unless sufficient antioxidants are provided in the diet (Lebret and Čandek-Potokar, 2021). Pork oxidative stability depends on the levels of antioxidant and pro-oxidant compounds and their activities. Dietary vitamin content, in particular vitamin E, can limit the oxidation of lipids and proteins. Selenium supplementation can also exert an antioxidant effect (Mourot, 2009). Antioxidant compounds, including vitamin E, must be added in moderate doses to limit the risk for pro-oxidant effects (Falowo et al., 2014). Work is currently underway to evaluate the efficacy of natural antioxidants and optimal supplementation time to achieve a favourable response while limiting additional costs.

The pig housing conditions or production system can affect pork nutritional properties by influencing lipid content and fatty acid profile, as the ambient temperature affects metabolic pathways for thermoregulation and feed intake, and consequently fat deposi-

tion and fatty acid composition. A decrease in ambient temperature is associated with an increase in voluntary feed intake and lipid deposition leading to greater monounsaturated fatty acid and lower saturated fatty acid and poly-unsaturated fatty acid contents, with the opposite effect in the case of high temperatures above the thermoneutral zone (Lebret, 2008). Besides ambient temperature, rearing system with grazing or forage supplementation affects the fatty acid composition of adipose tissue and meat. The content of n-3 fatty acid, esp. C18:3, is increased and the n-6:n-3 ratio decreased due to their high content in forages. This effect is likely associated with natural enrichment of pork with vitamin E (α and γ tocopherols) and other micronutrients, important for subsequent oxidative stability of meat (Lebret, 2008). The effect of the amount of forages consumed by pigs does not significantly affect pork iron or myoglobin concentrations (Tomažin et al., 2019). Forage consumption by pigs can be beneficial for pork nutritional properties through its effect on fatty acid profile. This can be observed in extensive production systems using local pig breeds, where pigs are often kept outdoors or have access to pastures and are fed exclusively or partially with local resources (acorns, chestnuts, forage). This particular production system promotes the endogenous synthesis of monounsaturated fatty acid, esp. C18:1, as well as n-3 fatty acid and the uptake of antioxidant compounds from pasture (Lebret, 2008; Tejerina et al., 2012) (Supplementary Table S1). Natural enrichment with antioxidants is particularly important, as these systems are used to produce high-quality products that undergo a long drying and ripening process, for which the control of lipid and protein oxidation during processing is essential from nutritional and organoleptic points of view (Lebret and Čandek-Potokar, 2021). While organic production requires obligatory outdoor access (in outside pens or on pasture) and supplementation with roughage, there is no consistent effect on pork fatty acid profile (Srednicka-Tober et al., 2016). Important differences in rearing and feeding practices under the umbrella of organic production can be held responsible for different results and also explain extensive variability in organic pork quality (Prache et al., 2021b; Supplementary Table S3). In summary, nutritional composition of pork results from the interaction of the various factors outlined above. Modelling approaches have been developed to integrate these data and offer predictive models for fatty acid composition as a function of diet with recent work also considering growth performance or carcass composition (Paulk et al., 2015). A further step would be to consider genotype, feeding techniques and target tissue (esp. intramuscular fat) to optimise lipid composition according to the qualitative objectives for the product.

Slaughter, meat ageing and cooking conditions

The peri-mortem conditions to which the pigs are subjected have no major effects on the meat nutritional properties. Pork ageing and especially storage conditions can influence lipid peroxidation, which increases with exposure to oxygen, light and temperature (Amaral et al., 2018). The conditioning method plays a major role for pork shelf life. Cooking has a major effect on the nutritional value of meat by altering the content and properties of its components, as well as by enhancing oxidation reactions, depending on the mode of thermal treatment and temperature. After cooking, mineral content (Na, Ca, Fe, Cu, Zn) in pork is increased by 1.5–2 fold due to moisture loss which represents 25–30% of the raw weight, depending on cooking method, temperature and duration. Conversely, concentrations of K, Mg, vitamin B1 and other water-soluble vitamins are reduced by cooking (Lawrie and Ledward, 2006). Fat-soluble, vitamin A is preserved in meat that has been cooked to an internal temperature of ≈ 80 °C. The oxidation products generated during cooking partici-

pate in the development of aromatic compounds and pork flavour, but in return, they can alter the nutritional properties including genotoxic and cytotoxic products from lipid peroxidation (Amaral et al. 2018). Oxidation reactions increase with cooking temperatures. Cooking can also produce newly formed compounds that are harmful to health, such as polycyclic aromatic hydrocarbons, which come from smoke and can be found on the surface of barbecued meats. Prolonged heating (≥ 150 – 200 °C) promotes the formation of mutagenic, heterocyclic amines on the surface of the product (in the “crust”) through the Maillard reaction (Rahman et al., 2014). Control of cooking conditions is therefore essential for maintaining both the nutritional value and sensory properties of meat.

Technological attributes

The technological properties for pork or its suitability to be processed into different products are extremely important as most pork is consumed as processed products. The primary technological property is water-holding capacity as it affects production yield. Water-holding capacity is primarily determined by *post mortem* changes, especially the rate and extent of *post mortem* pH decline, generally referred to as pH1 (determined at a given time during the first hour after slaughter) and the final or ultimate pH (pHu) after completion of the acidification process. Quality defects associated with *post mortem* conversion of muscle to meat are (a) pale, soft, exudative appearance due to a rapid pH decline (low pH1) while body temperature is still high), (b) acid meat (characterised by a very low pHu, close to isoelectric point), or dark, firm and dry meat, characterised by a high pHu (>6.0). Another important defect is the so-called “destructured” meat, characterised by a loss of the structure and fibrous aspect, presenting a soft mass. This defect, macroscopically similar to pale, soft, exudative, is mainly localised in the deep part of the ham muscles and thus not visible before deboning and strongly impairs cooked ham processing (Lebret and Čandek-Potokar, 2021).

Factors related to the animal: genotype, sex, tissue anatomical location, age/weight at slaughter

Pig genotype is one of the most important factors determining the technological quality of meat (Ciobanu et al., 2011). Previously described mutations with the RYR1 and PRKAG3 (R200Q substitution) genes can lead to pale, soft, exudative and acid meat, respectively, and therefore impair water-holding capacity; the impact is particularly marked if both are present which should be avoided (Škrlep et al., 2010). Although the allele N is considered dominant for stress resistance, its dominance for meat quality is not complete; meta-analysis found that the difference between NN and Nn genotypes was significant for the majority of technological quality traits (Salmi et al., 2010). On the other hand, the favourable 199I mutation in the PRKAG3 gene improves pHu and water-holding capacity (Ciobanu et al., 2011). Pork technological quality (pH1 and pHu, water-holding capacity, technological yield) has been negatively affected by genetic selection for efficiency of lean meat production, due to unfavourable genetic relationships between these traits (Ciobanu et al., 2011). To limit degradation of pork technological quality with genetic selection, some meat technological quality traits have been introduced into many breeding programmes. For example, a synthetic meat quality index based on ham muscle pHu, colour and water-holding capacity was included as a breeding objective for French pig populations in the early 1980s (Bidanel et al., 2020), with a constraint for not degrading this indicator, i.e. avoiding reduction of meat quality while selecting for carcass leanness. Similar strategies have been

established in other breeding schemes. The negative impact of selection on pork quality is supported by the results from divergent selection for residual feed intake, a measure of feed efficiency in growing pigs. Pork quality was decreased in loin and ham muscles (lower pHu, water-holding capacity and meat quality index, and lighter colour) due to increased muscle glycolytic metabolism and glycogen stores, in the line selected for low versus line selected for high residual feed intake (Faure et al., 2013b). The inclusion of pHu and drip loss in breeding objectives e.g. in the Pietrain breed may ultimately improve pork quality. Significant breed differences are also reported for pork technological quality, e.g. greater water-holding capacity and less light meat for Duroc compared to Piétrain, Large White or Landrace (Ciobanu et al., 2011) or for local Basque than Large White (Lebret et al., 2015). Sex has generally no significant influence on technological quality traits in the loin e.g. pHu, water-holding capacity (Pauly et al., 2012). However, a higher pHu was found in ham muscles for EM than CM (Trefan et al., 2013), which may be related to greater preslaughter physical activity and thus reduced muscle glycogen for EM, as their reactivity to novel environments and preslaughter handling may be more important. As explained for organoleptic attributes, anatomical location and physiological role for skeletal muscles markedly influence their contractile and metabolic properties, and thereby pork technological properties. Since glycolytic muscles are predominant in the pig carcass, the most valuable cuts i.e. loin and ham, generally have lower pHu and water-holding capacity than oxidative muscles, and are more prone to meat quality defects (pale, soft, exudative, acid meat, destructured meat) (Lustrat et al., 2016). For a given pig genotype or rearing conditions, an increase in age and weight at slaughter does not appear to have a significant effect on technological pork quality (Trefan et al., 2013).

Diet, housing conditions and production system

Overall, diet has rather limited impacts on technological pork quality parameters pHu, colour, water-holding capacity (Lebret, 2008; Li et al., 2015). However, strategic feeding (reduction in digestible carbohydrates) during a few weeks prior to slaughter can reduce muscle glycogen stores (Rosenvold and Andersen, 2003), key for *post mortem* pH decline. Dietary supplementation with methionine two weeks prior to slaughter decreased lipid oxidation, improved meat colour and increased pork pHu and water-holding capacity for loin and ham (Lebret et al., 2018). These results combined with findings from previous studies on the positive effect of dietary vitamin E supplementation on water-holding capacity of pork (Rosenvold and Andersen, 2003) show the possibility to improve technological pork quality by modulating the antioxidant status of muscle tissue through pig nutrition.

Housing conditions and production system can impact pork technological quality through their effects on muscle metabolic properties. Low ambient temperature (below thermoneutral zone) increases muscle glycogen stores especially in white muscles (loin, ham) leading to lower meat pHu and water-holding capacity (Lebret, 2008). This has been encountered in rearing conditions with outdoor access and even more in free-range systems during winter in which ambient temperature interacts with physical activity level of pigs to affect muscle metabolic properties and subsequent meat technological quality (Lebret, 2008). However, this negative effect is not always reported (Millet et al., 2005; Lebret et al., 2011), highlighting the variability and complexity of animal metabolic responses to rearing conditions and their consequences on pork quality (Supplementary Table S1). Rearing conditions will interact with preslaughter handling, i.e. sorting from the rearing pen, loading, transport, unloading... as pigs reared outdoors are generally more resistant to these preslaughter conditions (Foury et al., 2011; Terlouw et al., 2021).

Preslaughter handling, slaughter, meat refrigeration and ageing conditions

The conditions to which pigs are subjected before and at slaughter can markedly influence technological quality. Depending on the level and duration of stress, there will be extensive variation in hormone secretion, muscle metabolism and body temperature, which will subsequently impact pH (pH1 and pHu), water-holding capacity and colour. If the stress is of short duration, *post mortem* glycolysis may increase, resulting in pale, soft, exudative pork (low pH1). A longer duration of stress or a high physical activity level (e.g. due to fights between animals when mixed during preslaughter handling) may cause glycogen depletion and subsequently lead to a higher pHu and dark, firm and dry meat (Monin, 2004). The behavioural and physiological responses of pigs to preslaughter handling conditions are important for determination of pork technological quality. Pig rearing conditions, i.e. their 'previous experience', affect these responses and relate to the emotional state of the animal (Terlouw et al., 2021).

Stunning itself can also have a major impact on meat technological quality. If pigs are not properly stunned, this can accelerate *post mortem* glycolysis and favour production of pale, soft, exudative pork along with affecting meat appearance from mild or severe visual defects related to blood splashes (ecchymoses and petechiae). Finally, the way pigs are bled may also affect meat quality, with horizontal bleeding being advantageous over vertical exsanguination (fewer spontaneous muscle contractions, less blood splashes, slower pH decline). The rules and recommendations for handling of pigs during loading, transport, unloading, and at slaughter (stunning) aim to minimise the pain and suffering of the animals and to maintain pork quality (Monin, 2004). Procedures for dressing carcasses (skin left or taken off) do not have any major effect on pork quality. The limited advantages or disadvantages of dehairing versus dehiding may also depend on further processing needs, carcass size and fatness. Refrigeration is more efficient in the case of dehairing and results in darker muscle colour and better water-holding capacity; however, it is not compatible with dry-cured ham production. While refrigeration is used to limit microbial growth and increase pork shelf life, technological quality can also be affected. Rapid refrigeration decreases *post mortem* glycolysis and thus can improve meat water-holding capacity and colour. However, very fast chilling on a lean carcass with a very thin subcutaneous fat layer can induce cold shortening even in pigs that are not normally at risk from this phenomenon, as compared to chilling of lamb, veal or beef (Monin, 2004). *Post mortem* ageing is used to improve tenderness for meat from all animal species, including pork. Ageing occurs at refrigeration temperatures and moderately affects the technological quality, the main effect being related to decreased water-holding capacity (increased exudation) with ageing duration. As previously mentioned, freezing is the common method for preserving pork and is intended to maintain meat properties as much as possible. The rate and duration of freezing are major factors to preserve pork quality. The most favourable conditions to limit moisture loss to a minimum include fast freezing and slow thawing (Leygonie et al., 2012).

In pigs, the quality of fat tissue also plays a major role in its suitability for processing into dry-cured pork products with a long ripening period, as well as for minced products containing both fat and lean tissues (e.g. sausages). Technological quality of fat tissue is characterised by firmness, cohesion, colour and oxidation stability (Schwob et al., 2020). The firmness of fat tissue depends on chemical composition: lipid, water, collagen content and fatty acid composition. Adipose tissue lacking consistency has high water content and poly-unsaturated fatty acid proportion; these two traits are affected by carcass fatness, and qualitative/quantita-

tive dietary fatty acid. The higher the proportion of polyunsaturated fatty acid, the softer the fat is at a given temperature, due to the lower melting point ($-5\text{ }^{\circ}\text{C}$ for C18:2 n-6 versus $69\text{ }^{\circ}\text{C}$ for C18:0, Wood et al., 2008). Shelf life is also affected as lipid peroxidation reactions are favoured by high water content and polyunsaturated fatty acid concentrations, in the absence of antioxidants (Amaral et al., 2018). Pig fat with high proportion of saturated fatty acid and low water content has thus a better technological suitability. Therefore, there is an antagonism between the qualitative fatty acid composition of animal fats recommended for human health and characteristics that are more suitable for processing.

Convenience attributes

'Convenience' attributes correspond to meat product characteristics that save time or energy in home food preparation for consumers. Portion size and packaging are important convenience factors, the latter affecting pork shelf life. There are four types of packaging used with raw muscle foods: vacuum, high oxygen modified atmosphere, low oxygen modified atmosphere and controlled atmosphere packaging to prolong shelf life (Gil and Gill, 2005). The efficiency for type of packaging to delay meat spoilage depends on temperature control along the distribution chain, which is also the critical factor for ensuring product safety. Pork shelf life will mainly depend on storage conditions and packaging mode (presence of O_2). In addition, pH, redox potential, risk for oxidation and initial microbial contamination will also contribute to product shelf life (Kilcast and Subramaniam, 2000); these are dependent on primary production factors (pig genotype, rearing method, diet, slaughter and carcass refrigeration processes, etc.) as previously discussed. While packaging protects meat from environmental contamination during storage and transport and promotes preservation, packaging also provides information for consumers on product origin or pig production system, and advice for preparation, cooking and storage. To provide more functionality and ease to consumers, packaging is becoming more sophisticated, with 'active' packaging containing e.g. O_2 , CO_2 , moisture or odour absorbers, release agents or bactericides, and 'intelligent' packaging which can monitor storage conditions by integrating time-temperature indicators, gas (leak) detectors, or freshness or ripening indicators. Advances in nanotechnologies and nanomaterials are being used to develop new packaging methods to further improve freshness and shelf life. The use of packaging materials is regulated in Europe. Convenience attributes refer mainly to quick and easy preparation. Pork in precut packages in various forms (chops, roasts, ground, single serving and cuts of loin, ham, neck, shoulder, ribs etc.) offer consumers fast and easy ready-to-cook products. This contributes to consumer satisfaction, since convenience was considered by consumers as the second most important pork attribute, after taste (flavour) (Resano et al., 2011).

Societal image attributes

Societal image attributes denote all cultural, ethical and environmental aspects related to pork production. These include objective (e.g. animal welfare, environmental impacts, geographical origin, quality labels) and subjective dimensions related to primary production and pork processing, and how they affect the perception and expected quality by consumers and, more broadly, society. Understanding of consumer expectations, perceptions, and behaviours related to meat and pork products are essential as they influence purchasing decisions. These consumer attributes evolve and vary across consumer segments (Aboah and Lees, 2020) and for a given consumer, depending on the circumstances for pur-

chase and consumption. The societal image attributes are increasingly important for consumers, as shown by the increase in the relative share and volumes for pork and pork products with official quality labels or claims (branded products) relying on various quality attributes sold in France, whereas pork consumption per capita has been decreasing for 20 years, in parallel with the average individual meat consumption (IFIP, 2021). This constitutes a great opportunity for the pork industry to develop more societally acceptable production systems (Weible et al., 2016), in agreement with the orientation of the European policy (Green Deal) and the "Farm to fork strategy" for a fair, healthy and environmentally friendly food system (EU, 2020). In pork production, improving animal welfare (especially the end of current practice regarding male piglet castration), reducing the use of inputs (especially veterinary drugs) and reducing environmental impact are currently major issues related to societal image attributes. Their relative importance has evolved over the last twenty years in Europe, with animal welfare gaining more importance (Clark et al., 2017). Moreover, the interests in how pork is produced may depend on consumer segment and country (Grunert et al., 2018). Recent work highlights that, in addition to intrinsic (organoleptic, nutritional) pork quality attributes and animal welfare, environment and climate, other impacts and ecosystem services provided by pork production systems i.e. inputs, markets, work and employment, social and cultural issues have to be considered simultaneously for their global assessment (Rischawy et al., 2019). For long term sustainability of pork production, stakeholders need to consider key societal concerns for the future while linking different functions of the system including provision of ecosystem services.

Conclusions: lessons and perspectives

Pork quality is influenced by the interaction of many factors along the production chain and the preparation of pork, including pig genotype, nutrition and rearing conditions, peri-mortem and slaughter conditions, meat ageing and storage and finally cooking by the consumers. The respective effects of these factors on pork quality attributes, summarised in Table 1, are detailed in Supplementary Tables S4–S8. Overall, the influence of the individual factors on the various pork quality attributes may be fairly well known or well established (e.g. genetics and technological properties; diet composition and lipid profile; preslaughter and slaughter conditions and technological or organoleptic properties; ageing duration, cooking method and sensory properties). This review also highlights gaps in scientific knowledge to better understand factors impacting pork quality. At the biological (mechanistic) level, more knowledge regarding the regulatory pathways of oxidative stress from *in vivo* to peri- and *post mortem* steps is needed to optimise the organoleptic, nutritional, technological and convenience attributes. Pork production with EM is possible with progress in genetic selection against boar taint, and reliable online detection of carcasses with boar taint followed by use in further processed pork products. Immunocastration has the potential to solve issues involving EM, but its societal acceptance remains a question. Meta- and/or multivariate analyses could be used to compile the information available in the literature on factors influencing pork attributes, to detail their cause-effect relationships, and provide a more holistic assessment of pork quality. Some predictive models for tissue characteristics such as fatty acid profile as a function of diet composition are already available, but may be refined by integrating genotype and rearing conditions. Also, considering different target tissues (including intramuscular fat) would be useful to optimise pork quality according to priority attributes: nutritional (unsaturated fats), sensory or technological properties (less unsaturated fats, antioxidant content...).

This review illustrates the important interactions between production factors on pork quality, which are particularly strong in alternative production systems, leading to highly valued specific quality characteristics usually appraised by quality labels (e.g. Protected Designation of Origin, Protected Geographical Indication, organic production (Supplementary Tables S1 and S3; Lebret and Čandek-Potokar, 2021)). With diversification of pig production systems, these interactions between factors contribute to greater variability in pork quality attributes. This can be a disadvantage for pork chain stakeholders and consumers if they are “used to” or expect uniform pork quality. It can also be an asset to differentiate products within a production system or a pre-established specification. We also highlight antagonistic effects of some production factors according to the quality attributes considered, e.g. between the carcass commercial value (LMP) and the pork technological and organoleptic properties; between the nutritional (fatty acid profile) and the technological attributes of fat tissues; between societal perception and commercial value (greater carcass LMP) versus pork sensory quality (boar taint risk) in EM production. Finally, optimising pork quality attributes to better comply with the needs and expectations of various users (producers, packing plants/abattoirs, processors, consumers) requires a better knowledge of biological responses to production factors and their interactions. Optimisation of pork quality depends also on which attributes are priorities for users (chain stakeholders) and whether pork is to be consumed as a fresh or processed product. To this end, it would be helpful to develop multicriteria analyses and models to identify and possibly quantify the synergies and antagonisms between quality attributes, which could be used as decision support tools by stakeholders according to their biotechnical choices, constraints and priorities regarding pork quality.

Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.animal.2021.100402>.

Ethics approval

Not applicable.

Data and model availability statement

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

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Declaration of interest

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