Meat Science 208 (2024) 109390

Contents lists available at ScienceDirect

Meat Science

journal homepage: www.elsevier.com/locate/meatsci

Challenges and future perspectives for the European grading of pig carcasses – A quality view

Marjeta Čandek-Potokar[a,*], Bénédicte Lebret[b], Marina Gispert[c], Maria Font-i-Furnols[c]

[a] Agricultural Institute of Slovenia (KIS), Hacquetova ulica 17, 1000 Ljubljana, Slovenia
[b] PEGASE, INRAE, Institut Agro, 35590 Saint-Gilles, France
[c] IRTA-Food Quality and Technology, Finca Camps i Armet, E-17121 Monells, Girona, Spain

ARTICLE INFO

Keywords:
SEUROP classification
Carcass value
Pork quality
Consumer
Industry 5.0

ABSTRACT

This study sought to evaluate pig carcass grading, describing the existing approaches and definitions, and highlighting the vision for overall quality grading. In particular, the current state of pig carcass grading in the European Union (SEUROP system), its weaknesses, and the challenges to achieve more uniformity and harmonization across member states were described, and a broader understanding of pig carcass value, which includes a vision for the inclusion of meat quality aspects in the grading, was discussed. Finally, the noninvasive methods for the on-line evaluation of pig carcass and meat quality (hereafter referred to as pork quality), and the conditions for their application were discussed. As the way pigs are raised (especially in terms of animal welfare and environmental impact), and more importantly, their perception of pork quality, is becoming increasingly important to consumers, the ideal grading of pigs should comprise pork quality aspects. As a result, a forward-looking "overall quality" approach to pork grading was proposed herein, in which grading systems would be based on the shared vision for pork quality (carcass and meat quality) among stakeholders in the pig industry and driven by consumer expectations with respect to the product. Emerging new technologies provide the technical foundation for such perspective; however, integrating all knowledge and technologies for their practical application to an "overall quality" grading approach is a major challenge. Nonetheless, such approach aligns with the recent vision of Industry 5.0, i.e. a model for the next level of industrialization that is human-centric, resilient, and sustainable.

1. Introduction

Grading of pig carcasses at the slaughter line is used as a support tool to ensure market transparency and fair remuneration for farmers worldwide (Keenan, 2016). The overall objective of grading is to determine the commercial value of the carcass, which first requires carcass classification. Classification is achieved by assessing the characteristics of carcasses that are important to trade (e.g., lean meat content), whereas grading involves the assignment of different values to carcasses for pricing purposes depending on the market and the trader's requirements (Polkinghorne and Thompson, 2010). Historically, pigs have been an important source of not only meat but also fat for human nutrition. Since World War II, the paradigm of pig production has shifted toward efficient lean meat production owing to substantial progress in the fields of selective breeding, animal management, and nutrition. Thus, the lean meat content of carcasses and carcass weight are the most important factors in determining the price of standard hog carcasses in commodity pork markets. Since the 1960s, pig production performance has improved considerably, including the prolificacy, growth rate, and feed efficiency of pigs, and carcass lean meat content. Thus, pig production has succeeded in satisfying the increasing market demand for inexpensive pork. However, this achievement has been accompanied by a decrease in certain meat quality traits and consumer acceptance of pork (Lebret, 2004; Schwab, Baas, Stalder, and Mabry, 2006; Lebret and Čandek-Potokar, 2022a). In many countries, carcass grading systems and methods are regulated by law. In the European Union (EU), grading of pig carcasses became mandatory in the 1980s. In member countries, carcass classification involves estimating the lean meat content (expressed as a percentage) of the carcass at the slaughter line by measuring fat and muscle tissue depths at one or more anatomical sites and applying previously developed prediction equations. Various methods or devices have been developed to determine muscle and fat

* Corresponding author.
E-mail address: meta.candek-potokar@kis.si (M. Čandek-Potokar).

https://doi.org/10.1016/j.meatsci.2023.109390
Received 30 April 2023; Received in revised form 3 November 2023; Accepted 5 November 2023
Available online 10 November 2023

tissue depths or proportions in the carcass. These devices are either manual, semi-automatic, or fully automatic, ranging from a simple ruler to more sophisticated devices based on ultrasound, light reflection, computer vision, electromagnetism, or impedance technologies (Daumas, 2023; Pomar, Marcoux, Gispert, Font i Furnols, and Daumas, 2008). The pork supply chain begins on the farm, and before meat reaches the consumer, it passes through the processing and retail sectors. Each stakeholder in the supply chain has its own economic interests and goals, and a different understanding of pork quality. Although farmers consider pork quality in terms of carcass quality (e.g., carcass weight and lean meat percentage (LMP)) for remuneration, the meaning of pork quality for processors and consumers is more complex (Prache et al., 2022). Consumer demand for healthy food of good quality is steadily increasing (Font-i-Furnols and Guerrero, 2022) and the quality attributes required by the meat industry and consumers are becoming increasingly varied (Lebret and Čandek-Potokar, 2022a). In addition to the carcass lean meat content and prime cut yields, a "fair" and complete grading system should consider intrinsic (product-related) pork quality traits and extrinsic (production-related) pork quality traits (Fig. 1). According to previous studies, certain intrinsic quality traits that are good indicators of pork eating quality or nutritional attributes important for consumers have a great potential for on-line assessment; for example intramuscular fat content (IMF), fatty acid composition and boar taint. These characteristics can be determined with new, fast, and non-invasive technologies suitable for working under on-line conditions (Font-i-Furnols et al., 2020; Schmidt, Sowoidnich, and Kronfeldt, 2010; Sørensen, Petersen, and Engelsen, 2012). Extrinsic quality traits refer to the way pork is produced, including animal welfare and environmental impact. Animal husbandry practices have become an issue for consumers (Liu et al., 2023); thus, the inclusion of this information in grading systems would be useful for marketing pork to consumers. Therefore, the aims of this study were i) to provide an overview of pig carcass grading and its evolution, with focus on the European grading system (SEUROP), and ii) to consider future perspectives for grading that would include pork quality traits.

2. Lean meat content of pig carcass as the basis for the current classification and grading

2.1. Different approaches and definitions of lean meat content

Carcass grading systems have been developed to regulate the carcass market on a common basis and ensure that producers receive fair payments based on commercially important attributes specific to the market requirements for the commodity (Keenan, 2016). Classification is not always mandatory but is a globally recognized criterion for determining market value. The classification of pig carcasses is generally based on carcass characteristics assessed at the slaughter line before chilling. As the classification is performed on-line, methods adapted for the slaughter process are required. In addition to fair payments, the results can be used for genetic improvement to support stock management decisions, marketing, and processing purposes. In the swine sector, lean meat content is the most important attribute for carcass classification. This attribute is defined as the proportion of lean meat in the carcass and is determined using a reference method that specifies the carcass presentation and dissection procedures. Originally, the lean meat content was estimated by separating various tissues (muscle, fat, skin, and bone) from the carcass with a knife (i.e., the accuracy corresponding to the plant personnel's ability to dissect with a knife) (Nissen et al., 2006). As manual dissection is a cumbersome and operator-dependent procedure (although well described), alternative methods have been proposed and developed to replace dissection, such as computed tomography (CT; Fig. 2) (Font i Furnols, Teran, and Gispert, 2009; Olsen, Christensen, and Nielsen, 2017; Romvári et al., 2006).

Various classification and/or grading systems have been developed worldwide using different approaches and reference methods, and different definitions for describing lean meat content in carcasses. In the EU, classification is based on the close relationship between LMP and the amounts (in most cases as depths) of subcutaneous fat and sometimes muscle, measured at specific anatomical locations on the carcass (Engel, Buist, Walstra, Olsen, and Daumas, 2003). The United States (U.S.) pork grading system is based on the expected fat-free lean yield (i.e.,

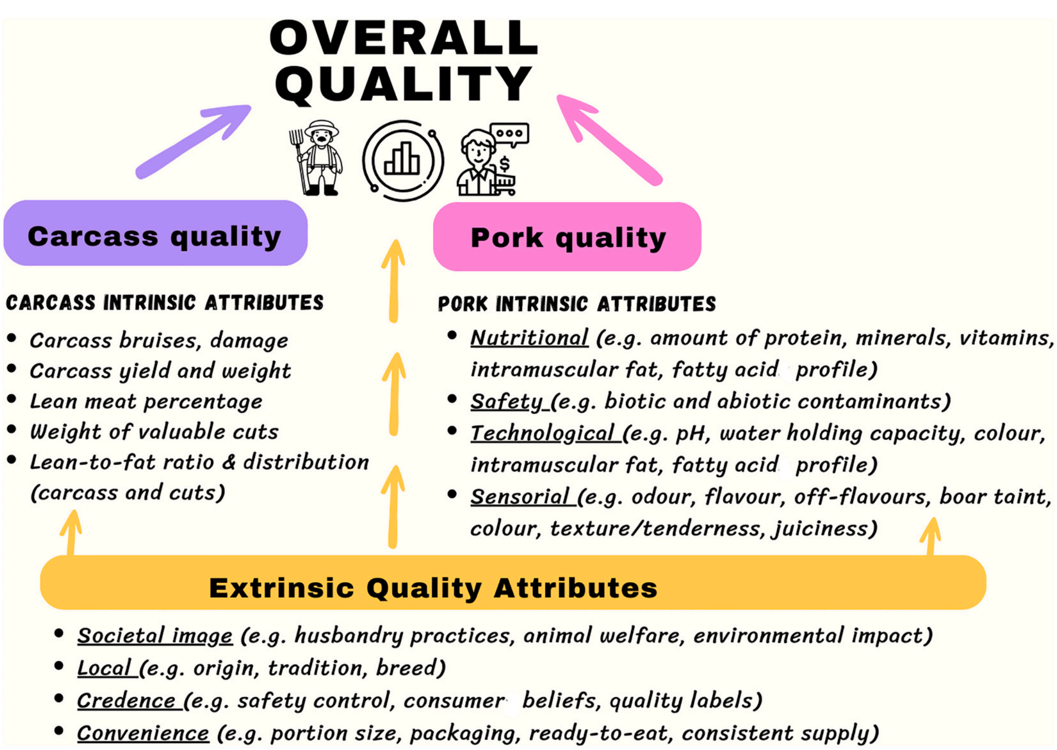

Fig. 1. "Overall quality" concept for pork grading.

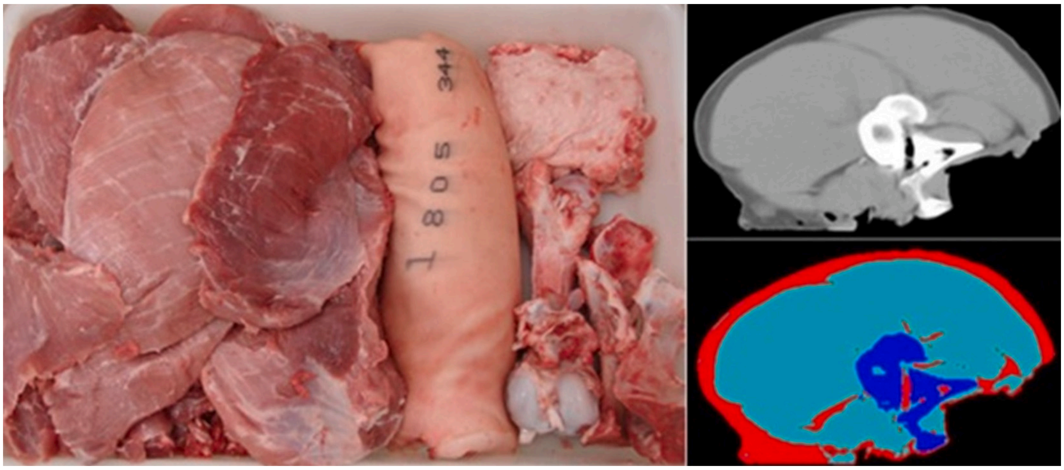

Fig. 2. Example of manual dissection of ham (left) and virtual dissection of ham via segmentation of the Computed Tomography images; fat, red; lean meat, light blue; and bones, dark blue (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

proportion of meat recovered from four primal cuts (ham, loin, picnic shoulder, and Boston butt)) using cutting and trimming methods and chemical extraction of fat from the muscle lean, referenced by the U.S. Department of Agriculture (USDA, 1985). In Canada, the grading system is based on the saleable lean yield (i.e., proportion of meat obtained from the commercial cuts of loin, picnic, butt, ham, belly, side ribs, and hock) (Marcoux, Pomar, Faucitano, and Brodeur, 2007; Pomar et al., 2008). The European classification system called SEUROP is based on the LMP, which is obtained by determining the amount of lean meat from the dissection of the whole carcass. Each letter represents a class covering a 5% range in LMP, with the letter S indicating carcasses with LMP above 60% and P indicating carcasses with LMP below 40%. The South African system, PORCUS, also estimates LMP (class P: >70% LMP, class O: 68–69% LMP, LMP class R: 66–67%, class C: 64–65% LMP, class U: 62–63% LMP, class S: < 61% LMP) based on wholesale cuts dissected into lean, fat, skin, and bone (Hugo and Roodt, 2015; Myburgh, 2019). The Australian, Korean, and Russian systems are not based on estimating lean meat content; however, payments for pork carcasses are based on warm carcass weight and fat depth, which is essentially equivalent to determining lean meat content, given the close relationship between lean meat content and subcutaneous fat depth (An et al., 2021; Hoa et al., 2021). The above systems also differ in terms of carcass presentation. For example, in the SEUROP classification, carcasses are presented with the head, whereas in the US, Canadian, and South African systems, they are presented without the head. Other parts of the body that may or may not be removed include the flare fat, kidneys, and skin. Dressing procedures can significantly influence carcass yield (i.e., the percentage of hot carcass weight to slaughtered live weight). Various systems also specify the categories of pigs for which grading is performed, involving mainly barrows and gilts within a certain weight range. In some cases, young boars (uncastrated males) and immunocastrated pigs are considered fattening pigs, and as such subject to classification. However, in this case, the predictive equations developed for on-line classification devices should include uncastrated males and/or immunocastrated pigs in the calibration step, if produced and marketed (this might be especially relevant in Europe; due to the initiative to stop castration, their proportion is increasing in some EU member states). Finally, the formulas used in different systems to calculate lean meat content differ in terms of the predictive variables and instruments used.

In the EU, grading of pig carcasses has been mandatory since 1984. The Council Regulation (1984) established a system for the classification, identification, and presentation of carcasses in the pig meat sector, also known as the SEUROP Union scale. The basis of this system is the estimation of the lean meat content "separable by knife" and is expressed as a percentage of the carcass. The SEUROP scale is based on objective measurements of carcass traits (at different anatomical positions) using different devices previously calibrated to predict LMP. Because the system also serves as a basis for market transparency and regulation, it is important to ensure a uniform application of pig carcass classification. These provisions have been established through a legislation that has evolved over time, particularly regarding the definition of LMP. The regulations that currently govern this system (Commission Regulation, 2017a, 2017b) prescribe that the value of a pig carcass is determined by its LMP in relation to its weight and is assessed by using a grading method that should consist of automated, semi-automated, or manual grading techniques and prediction equations. Estimations should be made by measuring certain anatomical parts of the carcass and applying authorized and statistically proven methods. To ensure that the statistically proven methods are applied on an objective basis, member states should be informed about dissection trial and results through protocols that are assessed and approved by the experts (Fig. 3). Accordingly, statistical guidelines were developed as part of the EUPIGCLASS project (Causeur et al., 2003) and remain valid 20 years later. The protocol for approving the method must include the results of the dissection trial performed on a representative sample (>120 pig carcasses) from a specific pig population for which the method shall be used. The sample should reflect the population of pigs that will be classified with respect to the breeds and/or crossbreeds used, range of carcass weights, and sexes. The dissection trial must also comply with a prescribed common methodology (carcass presentation, reference dissection method), and the prediction error for the proposed classification method must be below 2.5%. The legislation also highlights that different methods can be used to assess the lean meat content of a pig carcass; however, the choice of method should not affect the estimated lean meat content.

Some grading systems supplement lean meat content information with other relevant carcass traits, such as conformation (The Netherlands payment system), carcass bruises or damages (South African system), or pork quality characteristics, such as marbling (USDA, Japan), which are assessed by a trained operator. The USDA grading system (USDA, 1985) includes characteristics for the lean and firmness of fat and characteristics related to the combined carcass yields from the four lean cuts (ham, loin, picnic shoulder, and Boston butt). All carcasses with unacceptable lean quality, belly thickness, or soft and/or oily fat are graded as U.S. Utility. In Switzerland, fat quality is included in the determination of price for producers, assessing iodine value, and polyunsaturated fatty acid content using a near-infrared device (Scheeder and Müller Richli, 2014).

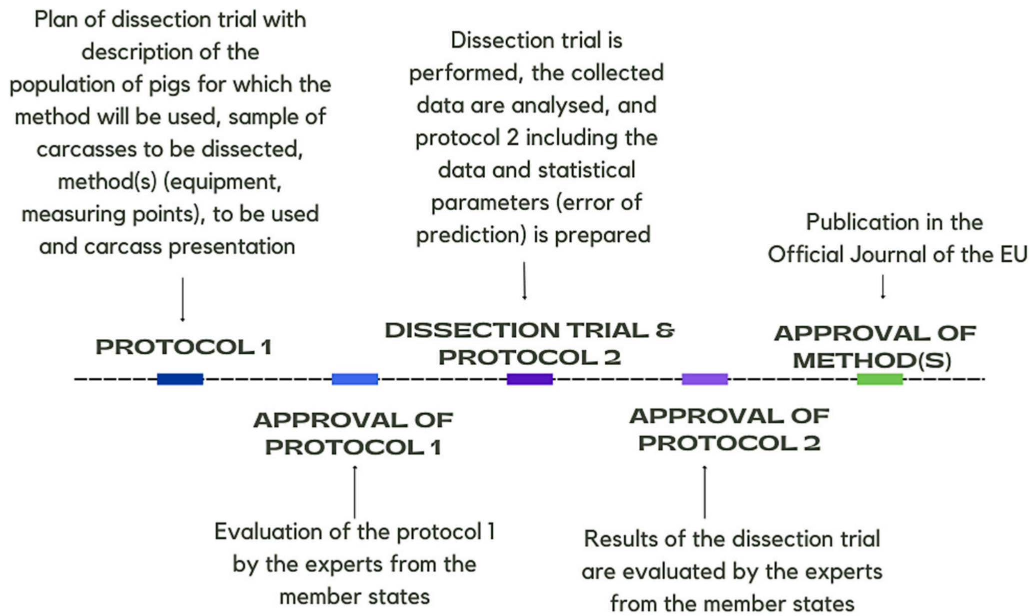

Fig. 3. Steps in the approval of pig carcass classification method(s) in the EU.

2.2. Technologies used for on-line assessment of lean meat content

Driven by the need for automation and accuracy in carcass evaluation, technological progress known as Industry 4.0 (the digital transformation of manufacturing and value processes in the industry) has led to potential technologies for evaluating carcass composition and characteristics, such as X-ray technologies (Dual Energy X-ray Absorptiometry (DEXA), Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Ultrasound (US), and Video Image Analysis (VIA). These new technologies have received extensive research interest for their potential application in carcass classification and/or grading for different livestock species (for a detailed review, refer to Delgado-Pando, Allen, Troy, and McDonnell, 2021). To the best of our knowledge, only US and VIA systems are currently used in the pig meat industry for classification and grading. However, DEXA is used in Australian abattoirs to determine carcass lean yield (Gardner et al., 2018).

Using various principles (e.g., light reflectance, ultrasound, computer vision), many types of equipment are available on the market for measuring carcass traits, that have been used to develop methods and applications for the on-line classification of pig carcasses. Depending on the degree of automation of the measurements, the devices/methods are mainly divided into manual, semiautomatic, or fully automatic (Fig. 4). In SEUROP classification, the precision of these devices/methods is evaluated as the residual standard deviation or root mean squared error of the prediction, which is usually obtained by cross-validation and

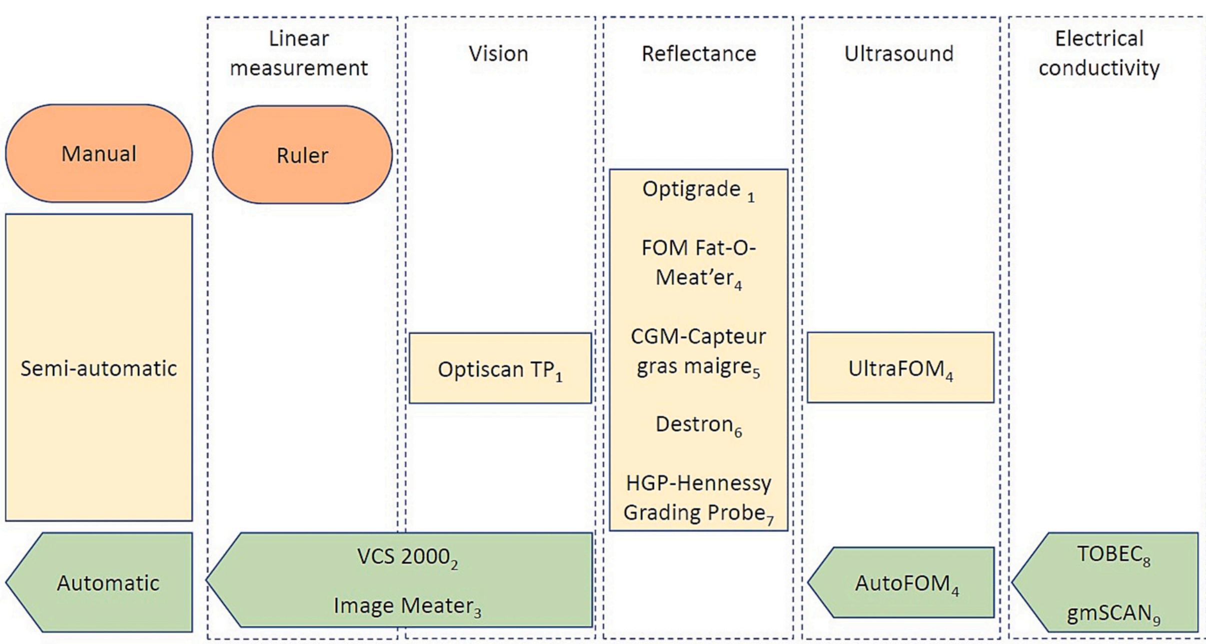

Fig. 4. Main pig carcass classification devices depending on the technology used (dash lines square) and the levels of automation (shape and colour) ($_1$ClassPro GmbH, Sielenbach, DE; $_2$e + V, Marel Oranienburg, Oranienburg, DE $_3$Frontmatec, Smørun, DK; $_4$Fives Syleps SA, Lorient, FR; $_5$Viewtrak Technologies Inc., Edmonton, CA; $_6$Hennessy Technology, Auckland, NZ; $_7$Meat Quality Inc., Springfield, Illinois, USA; and $_8$gmSteel, Dundalk, IE).

depends on the intrinsic characteristics of each instrument. Method precision is also influenced by factors external to the device, such as pig sample characteristics, dissection method accuracy, operator, ease of handling of the device, and the definition of lean meat content. Manual methods include rulers and calipers (manual or semi-automatic) and the Intrascope optical probe, in which the measurement error of tissue depth and the reading of results markedly depend on the operator. These instruments are used in manual devices/methods, such as the ZP (Zwei-Punkt-Messverfahren) and the Intrascope optical probe, where the operator is the main source of measurement uncertainty, with the highest reported prediction errors compared to semi-automatic or automatic devices (Daumas, 2023; Pomar et al., 2008). Despite this criticism, many EU member states continue to use these devices, primarily in small and low-speed abattoirs. Semi-automatic devices/probes are mostly used for the on-line classification of pig carcasses and mainly rely on the principle of light reflection or ultrasound for automatic detection of the fat and loin muscle depths. Semiautomatic devices/probes have been developed to reduce the operator effect, but with only moderate improvement, because both manual and semiautomatic probes are still manually operated. With the installation of automatic devices, the operator effect is no longer present, and the precision of LMP estimation has been markedly improved (Daumas, 2023; Pomar et al., 2008); however, such devices require more control to ensure proper functioning. Another advantage of automatic devices is the simultaneous measurement of numerous traits, which enables the estimation of other parameters of interest, such as the weight of primal cuts, with high precision. Devices/methods can also be divided into invasive (optical probes) and non-invasive (ZP, ultrasound, or vision systems) methods, with non-invasive methods having the advantage of avoiding carcass injury and contamination.

2.3. Issues for European classification based on lean meat content

2.3.1. Uncertainty associated with the reference method for lean meat content determination

The problem of harmonizing the LMP estimation within the SEUROP system depends on several factors. According to Olsen et al. (2017), carcass presentation can affect LMP by 0.77 percentage points, with improper splitting having the greatest contribution. The same study suggested that the effect on LMP can be reduced to 0.14 percentage points if a standard procedure for carcass presentation is followed. The second factor affecting the LMP is the reference dissection method. The first reference dissection method applied in EU calibration trials was employed in 1984 and was adapted from the German dissection method (EC, 1979; Olsen et al., 2017); this method is called "total dissection" (dissection of all tissues from the whole carcass to determine total carcass lean meat content). As this method is time-consuming, a simpler reference method was adopted in the EU in 1994 (Walstra & Merkus, 1996) to achieve a better balance between accuracy and costs. This simpler reference method uses only the weight of the lean meat from four dissected primal cuts (loin, shoulder, ham, and belly) and the tenderloin, which is then divided by the carcass weight. Agreement between the total dissection method and the simpler reference method was obtained using an upscaling correction ("cosmetic") factor of 1.3 on the calculation obtained with the simpler reference method. The accuracy of this simplified reference method was assessed (Nissen et al., 2006), and as a result the method was revised in 2008 to increase its accuracy. LMP was newly defined as the ratio between the weight of lean meat obtained as before (weight of the lean from four primal cuts + tenderloin) divided by the weight of the same five cuts and multiplied by a factor of 0.89 to account for non-dissected tissues compared to total dissection of the carcass. CT using medical X-ray scanners and magnetic resonance imaging were investigated as objective reference methods for on-line pig carcass classification in the EU project EUPIGCLASS (EUPIGCLASS, 2000). Several research institutions subsequently acquired CT scanners (FAIM, 2011) and established an initiative to recognize CT as a reference method (replacing manual dissection) within the framework of the SEUROP classification system (Olsen et al., 2017). As a result, CT was included in the EU legislation in 2008 (Commission Regulation, 2008). As CT determines the LMP for the entire carcass, two reference methods were part of this legislation: the simplified method already accepted (with a coefficient of 0.89) and total dissection method.

Manual dissection is subject to operator error, and the EUPIGCLASS project found that a "butcher" effect can contribute to up to 2 percentage points of LMP. According to Nissen et al. (2006), for an optimal knife dissection method with no systematic effect from butchers, the uncertainty could be reduced to 0.51 percentage point of the LMP. The use of CT is subject to error from image segmentation owing to i) the inability to fully separate elements with approximately the same density (structures with high protein content, such as tendons, glands, marrow, blood vessels, and cartilage, are considered meat in CT scanning) and ii) mixed voxels, known as the partial volume effect (i.e., voxels or 3D-pixels that contain more than one tissue). Nevertheless, CT is a potentially promising reference method owing to its low repeatability standard deviation (0.22 percentage points LMP) (Olsen et al., 2017). The challenge of using CT as a reference standard in practice is that the LMP is reported as a volume percentage rather than a mass percentage. As the entire half carcass is scanned, the results from CT must eventually be calibrated against a "gold standard," which is total dissection. Due to the strong initiative of member states disposing with a CT to approve it as a reference standard and because this method is based on total dissection, the European Commission decided in 2017 to renew the legislation and required that all simplified dissection methods, plus the CT method, be calibrated against total dissection. Thus, the current legislation since 2017 accepts three different "reference" methods in the EU to determine LMP: total dissection, partial dissection, or CT dissection. However, the last two must be referenced against the first, total dissection, and consequently, biases must be corrected.

2.3.2. Operator effect influencing the determination of LMP

Another challenge regarding the uncertainty of carcass grading is the influence of the operator when manually holding the equipment. This uncertainty can occur during the dissection trial (can be built into the method) and later when performing on-line classification with manual or semiautomatic devices held by one operator. The accuracy of the LMP assessment depends on the accuracy of the reference method, validity of the calibration, and precision of on-line measurements (Olsen et al., 2007). If the rules regarding the reference method and calibration protocol for the approval of methods are strict and covered by the legislation, no equivalent is available for on-line measurement uncertainty. As shown by Olsen et al. (2007), two "identical" pig carcasses measured in two different places by approved instruments and operators could differ by approximately 2 percentage points LMP only because of the uncertainties caused by differences between operators, environments, instruments, etc. On-line carcass classification results are not only used to compensate farmers based on a payment grid but are often used by value chain stakeholders for other purposes, such as evaluating feeding practices and in breeding programs. However, as discussed earlier, the uncertainty of this assessment is quite high; therefore, caution must be exercised when using individual classification results or comparing methods. For example, the ZP method is widely used by small slaughter plants in many EU member states but with different equations. In a study by Font-i-Furnols et al. (2016), large differences were found in the LMP obtained using different equations for the same dataset (up to almost five percentage points LMP), indicating a problem with low harmonization. Although accuracy is a problem when results from different member states are compared, reproducibility is important at the local level and depends on the operator, instrument, or other influencing factors. As mentioned previously, no common rules or guidelines exist for an acceptable level of measurement uncertainty. However, this issue has not been completely neglected by the European community, and the

EU legislation foresees that operators must be adequately trained, and each member state must perform and report regular quality checks (external verification of results) in the abattoirs.

2.3.3. Issue of harmonization regarding the EU approved methods for LMP estimation

The purpose of having a harmonized classification is to ensure that all approved methods *for LMP estimation* produce approximately the same results if they are compared on the same carcasses. However, despite the legislative framework and strict controls to ensure harmonization of classification methods across member states in the EU, the question remains whether this is sufficient to ensure comparability of carcass classification methods among member states and even among slaughterhouses within a member state that uses different carcass classification methods.

All efforts made in the last 20 years to better harmonize the classification of pig carcasses for transparency in the EU market have been unsuccessful, and today, the problem has not been solved or is even more pronounced. Currently, 126 equations are approved in the EU for classifying pig carcasses with approximately 20 different devices. The prediction error of these methods ranges from 1.1 to 2.5% LMP, and to date, only eight member states have adapted their methods to the latest definition introduced in the legislation in 2018 (Daumas, 2023).

3. Future perspectives – A quality view

Carcass characteristics should represent the actual value to the meat trade using a grading system that is meaningful for all stakeholders in the value chain. However, the correlation between carcass lean yield and market value is not obvious; this correlation is relatively low and depends on the definition of lean yield used (Marcoux et al., 2007). The commercial value of a carcass is also affected by the amount of trimming and the potential damage to the carcass (e.g., carcass bruises). In the meat industry, not only carcass weight and meat quantity are important, but also the weight and lean meat content of the most valuable cuts as well as the quality characteristics of the lean meat and fat. Thus, the classification and grading of primal cuts, such as loin, ham, or belly are important for processing and retail. For example, on-line classification of pig carcasses with AutoFOM (Frontmatec A/S, Smørum, Denmark) is widely used in Europe. By scanning the whole carcass, prediction models can be developed to estimate the weights and/or lean content of prime cuts, which can be useful for optimizing further processing (Masferrer et al., 2018, 2019). In addition to estimating carcass LMP, this non-invasive and fully automated ultrasound device provides additional information on individual carcass characteristics, such as the weight and LMP for pork primal cuts with great accuracy (Choi et al., 2018; Janiszewski, Borzuta, Lisiak, Grześkowiak, and Stanisławski, 2019). Semi-automatic devices, typically only used to measure fat thickness and muscle depth in the half carcass, could also be used to estimate the weights or lean content of primal cuts with previously developed prediction equations (Gispert and Font i Furnols, 2012). However, to the best of our knowledge, semi-automatic devices have only been used for whole-carcass classification. Other options include the use of devices in the cutting and processing room that allow sorting of cuts (i.e., VPS2000, e + V Technology GmbH, Oranienburg, DE, USA; Meat Master™II, Foss, DK, USA). In addition to evaluating the carcass lean meat content and prime cut yields, a grading system that considers the intrinsic and ideally, extrinsic traits of pork quality is needed. Such grading system would require clearly defined pork quality attributes, indicators, and/or metrics agreed upon by stakeholders along the pork value chain to ensure consistent meat quality and satisfaction for all end users.

3.1. Pork quality in the context of grading

The definition of pork quality is not simple; it represents a combination of different intrinsic and extrinsic properties (Fig. 1), and includes many aspects related to technological suitability and consumer acceptance (Prache et al., 2022). Consumer demand for high-quality healthy foods is steadily increasing, and lean meat content is no longer the only attribute sought by the meat industry. Moreover, with intensive selection for the efficiency of lean meat production, the quality of muscle and fat tissues has decreased owing to increased muscle glycolytic metabolism, leading to low meat pH and increased softness and degree of unsaturation of lipids, respectively (Lebret and Čandek-Potokar, 2022a). Current pig carcass classification and/or grading systems are adapted to the commodity market and follow the concept of quantity, making it difficult to meet the quality requirements of specific processing sectors for raw materials or consumer requirements. This is partly due to the carcass being composed of different muscles and fat tissues with different quality characteristics (e.g., compositional and sensory), but also because quality characteristics for meat in general are difficult to evaluate on-line. Priorities regarding quality attributes depend on the value chain stakeholders (farmers, slaughterhouses, processors (for dry or cooked products), retailers, and consumers) (Prache et al., 2022). Studies have shown that pork sensory quality, especially taste, is one of the most important quality traits for consumers (Lin-Schilstra, Backus, Snoek, and Mörlein, 2022). With the increasing market share for pork from uncastrated males, there is a greater risk for boar taint, which may become a limiting factor for pork consumption by many consumers, as shown for Australian consumers who recognize taste, succulence, and the smell of boar taint as the most important intrinsic pork quality traits (Duong, Sung, Lee, and Easton, 2022). Generally, studies mention drip, colour, marbling, and fat cover as the four most relevant intrinsic traits for consumers to determine pork chop quality (Verbeke et al., 2005). Intramuscular fat content (also assessed as marbling) is a characteristic well known to have a positive effect on the taste, succulence, and tenderness of pork, although not all consumers like to see a lot of intramuscular fat in meat (Font-i-Furnols, Tous, Esteve-Garcia, and Gispert, 2012; Ngapo, Martin, and Dransfield, 2007). Intramuscular fat content has been the focus of grading systems that go beyond carcass evaluation (e.g., this trait has recently been included in the Australian grading system for lamb; Gardner, Alston-Knox, and Stewart, 2022), and is the most studied meat quality trait with non-invasive technologies that can be used on-line. Fatty acid composition and boar taint are additional traits of interest that have great potential for use in grading systems.

Pork should not be marketed only as a commodity because consumers have different requirements for the eating quality of pork and how it is produced. The requirements include many aspects that usually differ depending on the value chain (i.e., farmers, processors, retailers, or consumers) and quality (i.e., technological, nutritional, safety, ethical, sensorial, or social) considered. In the current EU grading system, the quality aspects for the farmer include the LMP and carcass weight, as the carcass is purchased from farmers on this basis in most countries. However, the meaning of carcass quality differs depending on the processing of different types of products (integral cuts or minced products, cooked or dried, etc.), or the characteristics of the fresh meat according to market demands (e.g., highly marbled meat for the Japanese market or organic-produced meat for some consumers); this is particularly important when dealing with non-commodity, high-quality, or value-added products that require special raw material characteristics (Lebret and Čandek-Potokar, 2022b). The best management option involves the use of the correct raw material for each product (Christensen & Engell-Nørregård, 2016). Therefore, carcass classification, grading, and payment to producers should consider the relevant qualitative characteristics of the carcasses and/or meat. Such approach requires carcass (and meat) grading that aligns with the value chain priorities for all stakeholders, including consumer expectations. Meat purchasing decisions markedly depend on the region. However, an analytical literature review by Aboah and Lees (2020) indicated that the top five quality traits for meat-purchasing decisions are extrinsic and relate to credence attributes; for pork they found safety ranked as the top priority. The country of origin is also important for consumers (Aboah and Lees, 2020). Consumers encounter meat of different origins daily, and meat origin is often associated with its safety (e.g., trust in domestic production), even though an official food safety system is considered more trustworthy in some countries than in others (Font-i-Furnols and Guerrero, 2014). Pork should be convenient for consumers to prepare, taste good and should be produced in accordance with consumer's personal ethical values (Grunert, 2006; Lin-Schilstra et al., 2022). Consumer attitudes toward rearing animals for meat have markedly changed, and consumers are becoming more concerned about animal welfare and the environmental impacts of animal production (Liu et al., 2023). The relative importance of various extrinsic traits has evolved over the last twenty years in Europe, with animal welfare gaining relevance (Clark, Stewart, Panzone, Kyriazakis, and Frewer, 2017). Moreover, consumer interest in how pork is produced may depend on the consumer segment and country (Aboah and Lees, 2020; Grunert, Sonntag, Glanz-Chanos, and Forum, 2018). Individual consumer priorities for quality attributes also depend on purchase and consumption circumstances. The qualitative aspects of pork are becoming increasingly important because a growing proportion of consumers prefer to eat less meat but of higher quality. Consumer purchasing behavior is influenced by quality traits ranging from the functional or healthy properties of the meat product to product sourced from a more sustainable production system (Argemí-Armengol, Villalba, Ripoll, Teixeira, and Álvarez-Rodríguez, 2019). However, it should be noted that for a significant part of the population, the price of meat remains a major benchmark for purchase decisions, even in countries with greater consumer purchasing power (Aboah and Lees, 2020; Casal, Font-i-Furnols, Gispert, Manteca, and Fabrega, 2018; Liu et al., 2023). Moreover, the relationships between citizen attitudes (toward animal welfare and the need for environmentally friendly food production) and consumer behavior can be weak (i.e., what they think in their role as citizens about pig production does not always influence their pork consumption choices) (Krystallis, de Barcellos, Kuegler, Verbeke, and Grunert, 2009). When consumer behavior is examined, the dimensions of quality that affect repurchase of the product can be distinguished in terms of demand, experience, and credence (Grunert, Bredahl, and Brunsø, 2004). As mentioned earlier, societal demands for more sustainable production systems that ensure better animal welfare, biodiversity (e.g., local breeds), reduced use of inputs (especially veterinary drugs), and lower environmental impacts (precision feeding, use of local feed resources, and valorization of byproducts of the feed/food industry) are important factors that drive the demand for pork. This evolution is also promoted at the European level with the Green Deal policy and the “Farm to fork strategy” for a fair, healthy, and environmentally friendly food system (EU, 2020). Thus, the grading system for carcasses and pork should consider these aspects; however, how to incorporate these aspects remains unclear. Commonly accepted objective indicators and metrics for extrinsic quality must be discovered and a system that includes extrinsic and intrinsic quality assessments must be developed. As carcasses from different production systems cannot meet all the specific requirements, a grading system adapted to the value chain for the product seems a feasible solution, whether for standard commodity pork, organic pork, free-range pork, quality dry-cured ham, etc.

4. Meat grading in view of the principles of Industry 4.0 and Industry 5.0

The complexity and multidimensionality of pork quality require a feasible and efficient system of data recording along the supply chain and measurement capabilities for the on-line evaluation of intrinsic quality characteristics. Powerful tools are currently available to enable such approach, although not yet in every respect and in a complete manner. These advanced technologies are implemented in many manufacturing sectors, including agri-food, with examples from Industry 4.0 technologies applications in the meat industry, as reviewed by Echegaray et al. (2022). This concept is based on the digital transformation and automation of processes, such as autonomous robots, the Internet of Things (connecting and exchanging data over the internet), Big Data (complex data sets), cloud computing, augmented reality, cybersecurity, and blockchain, and refers to a new level of organization of the value chain that provides a mass of data that can be combined and used for grading. The concept of Industry 4.0 encompasses the entire value chain, including suppliers and the origin of the materials and components required for the process, which are key elements for the “overall quality” approach, requiring an efficient traceability system and advanced noninvasive technologies for on-line use in meat plants. A more recent vision is Industry 5.0, a model for the next level of industrialization that is human-centric, resilient, and sustainable. Industry 5.0 complements Industry 4.0 by considering social responsibility and contributions to society (EC, 2021). Consumers, and more widely citizens, are viewed as drivers of change in the quest for sustainable food systems, also affecting the pork sector. Eventually, the pork sector will integrate this paradigm, and the grading system will not only have to adopt this evolution but should be able to reinforce it.

4.1. Non-destructive methods for on-line evaluation of intrinsic pork quality

Several non-invasive techniques have been tested to determine their ability to analyze intrinsic meat quality traits, including X-ray technology, nuclear magnetic resonance, computer image analysis, infrared spectroscopy, Raman spectroscopy, dielectric microwave spectrometry, hyperspectral imaging, ultrasound, and sensor technology; only general concepts on these techniques are presented here as this topic was recently reviewed by several authors (Font-i-Furnols, Fulladosa, Prevolnik Povše, and Čandek-Potokar, 2015; Delgado-Pando et al., 2021; Leighton et al., 2022). Owing to the physical principles on which the abovementioned technologies are based, the internal structure of the material can be evaluated and/or visualized or response signals can be used to quantify the compounds of interest in lean and fat pig tissues. These technologies have been tested to elucidate their ability to predict pork quality traits with highly variable predictive ability and accuracy (for details, refer to Font-i-Furnols et al., 2015; Wu, Liang, Wang, Wu, and Sun, 2022; Sanchez, Arogancia, Boyles, Pontillo, and Mohd, 2022). Spectroscopic methods have provided very promising results for the evaluation of meat quality. Both near-infrared (NIR) and Raman spectroscopy probes have demonstrated good potential for predicting intramuscular fat content and fat tissue properties (content and fatty acid composition). The combination of spectroscopic and imaging techniques, such as hyperspectral imaging, also appears promising. Improvements in machine learning and artificial intelligence will likely increase the applications for pork quality assessments. A technique combining computer vision and machine learning has recently been developed to estimate the intramuscular fat content and marbling scores in pork (Chen et al., 2022). The literature mainly mentions the testing of methods under experimental conditions and the potential for on-line use of the devices for meat quality assessment (Clarke, Craigie, and Hitchman, 2022; Gou et al., 2013; Prieto et al., 2009; Schmidt et al., 2010; Wang, Zhang, Zhang, Peng, and Sun, 2020). Industrial application of the mentioned non-invasive technologies, although still limited, is already used in practice. As an example, a hand-held near infrared device (NitFOM, Frontmatec A/S, Smørum, DK) is used in some slaughterhouses to determine fat quality as fatty acid composition (Font-i-Furnols et al., 2020). Sensor technology, particularly electronic nose (machine olfaction), has also been studied to determine its application potential in the meat sector. This technology uses an array of sensors to convert gas molecular signals in meat into electrical signals using different chemical detection principles for volatile compounds. The electronic nose has been widely applied to distinguish between “spoiled” and “unspoiled” meat, but in the context of carcass grading, this technology may be able to detect boar taint or other potential off flavors. According to Wojnowski, Majchrzak, Dymerski, Gębicki, and Namieśnik (2017), detecting the presence of main boar taint substances (skatole and androstenone) using the electronic nose is limited by the relatively high molecular weight of both compounds compared to other odorants, which results in lower volatility, thereby reducing the detection ability and on-line application.

4.2. Requirements for on-line equipment installation

Performing on-line evaluation of pork quality directly on the carcass at the slaughter line or in meat cuts in the cutting room is associated with several advantages. Packing plants can sort products directly on a production line according to their further use or processing techniques. Such sorting could be very useful in the pork industry, including in some regions, such as Europe, where most pork is consumed as processed products derived using various processing procedures, which require specific quality characteristics for the raw material according to the process (Lebret and Čandek-Potokar, 2022b). However, to achieve such sorting, certain requirements concerning the characteristics of the line and equipment must be satisfied.

The slaughter floor and cutting room lines must have sufficient space to accommodate the equipment and technology required for carcass classification and pork quality assessment. This equipment/technology needs to be connected to the slaughter/cutting plant line network to ensure that all available information is integrated into the system and traceable. The equipment and technology characteristics must be sufficiently robust to work in industrial environmental conditions (i.e., wide ranges in humidity and temperature) and have sufficient capacity to work at line speeds, which can exceed 800 pigs/h. The ability to work at high line speeds is especially important when sampling or sample pretreatment is necessary; for example, on-line determination of boar taint components, androstenone and skatole, must be extracted from fat before chemical determination (Font-i-Furnols et al., 2020). An equipment/technology that is fully automatic is preferred, although semi-automatic or manual equipment connected to the circuit can also be used if the line speed permits. If sampling is required, automation of the process is desirable. Another important aspect is performance as the classification devices/technologies must meet the accuracy requirements that users need to achieve their prediction objectives. The prediction performance and maximum achievable accuracy depend on several factors, including the device characteristics (Engel, Lambooij, Buist, and Vereijken, 2012; Font i Furnols et al., 2009), samples used for the calibration (Engel et al., 2003), acquisition conditions and operators/monitors as needed (Fulladosa, Santos-Garcés, Picouet, and Gou, 2010; Nissen et al., 2006; Olsen et al., 2017), predicted trait (Prevolnik, Čandek-Potokar, Novič, and Škorjanc, 2009; Prieto, Roehe, Lavín, Batten, and Andrés, 2009), type of product and form of presentation of the sample (Prevolnik et al., 2005; Weeranantanaphan, Downey, Allen, and Sun, 2011) and the chemometric method used to develop the prediction formulas (Afseth, Segtnan, and Wold, 2006; Kucha, Liu, Ngadi, and Gariépy, 2022). In some cases, on-line measurement may not be possible (e.g., if a sample must be taken before measurement and whether pretreatment is required). Finally, the cost of the equipment, in terms of purchase, installation, and maintenance, must be considered to assess the different possibilities and advantages/disadvantages of its incorporation into the line.

5. Conclusions

The current classification for grading pigs in the EU, the SEUROP classification, refers to the quality of the carcass in terms of lean quantity, and is mainly used for market transparency. Over the years, the SEUROP classification system has lost its importance to some degree, as almost all carcasses are classified into the two highest classes, S and E (92.5% of classified carcasses according to Pigmeat Dashboard, 2023). In addition, the harmonization for estimating the LMP among member states is insufficient, as calibration of the device/method is performed at the member-state level rather than at EU level. Currently, the EU pig meat grading system does not consider other qualitative aspects of the carcass and/or meat which are important for pork processors and consumers. In addition to eating satisfaction, consumers increasingly perceive pork quality based on how pigs are raised, particularly in terms of animal welfare and environmental impacts. This situation highlights the need to redesign grading systems and evaluate the possibilities for their implementation. For an efficient supply chain to respond to consumer expectations and needs, the interests of various stakeholders in the supply chain must be better aligned. This alignment requires a common definition and understanding of pork quality for all stakeholders, quality standards shared by all levels of the supply chain, and traceability from farm to fork. Another important challenge is identifying common indicators and metrics accepted by stakeholders. Technological developments have provided tools that are currently available for grading pig carcasses based on "overall quality." However, integrating all knowledge and technologies for such approach represents a major challenge for the future of the pork industry. The industry could start by incorporating certain extrinsic traits related to the rearing of pigs into the grading system, similar to the current marketing standards for eggs (Commission Regulation, 2008) or some traditional pig products, such as labels of hams from Iberian pigs (BOE, 2014).

Ethical statement

Not applicable.

CRediT authorship contribution statement

Marjeta Čandek Potokar: Conceptualization; Investigation; Methodology; Resources; Visualization; Roles/Writing–original draft; and Writing–review and editing. Bénédicte Lebret: Conceptualization; Investigation; Methodology; Visualization; and Writing–review, and editing. Marina Gispert: Visualization; Investigation; Methodology; and Writing–review and Editing. Maria Font-i-Furnols: Conceptualization; Investigation; Methodology; Resources; Visualization; Roles/Writing–original draft; and Writing–review and editing.

Financial support statement

This work was supported by the core financing of the Slovenian Research and Innovation Agency (program, P4-0133 "Sustainable agriculture"), and CERCA program from the Generalitat de Catalunya.

Declaration of Competing Interest

The authors have no competing interests to declare.

Data availability

No data was used for the research described in the article.

Acknowledgements

The authors thank the reviewers for their comments and suggestions, which helped improve the manuscript. We would like to thank Editage (www.editage.com) for English language editing.

References

Aboah, J., & Lees, N. (2020). Consumers use of quality cues for meat purchase: Research trends and future pathways. *Meat Science, 166*, Article 108142. https://doi.org/10.1016/j.meatsci.2020.108142

Afseth, N. K., Segtnan, V. H., & Wold, J. P. (2006). Raman spectra of biological samples: A study of preprocessing methods. *Applied Spectroscopy, 60*(12), 1358–1367. https://doi.org/10.1366/000370206779321454

An, J. S., Lee, J. H., Song, M. H., Yun, W., Oh, H. J., Kim, Y. J., … Cho, J. H. (2021). Predicting body compositions of live finishing pigs based on bioelectrical impedance analysis. *Journal of Animal Science and Technology, 63*(2), 332–338. https://doi.org/10.5187/jast.2021.e31

Argemí-Armengol, I., Villalba, D., Ripoll, G., Teixeira, A., & Álvarez-Rodríguez, J. (2019). Credence cues of pork are more important than consumers' culinary skills to boost their purchasing intention. *Meat Science, 154*, 11–21. https://doi.org/10.1016/j.meatsci.2019.04.001

BOE. (2014). Real Decreto 4/2014, de 10 de enero, por el que se aprueba la norma de calidad para la carne, el jamón, la paleta y la caña de lomo ibérico. Retrieved from https://www.boe.es/eli/es/rd/2014/01/10/4. assessed on July 4, 2023.

Casal, N., Font-i-Furnols, M., Gispert, M., Manteca, X., & Fabrega, E. (2018). Effect of environmental enrichment and herbal compounds-supplemented diet on pig carcass, meat quality traits, and consumers' acceptability and preference. *Animals, 8*(7), 118. https://doi.org/10.3390/ani8070118

Causeur, D., Daumas, G., Dhorne, T., Engel, B., Font i Furnols, M., & Højsgaard, S. (2003). Statistical Handbook for Assessing Pig Carcass Classification Methods: Recommendations from the 'EUPIGCLASS' Project Group, 132 p. Retrieved from http://ec.europa.eu/agriculture/pigmeat/policy-instruments/statistical-handbook-for-assessing-pig-classification-methods_en.pdf.

Chen, D., Wu, P., Wang, K., Wang, S., Ji, X., Shen, Q., Yu, Y., Qiu, X., Xu, X., Liu, Y., & Tang, G. (2022). Combining computer vision score and conventional meat quality traits to estimate the intramuscular fat content using machine learning in pigs. *Meat Science, 185*, Article 108727. https://doi.org/10.1016/j.meatsci.2021.108727

Choi, J. S., Kwon, K. M., Lee, Y. K., Joeng, J. U., Lee, K. O., Jin, S. K., … Lee, J. J. (2018). Application of AutoFom III equipment for prediction of primal and commercial cut weight of Korean pig carcasses. *Asian-Australasian Journal of Animal Science, 31*, 1670–1676. https://doi.org/10.5713/ajas.18.0240

Christensen, L. B., & Engell-Nørregård, M. P. (2016). Augmented reality in the slaughterhouse - a future operation facility? *Cogent Food & Agriculture, 2*(1), 1188678. https://doi.org/10.1080/23311932.2016.1188678

Clark, B., Stewart, G. B., Panzone, L. A., Kyriazakis, I., & Frewer, L. J. (2017). Citizens, consumers and farm animal welfare: A meta-analysis of willingness-to-pay studies. *Food Policy, 68*, 112–127. https://doi.org/10.1016/j.foodpol.2017.01.006

Clarke, R., Craigie, C., & Hitchman, S. (2022). On-line measurement of meat. In *Reference Module in Food Science*. Elsevier. https://doi.org/10.1016/B978-0-323-85125-1.00155-1.

Commission Regulation. (2017a). Commission implementing Regulation (EU) 2017/1184 of 20 April 2017 laying down rules for the application of Regulation (EU) No 1308/2013 of the European Parliament and of the Council as regards the Union scales for the classification of beef, pig and sheep carcasses and as regards the reporting of market prices of certain categories of carcasses and live animals. *Official Journal of the European Union, L 171*, 103–112, 4.7.2017.

Commission Regulation. (2017b). Commission delegated Regulation (EU) No 2017/1182 of 20 April 2017 supplementing Regulation (EU) No 1308/2013 of the European Parliament and of the Council as regards the Union scales for the classification of beef, pig and sheep carcasses and as regards the reporting of market prices of certain categories of carcasses and live animals. *Official Journal of the European Union, L 171*, 74–99, 4.7.2017.

Commission Regulation. (2008). Commission Regulation (EC) No 589/2008 of 23 June 2008 laying down detailed rules for implementing Council Regulation (EC) No 1234/2007 as regards marketing standards for eggs. Accessed on July 6, 2023 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008R0589.

Council Regulation. (1984). Council Regulation (EEC) No 3220/84 of 13 November 1984 determining the Community scale for grading pig carcasses. *Official Journal of the European Union, L 301*, 1–3, 20.11.1984.

Daumas, G. (2023). Classification des cacassesde porcs selon leur teneur en muscle en france et dans l'Union Européenne. *Journées de la Recherche Porcine en France, 55*, 315–326.

Delgado-Pando, G., Allen, P., Troy, D. J., & McDonnell, C. K. (2021). Objective carcass measurement technologies: Latest developments and future trends. *Trends in Food Science & Technology, 111*, 771–782. https://doi.org/10.1016/j.tifs.2020.12.016

Duong, C., Sung, B., Lee, S., & Easton, J. (2022). Assessing Australian consumer preferences for fresh pork meat attributes: A best-worst approach on 46 attributes. *Meat Science, 193*, Article 108954. https://doi.org/10.1016/j.meatsci.2022.108954

EC. (1979). Development of uniform methods for pig carcass classification in the EC (No. 70). Retrieved from https://op.europa.eu/en/publication-detail/-/publication/35588033-4b7a-46ab-94c8-5f897a5a566a Accessed on April 28, 2023.

EC. (2021). *European Commission, Directorate-General for Research and Innovation, Industry 5.0: human-centric, sustainable and resilient*. Publications Office of the European Union, 2021. Retrieved from https://data.europa.eu/doi/10.2777/073781. Accessed on April 28, 2023.

Echegaray, N., Hassoun, A., Jagtap, S., Tetteh-Caesar, M., Kumar, M., Tomasevic, I., … Lorenzo, J. M. (2021). Meat 4.0: Principles and applications of industry 4.0 technologies in the meat industry. *Applied Science, 12*, 6986. https://doi.org/10.3390/app12146986

Engel, B., Buist, W. G., Walstra, P., Olsen, E. V., & Daumas, G. (2003). Accuracy of prediction of percentatge lean meat and authorization of carcass measurement instruments: Adverse effects of incorrect sampling of carcasses in pig classification. *Animal Science, 76*, 199–209.

Engel, B., Lambooij, E., Buist, W. G., & Vereijken, P. (2012). Lean meat prediction with HGP, CGM and CSB-Image-Meater, with prediction accuracy evaluated for different proportions of gilts, boars and castrated boars in the pig population. *Meat Science, 90*(2), 338–344. https://doi.org/10.1016/j.meatsci.2011.07.020

EU. (2020). Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system. In *Document Ares (2020) 1008142*, 23 p https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=PI_COM%3AAres%282020%291008142I.

EUPIGCLASS. (2000). tandardisation of pig carcass classification in the eu through improved statistical procedures and new technological developments (EUPIGCLASS) (2000). Retrieved from http://www.cordis.europa.eu/project/rcn/51397_en.html Accessed on April 28, 2023.

FAIM. (2011). Action FA1102: Optimising and standardising non-destructive imaging and spectroscopic methods to improve the determination of body composition and meat quality in farm animals (FAIM) (2011). Retrieved from https://www.cost.eu/actions/FA1102/ Accessed on April 28, 2023.

Font i Furnols, M., Teran, M. F., & Gispert, M. (2009). Estimation of lean meat content in pig carcasses using X-ray computed tomography and PLS regression. *Chemometrics and Intelligent Laboratory Systems, 98*(1), 31–37. https://doi.org/10.1016/j.chemolab.2009.04.009

Font-i-Furnols, M., Čandek-Potokar, M., Daumas, G., Gispert, M., Judas, M., & Seynaeve, M. (2016). Comparison of national ZP equations for lean meat percentage assessment in SEUROP pig classification. *Meat Science, 113*, 1–8. https://doi.org/10.1016/j.meatsci.2015.11.004

Font-i-Furnols, M., Fulladosa, E., Prevolnik Povše, M., & Čandek-Potokar, M. (2015). Future trends in non-invasive technologies suitable for quality determinations. In M. Font-i-Furnols, M. Čandek-Potokar, C. Maltin, & M. Prevolnik Povše (Eds.), *A Handbook of Reference Methods for Meat Quality Assessment: Cost Action FA1102 "Optimising and Standardising Non-destructive Imaging and Spectroscopic Methods to Improve the Determination of Body Composition and Meat Quality in Farm Animals (FAIM)"* (pp. 90–103). SRUC.

Font-i-Furnols, M., & Guerrero, L. (2014). Consumer preference, behaviour and perception about meat and meat products: An overview. *Meat Science, 98*, 361–371. https://doi.org/10.1016/j.meatsci.2014.06.025

Font-i-Furnols, M., & Guerrero, L. (2022). Understanding the future meat consumers. *Meat Science, 193*, Article 108941. https://doi.org/10.1016/j.meatsci.2022.108941

Font-i-Furnols, M., Martín-Bernal, R., Aluwé, M., Bonneau, M., Haugen, J.-E., Mörlein, D., … Škrlep, M. (2020). Feasibility of on/at line methods to determine boar taint and boar taint compounds: An overview. *Animals, 10*, 1886. https://doi.org/10.3390/ani10101886

Font-i-Furnols, M., Tous, N., Esteve-Garcia, E., & Gispert, M. (2012). Do all the consumers accept the marbling in the same way? The relation between visual and sensory acceptability of pork. *Meat Science, 91*, 448–453. https://doi.org/10.1016/j.meatsci.2012.02.030

Fulladosa, E., Santos-Garcés, E., Picouet, P., & Gou, P. (2010). Prediction of salt and water content in dry-cured hams by computed tomography. *Journal of Food Engineering, 96*(1), 80–85. https://doi.org/10.1016/j.jfoodeng.2009.06.044

Gardner, G. E., Alston-Knox, C. L., & Stewart, S. M. (2022). An international trading language for intramuscular fat% in sheep meat. In *Book of Abstracts of the 73th Annual Meeting of the European Federation of Animal Science, Porto, Portugal, 5-9 September 2022, no. 18* (p. 508).

Gardner, G. E., Starling, S., Charnley, J., Hocking-Edwards, J., Peterse, J., & Williams, A. (2018). Calibration of an on-line dual energy X-ray absorptiometer for estimating carcase composition in lamb at abattoir chainspeed. *Meat Science, 173*, 91–99. https://doi.org/10.1016/j.meatsci.2018.06.020

Gispert, M., & Font i Furnols, M. (2012). The use of pig carcass devices and computer tomography for predicting lean meat in the carcass and the main joints. In *58th International Congress of Meat Science and Technology (ICoMST). Montreal, Canada*.

Gou, P., Santos-Garcés, E., Høy, M., Wold, J. P., Liland, K. H., & Fulladosa, E. (2013). Feasibility of NIR interactance hyperspectral imaging for on-line measurement of crude composition in vacuum packed dry-cured ham slices. *Meat Science, 95*(2), 250–255. https://doi.org/10.1016/j.meatsci.2013.05.013

Grunert, K. G. (2006). Future trends and consumer lifestyles with regard to meat consumption. *Meat Science, 74*, 149–160. https://doi.org/10.1016/j.meatsci.2006.04.016

Grunert, K. G., Bredahl, L., & Brunsø, K. (2004). Consumer perception of meat quality and implications for product development in the meat sector—A review. *Meat Science, 66*, 259–272. https://doi.org/10.1016/S0309-1740(03)00130-X

Grunert, K. G., Sonntag, W. I., Glanz-Chanos, V., & Forum, S. (2018). Consumer interest in environmental impact, safety, health and animal welfare aspects of modern pig production: Results of a cross-national choice experiment. *Meat Science, 137*, 123–129. https://doi.org/10.1016/j.meatsci.2017.11.022

Hoa, V. B., Seo, H. W., Seong, P. N., Cho, S. H., Kang, S. M., Kim, Y. S., … Seol, K. H. (2021). Back-fat thickness as a primary index reflecting the yield and overall acceptance of pork meat. *Animal Science Journal = Nihon chikusan Gakkaiho, 92*(1), Article e13515. https://doi.org/10.1111/asj.13515

Hugo, A., & Roodt, E. (2015). Fat quality of South African pigs with different carcass classification characteristics. *South African Journal of Animal Science, 45*(3), 302–312. https://doi.org/10.4314/SAJAS.V45I3.8

Janiszewski, P., Borzuta, K., Lisiak, D., Grześkowiak, E., & Stanisławski, D. (2019). Prediction of primal cuts by using an automatic ultrasonic device as a new method for estimating a pig carcass slaughter and commercial value. *Animal Production Science, 59*, 1183–1189. https://doi.org/10.1071/AN15625

Keenan, D. F. (2016). *Encyclopedia of Food and Health* (pp. 419–431). Academic Press. https://doi.org/10.1016/B978-0-12-384947-2.00551-1

Krystallis, A., de Barcellos, M. D., Kuegler, J. O., Verbeke, W., & Grunert, K. G. (2009). Attitudes of European citizens towards pig production systems. *Livestock Science, 126* (1–3), 46–56. https://doi.org/10.1016/j.livsci.2009.05.016

Kucha, C. T., Liu, L., Ngadi, M., & Gariépy, C. (2022). Improving intramuscular fat assessment in pork by synergy between spectral and spatial features in hyperspectral image. *Food Analytical Methods, 15*(1), 212–226. https://doi.org/10.1007/s12161-021-02113-1

Lebret, B. (2004). Rationalization of pig production: Consequences on meat quality. *INRA Productions Animales, 17*(2), 79–91.

Lebret, B., & Čandek-Potokar, M. (2022a). Review: Pork quality attributes from farm to fork. Part I. Carcass and fresh meat. *Animal, 16*(Supplement 1). https://doi.org/10.1016/j.animal.2021.100402

Lebret, B., & Čandek-Potokar, M. (2022b). Review: Pork quality attributes from farm to fork. Part II. Processed pork products. *Animal, 16*(Supplement 1), Article 100383. https://doi.org/10.1016/j.animal.2021.100383

Leighton, P. L., Segura, J., Lam, S., Marcoux, M., Wei, X., Lopez-Campos, O., … Prieto, N. (2022). Prediction of carcass composition and meat and fat quality using sensing technologies: A review. *Meat and Muscle Biology, 5*(3), 1–21. https://doi.org/10.22175/mmb.12951, 12951.

Lin-Schilstra, L., Backus, G., Snoek, H., & Mörlein, D. (2022). Consumers' view on pork: Consumption motives and production preferences in ten European Union and four non-European Union countries. *Meat Science, 187*, Article 108736. https://doi.org/10.1016/j.meatsci.2022.108736

Liu, J., Chriki, S., Kombolo, M., Santinello, M., Bertelli Pflanzer, S., Hocquette, E., Ellies-Oury, M. P., & Hocquette, J. F. (2023). Consumer perception of the challenges facing livestock production and meat consumption. *Meat Science, 200*, Article 109144. https://doi.org/10.1016/j.meatsci.2023.109144

Marcoux, M., Pomar, C., Faucitano, L., & Brodeur, C. (2007). The relationship between different pork carcass lean yield definitions and the market carcass value. *Meat Science, 75*(1), 94–102. https://doi.org/10.1016/j.meatsci.2006.07.001

Masferrer, G., Carreras, R., Font-i-Furnols, M., Gispert, M., Marti-Puig, P., & Serra, M. (2018). On-line ham grading using pattern recognition models based on available data in commercial pig slaughterhouses. *Meat Science, 143*, 39–45. https://doi.org/10.1016/j.meatsci.2018.04.011

Masferrer, G., Carreras, R., Font-i-Furnols, M., Gispert, M., Serra, M., & Marti-Puig, P. (2019). Automatic ham classification method based on support vector machine model increases accuracy and benefits compared to manual classification. *Meat Science, 155*, 1–7. https://doi.org/10.1016/j.meatsci.2019.04.018

Myburgh, R. (2019). *Verification of the South African pork classification system*. Faculty of Natural and Agricultural Sciences University of the Free State January. Retrieved from https://scholar.ufs.ac.za/bitstream/handle/11660/10030/MyburghR.pdf?sequence=1&isAllowed=y Accessed on April 28, 2023.

Ngapo, T. M., Martin, J. F., & Dransfield, E. (2007). International preferences for pork appearance: I. Consumer choices. *Food Quality and Preference, 18*(1), 26–36. https://doi.org/10.1016/j.foodqual.2005.07.001

Nissen, P. M., Busk, H., Oksama, M., Seynaeve, M., Gispert, M., Walstra, P., Hansson, I., & Olsen, E. (2006). The estimated accuracy of the EU reference dissection method for pig carcass classification. *Meat Science, 73*(1), 22–28. https://doi.org/10.1016/j.meatsci.2005.10.009

Olsen, E. V., Candek-Potokar, M., Oksama, M., Kien, S., Lisiak, D., & Busk, H. (2007). On-line measurements in pig carcass classification: Repeatability and variation caused by the operator and the copy of instrument. *Meat Science, 75*, 29–38. https://doi.org/10.1016/j.meatsci.2006.06.011

Olsen, E. V., Christensen, L. B., & Nielsen, D. B. (2017). A review of computed tomography and manual dissection for calibration of devices for pig carcass classification - Evaluation of uncertainty. *Meat Science, 123*, 35–44. https://doi.org/10.1016/j.meatsci.2016.08.013

Pigmeat Dashboard. (2023). Retrieved from https://agridata.ec.europa.eu/Reports/Pigmeat_Dashboard.pdf. assessed on 4.7.2023.

Polkinghorne, R. J., & Thompson, J. M. (2010). Meat standards and grading: A world view. *Meat Science, 86*(1), 227–235. https://doi.org/10.1016/j.meatsci.2010.05.010

Pomar, C., Marcoux, M., Gispert, M., Font i Furnols, M., & Daumas, G. (2008). Determining the lean meat content of pork carcasses. In J. Kerry, & D. Ledward (Eds.), *Improving the Sensory and Nutritional Quality of Fresh Meat (capítulo 21)* (pp. 493–518). Cambridge, UK: Woodhead Publishing Limited.

Prache, S., Adamiec, C., Astruc, T., Baéza-Campone, E., Bouillot, P. E., Clinquart, A., Feidt, C., Fourat, E., Gautron, J., Guillier, L., Kesse-Guyot, E., Lebret, B., Lefèvre, F., Martin, B., Mirade, P. S., Pierre, F., Raulet, M., Remond, D., Sans, P., … Santé-Lhoutellier, V. (2022). Review: Quality of animal-sourced foods. *Animal, 16* (Supplement 1), Article 100376. https://doi.org/10.1016/j.animal.2021.100376

Prevolnik, M., Čandek-Potokar, M., Novič, M., & Škorjanc, D. (2009). An attempt to predict pork drip loss from pH and colour measurements or near infrared spectra using artificial neural networks. *Meat Science, 83*(3), 405–411. https://doi.org/10.1016/j.meatsci.2009.06.015

Prevolnik, M., Čandek-Potokar, M., Škorjanc, D., Velikonja-Bolta, Š., Škrlep, M., Žnidaršič, T., & Babnik, D. (2005). Predicting intramuscular fat content in pork and beef by near infrared spectroscopy. *Journal of Near Infrared Spectroscopy, 13*(2), 77–85. https://doi.org/10.1255/jnirs.460

Prieto, N., Roehe, R., Lavín, P., Batten, G., & Andrés, S. (2009). Application of near infrared reflectance spectroscopy to predict meat and meat products quality: A review. *Meat Science, 83*(2), 175–186. https://doi.org/10.1016/j.meatsci.2009.04.016

Prieto, N., Ross, D. W., Navajas, E. A., Nute, G. R., Richardson, R. I., Hyslop, J. J., Simm, G., & Roehe, R. (2009). On-line application of visible and near infrared reflectance spectroscopy to predict chemical–physical and sensory characteristics of beef quality. *Meat Science, 83*(1), 96–103. https://doi.org/10.1016/j.meatsci.2009.04.005

Romvári, R., Dobrowolski, A., Repa, I., Allen, P., Olsen, E., Szabó, A., & Horn, P. (2006). Development of a computed tomographic calibration method for the determination of lean meat content in pig carcasses. *Acta Veterinaria Hungarica, 54*(1), 1–10. https://doi.org/10.1556/avet.54.2006.1.1

Sanchez, P. D. C., Arogancia, H. B. T., Boyles, K. M., Pontillo, A. J. B., & Mohd, A. M. (2022). Emerging nondestructive techniques for the quality and safety evaluation of pork and beef: Recent advances, challenges, and future perspectives. *Applied Food Research, 2*, Article 100147. https://doi.org/10.1016/j.afres.2022.100147

Scheeder, M., & Müller Richli, M. (2014). Neues Bewertungssystem für die Fettqualität bei Mastschweinen. *ETHSchr. zur Tierernährung, 37*, 148–151.

Schmidt, H., Sowoidnich, K., & Kronfeldt, H. D. (2010). A prototype hand-held Raman sensor for the in situ characterization of meat quality. *Applied Spectroscopy, 64*(8), 888–894. https://doi.org/10.1366/000370210792081028

Schwab, C. R., Baas, T. J., Stalder, K. J., & Mabry, J. W. (2006). Effect of long-term selection for increased leanness on meat and eating quality traits in Duroc swine. *Journal of Animal Science, 84*, 1577–1583. https://doi.org/10.2527/2006.8461577x

Sørensen, K. M., Petersen, H., & Engelsen, S. B. (2012). An on-line near infrared (NIR) transmission method for determining depth profiles of fatty acid composition and iodine value in porcine adipose fat tissue. *Applied Spectroscopy, 66*(2), 218–226. https://doi.org/10.1366/11-06396

USDA. (1985). United States Standards for Grades of Pork Carcasses. Retrieved from https://www.ams.usda.gov/sites/default/files/media/Pork_Standard%5B1%5D.pdf Accessed on April 20, 2023.

Verbeke, W., De Smet, S., Vackier, I., Van Oeckel, M. J., Warnants, N., & Van Kenhove, P. (2005). Role of intrinsic search cues in the formation of consumer preferences and choice for pork chops. *Meat Science, 69*, 343–354. https://doi.org/10.1016/j.meatsci.2004.08.005

Wang, W., Zhang, C., Zhang, F., Peng, Y., & Sun, J. (2020). Real-time and online inspection of multiple pork quality parameters using dual-band visible/near-infrared spectroscopy. *Food Analytical Methods, 13*(9), 1764–1773. https://doi.org/10.1007/s12161-020-01801-8

Weeranantanaphan, J., Downey, G., Allen, P., & Sun, D.-W. (2011). A review of near infrared spectroscopy in muscle food analysis: 2005–2010. *Journal of Near Infrared Spectroscopy, 19*(2), 61–104. https://opg.optica.org/jnirs/abstract.cfm?URI=jnirs-19-2-61.

Wojnowski, W., Majchrzak, T., Dymerski, T., Gębicki, J., & Namieśnik, J. (2017). Electronic noses: Powerful tools in meat quality assessment. *Meat Science, 131*, 119–131. https://doi.org/10.1016/j.meatsci.2017.04.240

Wu, X., Liang, X., Wang, Y., Wu, B., & Sun, J. (2022). Non-destructive techniques for the analysis and evaluation of meat quality and safety: A review. *Foods, 11*(22), 3713. https://doi.org/10.3390/foods11223713

Walstra, P., & Merkus, G. S. M. (1996). *Procedure for assessment of the lean meat percentage as a consequence of the new EU reference dissection method in pig carcass classification : based on discussion in the EU Management Committee on Pig Meat and based on discussions with dissection experts during a meeting on May 18-19, 1994 at Zeist, NL. (Report / ID-DLO; No. 96.014). ID-DLO*.