REVIEW

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Exploring the multifaceted factors affecting pork meat quality

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Abstract

The significance of pork meat quality extends far beyond mere consumer satisfaction, encompassing crucial aspects such as health and nutrition, economic impact, reputation and branding, food safety, and sustainability within the global food system. Influenced by a multitude of factors, each playing a pivotal role in shaping its sensory attributes and consumer appeal, pork meat quality stands as a cornerstone of the meat industry. Thus, understanding these factors are imperative for ensuring consistent high-quality pork production, aligning with consumer preferences, and elevating overall satisfaction levels. In this review, we provide a comprehensive overview of the diverse factors affecting pork meat quality, including genetic characteristics, rearing systems, feed composition, gender differences, pre-slaughter handling, and meat aging processes.

Keywords: Pig, Meat quality, Pork

INTRODUCTION

Pork is one of the most widely consumed red meats worldwide, accounting for 35% of global meat consumption [1]. In consumers' diets, pork is one of the important sources of rich animal protein and other essential nutrients (essential vitamin, mineral, and fatty acids) [2–4]. As consumers' lives become enriched, interest in meat with high nutritional and functional value and excellent taste and texture is increasing, and there is a trend in placing high value on the quality of meat in consumption patterns [5–7]. In order to meet these consumer demands, meat quality is also emphasized at the production and processing stages and is becoming more economically important [3,8–10].

The concept of pork meat quality can be categorized into two main aspects: production process quality and product (meat) quality [11,12]. Production process quality include all measures used in animal production, pre-slaughter handling of animals, carcass and meat processing, and more and more consumers are considering process quality as a value in itself [13]. Product quality can be subdivided

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into functional (initial and final pH, water holding capacity, marbling, and fat quality), sensory (eating experience, ethical, and cultures), nutritional value, and hygienic (food safety) quality [10–12]. However, most pork meat quality is defined as the culmination of several important characteristics such as color, smell, flavor, texture, firmness, tenderness, pH, water holding capacity, drip loss, etc. [14–16]. From the processor's perspective, meat properties such as moisture holding capacity, drip loss, cooking loss, pH, collagen content, protein solubility, and fat binding capacity are objective characteristics that ensure a final product of excellent quality [17,18]. However, from the consumer's perspective, an important factor that influences the final evaluation of meat quality and repeat purchase decisions is the organoleptic properties (such as color, appearance, flavor, texture, juiciness, firmness, and tenderness etc.) that consumers perceive through their senses [19,20].

In general, meat quality is recognized as a complex and difficult characteristic because it is evaluated across a wide range of characteristics and attributes that are objectively and subjectively composed, and it is difficult to judge clearly [5,9,11,21]. The final determination of product quality can be influenced by various interaction factors among the quality of the production process described above [12,20]. Thus, this review discusses the pork meat quality and the various factors that have an influence to change its quality.

VARIOUS FACTORS AFFECTING PORK MEAT QUALITY

Pork meat quality is influenced by a multitude of factors including genotype (genetic background of pig), rearing conditions (level of feeding, environmental and housing system), pre-slaughter handling, slaughter method, storage conditions, etc. (Fig. 1) [22]. The important factors affecting pork quality before and after slaughter are classified as follows: 1) Factors influencing quality before slaughter: genetic, breed, sex, age and weight, rearing system, diet, pre-slaughter handling; 2) Quality influencing factors after slaughter: meat aging, storage condition.

Factors influencing pork meat quality before slaughter

Genetics

The meat industry has long considered genetic considerations in the production of high-quality processed meats for culinary and technological quality as the genetic background of an animal can impact the growth, feed efficiency, carcass composition, and meat quality [23]. Taking into consideration of developments in pig breeding, it is estimated that genetic variables influence pork quality by 10% to 30% [12], with the remainder attributable to environmental factors such as pre-slaughter market circumstances (15%–25%) and actual slaughter process (40%) [24]. Although there are large number of pig breeds, the majority of pork industry employs crossbreeding with a restricted number of breeds in order to capitalize on the impacts of hybrid offspring on key economic characteristics [25]. One of the major reasons behind this selection is to prevent the detrimental effects of specific genes on the pork quality. Two widely recognized significant genes that exert a direct impact on technological and organoleptic pork quality after mutation are the Halothane gene (causative mutation recognized as the R615C substitution in the RYR1 gene) and rendement napole (RN) gene (also known as R200Q substitution in PRKAG3 gene. Both of these genes affect post-mortem muscle glycolysis (declining pH), reducing water holding capacity and eventually increasing meat toughness [26]. The halothane gene, also known as the porcine stress syndrome gene, is associated with malignant hyperthermia [27] and the production of pale, soft, and exudative meat (PSE). Pre-slaughter stress causes abnormal lactic acid metabolism and accelerates glycolysis; the temperature of the carcass is abnormally high due to stress, the glycolysis is accelerated, ultimately resulting in excessive accumulation of lactic acid in a short time [28].

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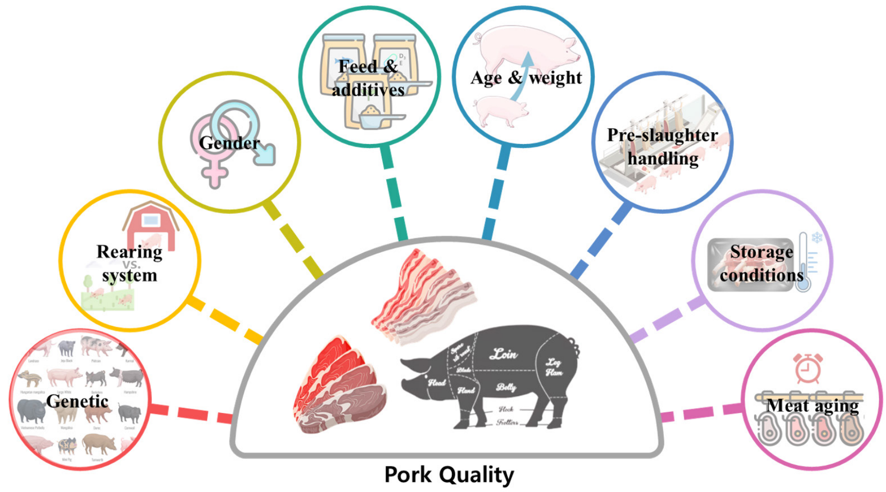

Fig. 1. Schematic diagram of factors affecting pork quality. Adapted from Freepik [22] with attribution as required by the copyright holder.

This results in rapid pH reduction and denaturation of muscle cell proteins, ultimately leading to the development of PSE meat with reduced water retention in muscle fiber tissue. Hamilton et al. reported that halothane genes independently affect growth performance, carcass composition, and pork quality [29]. A number of previous studies have reported that halothane-carrying pigs have advantages over halothane-negative pigs, such as better feed efficiency and carcass yield, but have a higher incidence of PSE [30–32]. The RN-, on the other hand, was discovered in Hampshire breed and is linked with extended pH decline postmortem and hence the meat from animals carrying of RN- gene is often referred to as "acid meat" due to its low pH [27]. The detrimental effects of the Halothane gene and the RN- gene are additive for color and water holding capacity [29].

Breed

Breeding (selective breeding), feeding, husbandry, and processing are the main traditional methods used to enhance pork quality [26,33]. A study by Li et al. [3] revealed that breed has significant impact on the pork meat quality. In a study comparing three breeds of Duroc, landrace and Yorkshire, Duroc pigs had the highest ultimate pH, carcass back fat thickness, marbling scores, yellowness, and fat content, while Landrace had the highest color lightness and cooking loss values. Gjerlaug-Enger et al. reported similar results for Duroc and Landrace animals [34]. Jeleníková et al. looked at the effect of pig breed on meat shear force and found that the Duroc breed was the most tender. Compared to other breeds, Duroc has distinct characteristics [35]. Alfeo et al. studied the variation in meat quality characteristics between Landrace and Sicilian pigs and found that the meat from Sicilian pigs was more tender than that from Landrace pigs [36]. Though meat quality depends on numerous factors, the majority of which are influenced by the breed and species of an animal.

Gender

Gender is supposed to have a small impact on the sensory quality of pork, including of boar taint, an off-flavor that is attributed to the presence of aldosterone, skatole and indole in the adipose tissue of mature male pigs [37–40], while gender plays an important role in determining the carcass commercial value. It is widely recognized that entire males (EM) have the lowest body fat percentage, followed by females (FE) and Castrated males (CM) [41,42]. Although it is generally acknowledged that gender variations exist in carcass traits, research findings vary greatly [43]. The occurrence of boar taint is comparatively low but highly variable (5%–25%) in context of standard pig production, the reason behind which is the detection method and production factors such as age of the pig at the time of slaughter, genotype of the pig, diet given to the pig, etc. [40,44]. At present, "human nose" is the way of scoring the strength of the taint from the carcass. However, extensive research is being conducted for developing rapid online methods. Other than the boar taint, the meat from EM can be less tender then meat from CM or FE, which is attributed to the lower content of intramuscular fat [42]; however, the difference in texture is not always prominent [41]. Xia et al. [45] studied the gender effects on novel Duroc line pig carcass characteristics and meat quality and found higher ($p < 0.05$) carcass weight, slaughter backfat, loin muscle area, loin muscle depth, carcass yield in female pigs compared to castrated males. Kim et al. [46] in his study on the effects of gender and breed on meat quality in Duroc, Pietrain and crossbred pigs found fewer effects based on gender.

Age and weight

Age and slaughter weight increases that occur at the same time are linked to higher intramuscular fat content and carcass adiposity, both of which are predicated on better sensory quality. However, as feed restriction lowers fat deposition at both the carcass and muscle levels, a particular increase in age at slaughter brought on by limited feeding may offset the effect on intramuscular fat accumulation [40,47]. The inconsistent effects of higher slaughter weight and age on organoleptic qualities have been recorded and this discrepancy may be due to various confounding variables, such as the different age/weight at the time of pig marketing, variation in diet and rearing systems, or cooking techniques. Hwang et al. [48] in their study evaluated the effects of increasing carcass weight on meat quality and sensory attributes and found that the increase in carcass weight improves the overall taste of pork; and revealed that the carcass weight had a positive correlation with flavor but negative correlation with tenderness.

Rearing system

The pig production methods when livestock technology was not advanced past were significantly more varied than those of today, and were based on factors such soil, climate, breeds-reared cattle, vegetative and productive qualities of husbandry regions, agricultural conditions, and technologies used. But with the growing competition, and development of pig rearing systems, these distinctions have become less clear [27]. The rearing system can influence the commercial value (variation in lean-to-fat deposition) of pork carcass, along with the organoleptic attributes [40]. The impact of rearing system on organoleptic qualities of pork have been associated indirectly to housing conditions (including space, floor type, outdoor access) and feeding level and composition, which influences feed requirements and physical activity, having combined effects on muscle tissue characteristics of the pork meat [40,47]. The pigs reared in outdoor conditions had enhanced juiciness in their meat [49], and improved taste and texture of bacon in the pigs reared on straw-based floors (indoor conditions) [50]. However, a study by Dostálová et al. [51] did not show any significant effect on carcass features and meat quality among the pigs reared in outdoor and conventional indoor conditions. Similarly, a previous study by Millet et al. [52] have not shown any significant impact of housing condition or production system on meat sensory quality. But, in a study done on Heigai pigs, those grown on grazing farms had a better meat quality and higher nutritional value than those grown on indoor feeding [53]. Since the sample size was small, the results can't be representative.

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Diet (Feed and feed additives)

In recent years, there has been a growing interest in studying the potential of nutrition (feed and feed additives) for enhancing pork meat quality. The kind of diet fed to a pig has an influence on its organoleptic properties of meat and overall pig carcass quality [40,54]. The level of feeding, its pattern, and the protein-energy ratio of the diet, along with the genotype of the pig, determines the rate of growth and the weight gain at both the whole-body and muscle levels in a pig. It is therefore a primary component for modulating body compositions and therefore directly impacting pig carcass value. Also, pigs being mono-gastric animals, many dietary ingredients get easily deposited to muscles and fat tissue, subsequently impacting the quality of pork [27]. Swine feeding is a significant environmental component that affects both the outcomes of fattening and the amount, and the quality of meat obtained i.e., final product [21]. The feeding strategy, level of feed given as well as dietary nutrient composition all have an impact on carcass quality [47]. Feed intake restrictions, a type of feeding strategy, are frequently implemented during the finishing stage to increase the carcass value, as it decreases body fatness during pig growth. This is because fat deposition increases more rapidly than lean deposition with increasing body weight [47]. Metabolizable energy and protein levels are the two major nutritional parameters that affect tissue composition, quantity, and quality of meat products [21]. Also, according to Ngapo and Gariépy [55], the dietary factors can impact the sensory qualities of pork in several ways by a) direct transfer of flavor/aroma from given feed to pig meat (e.g., when feeding fish oil), b) due to change in quantity of nutritional components in the feed (saturated, monounsaturated and polyunsaturated fatty acids), c) absorption of compounds from their environment, leading to increased boar taint chemicals from the mix of feces and urine, etc. (Table 1). Hertzaman et al. [56] reported that in the sensory evaluation of pork fed a diet containing graded fishmeal up to a 5.5% level, there was a difference in off-flavor in pork stored frozen for 6 months, but there was no difference in fresh meat. Likewise, Valaja et al. [57] also reported that there was no statistical difference in fresh meat samples based on the fishmeal content (5% and 10%) in the feed. However, it was reported that off-flavors increased depending on the fishmeal supply period. According to a review study by Rosenvold and Andersen [27], pigs fed diets high in polyunsaturated fatty acids can have 'soft' characteristics and are more sensitive to oxidation, so the type of fatty acids in the feed is a factor affecting meat quality and storage. Since animal fats are high in saturated fats, and vegetable fats are high in unsaturated fats, dietary fat sources can be controlled to produce the expected meat quality.

Pig diets are supplemented with various types of feed additives in order to enhance the meat quality. Addition of Vitamin E in the diet helps reduce the oxidation of pork and hence increase the shelf-life and quality of pork meat [58]. Lately, there has been significant interest in adding high levels of Vitamin D3 to improve tenderness of meat from cattle. Wilborn et al. in a study assessed the effects of feeding high amounts of Vitamin D3 to the finishing pigs during the last 10 days before

Table 1. Feed and feed additives that affect pork quality and their effects

Feed/additive	Impact on flavor/aroma	Impact on meat quality	References
Fish oil	Direct transfer of flavor/aroma to meat	Not specified	[55]
Algae	Improves fat quality, possibly impacts flavor	Increases levels of PUFA	[58,61]
Vitamin E	Not specified	Increases shelf-life and quality (Reduces oxidation, enhances shelf-life and quality)	[58]
Vitamin D3	Not specified	Improves tenderness, reduces drip loss, improves color	[59]
Sodium bicarbonate	Not specified	Reduces cases of PSE	[58]
Sugar cane extract	Enhances sweetness	Increases pH24h, reduces shear force, decreases drip loss	[60]

PUFA, polyunsaturated fatty acid; PSE, pale, soft, exudative.

slaughter [59]. The results did not find any significant effects on palatability qualities. However, there was reduction in drip loss and improvement in muscle color compared to the control group. The oral administration of sodium bicarbonate (an oral electrolyte) has been found to reduce the cases of PSE [58]. The study by Xia et al. indicated improvement in the pork meat quality with the addition of sugar can extract as a feed additive [60]. Sugar cane extract administration significantly increased the *Longissimus dori* muscle pH_{24h}, tended to reduce ($p < 0.01$) shear force and significantly decreased drip loss, myofiber cross sectional area and lactate dehydrogenase activity. Algae is also used in improving red meat quality. Though algae in pigs have mainly been studied for improving immune status and gut health [61], some studies have even found its impact on fat quality increasing the levels of polyunsaturated fatty acid in pork [58].

Pre-slaughter handling and slaughter conditions

Pre-slaughter activities encompass all animal-related activities and procedures from the farm to the slaughterhouse, including transportation, lairage and stunning [62]. At each stage of these activities, pigs are subjected to various stressors, including on-farm feed withdrawal, loading and transport, human interaction, and finally slaughtering, which indues stress in pigs and results in negative changes to carcass and meat quality, thus affecting overall pork meat quality. A study by Driessen et al. demonstrated that pork quality is affected by housing conditions and various parameters from birth on transport to lairage and slaughtering procedures [63]. The stunning and exsanguination phases are crucial to prevent issues related to undesired meat appearance, such as ecchymosis and petechiae [40]. The important pork characteristics that are impacted by pre-slaughter stress include colour, ultimate pH, water holding capacity, shelf-life, tenderness, which are of significant importance in meat science and technology industry [64]. PSE and dark, firm, dry (DFD) meats are the two major issues faced by meat industry impacting the value of quality of pork meat and is correlated with how the animals were treated before slaughter [65,66]. Both of these conditions are undesirable to consumers due to the subpar quality of the meat and low standard of processing for further processed products [67]. The two most widely used stunning methods for pigs are; Carbon dioxide (CO_2) and electrical stunning; There is a difference in the quality of meat. CO_2 stunning is considered a more advantageous method than electrical stunning in terms of pork meat quality and economics. Electrical stunning causes great physiological stress in pigs, increasing postmortem muscle activity and the release of catecholamines into the blood [68,69]. This results in accelerated glycogen metabolism, leading to a rapid pH decline and low water-holding capacity [27], thus increasing the likelihood of PSE pork [70]. Marcon reported that electrically stunned pork had higher cooking loss and lightness (L*) values. On the other hand, CO_2 stunning has a higher muscle water retention capacity and less drip loss compared to electric stunning. CO_2 stunning appears to be economically advantageous as it reduces PSE meat and lowers the incidence of petechiae [71], thus reducing losses due to disposal at the slaughterhouse [72].

After-slaughter factors influencing pork meat quality

Chilling and electrical stimulation

Many postmortem factors affecting pork quality have been studied, among them cooling and electrical stimulation of the carcass [73,74]. Because PSE muscle occurs when muscle proteins are denatured by high temperature and low pH immediately after death [75], reducing early postmortem metabolism, temperature, and pH decrease can reduce PSE and produce higher quality products [76,77]. Rapid cooling can quickly reduce temperature and improve pork quality by reducing PSE myogenesis [76,78]. Accelerated cooling methods include flash or cryo-cooling, hot fat trimming, cold water showers, etc., and typically involve accelerated processing using liquid

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nitrogen, propylene glycol, or cryogenic cooling systems [77]. Although these are all expensive processes, there are conflicting results regarding their impact on pork quality. Previous studies have confirmed that the L* value of quick-frozen pork is lowered compared to regular chilled pork, improving meat color and quality [76,79]. However, previous studies, including those by Gigiel and James [80], reported that cold muscle toughening can occur during rapid cooling [81,82]. Electrical stimulation is a method that can reduce this cold-temperature muscle toughening [74,83]. Several studies have shown that electrical stimulation can improve meat tenderness by increasing the rate of pH drop, creating conditions where cold toughness cannot occur [84–86]. However, it was also reported that the use of electrical stimulation was associated with the problem of increasing pork carcass drip loss, suggesting that the effect of electrical stimulation on pork quality may be ambiguous, and that the correlation between cooling and electrical stimulation requires further research [82,85].

Meat aging

Aging is a method that enhances the sensory attributes tenderness, juiciness, and flavor of fresh meat by postmortem proteolysis [87]. The aging process happens to do so through changes in the composition and content of different flavor precursors in the meat [88]. Aging is generally classified into vacuum and dry aging. Wet-aging by vacuum packaging is the widely adopted method across the industry [89]. Setyabrata et al. in their study evaluated the effects of aging methods (wet-aging, conventional dry-aging, and UV-light dry-aging) and found similar results [89]. Instrumental tenderness was similar across all the three treatments ($p < 0.05$); however dry-aging and UV-light dry-aging had a greater water-holding capacity than wet-drying. The consumer panel was unable to discern any differences in overall similarity and sensory attributes across the treatments, even though the metabolomics analysis revealed more flavor- related compounds in dry-aged meat. However, the results from another study suggested that both dry and wet-aging methods affect pork meat quality differently [90]. Though dry aging resulted in greater pH, redness values and moisture content, it exhibited lower drip loss and texture profiles.

Storage conditions

Freshness is one of the most crucial considerations for consumers buying meat [91] since meat is one of the most perishable foods because of its high-water content. Freezing, which has seen significant advancements over the past century, is a widely adopted preservation method to preserve pork meat and facilitate the meat trade [92]. One of the positives of freezing is that it prevents microbial deterioration at temperatures lower than -12℃, thus extending the product's shelf life [93]. In the meat industry, the value of meat exports worldwide is presently over US$ 13 billion, and freezing is crucial to guaranteeing the safety of meat provided to all parts of the globe [92]. The freeing process can also degrade the pork meat quality because of formation of ice crystals, affecting microstructure of frozen meat, due to repeated cycles of freeze-thawing [94]. Freeze-thawing cycles arise due to temperature fluctuations or mishandling during storage, retail display, transportation, etc. [95]. The repeated freezing-thawing cycles damage the muscle integrity and structure [96], causing destruction of cells and resulting in release of enzymes promoting protein and lipid oxidation, leading to discoloration and deterioration in flavor, affecting the pork meat quality [40,97]. However, the impact of freezing and thawing on pork texture appears to be a subject of discussion [40].

CONCLUSION

Consumer demands are constantly evolving, and optimizing meat quality is essential to meet these demands. It is important to consider various aspects such as taste, texture, and nutritional value to supply products that satisfy consumers. With the increasing demand for pork, sustainable production and quality optimization are becoming increasingly important. Research that considers both production processes and quality improvement is needed. This will help develop efficient and environmentally friendly production methods while enhancing the quality of meat. Multiple factors influence the quality of pork, and these factors are often interconnected. For example, genetic characteristics can affect feed supply conditions and dietary choices, while gender can influence intake and growth rates. Understanding these interactions is crucial. While past studies have mainly focused on the impact of individual factors, optimizing pork quality requires understanding the complex interactions among these factors. Therefore, future research should focus on integrated studies that consider these interactions. Through such research, comprehensive consideration of various factors influencing pork quality can be achieved, thereby meeting consumer demands and achieving sustainable production and quality optimization.

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