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Abstract

Pork belly is one of the most valuable primal cuts of pork with high preferences. Although meat quality is becoming increasingly important, defining pork belly quality is challenging owing to the structure and diversity of the preferred characteristics. This study identified the factors influencing pork belly quality traits through a literature review. In total, 55 articles related to pork belly quality were selected and summarized. The quality traits of pork belly are considered to be various factors, including belly yield (weight, length, thickness, etc.), firmness, fatty acid composition, color, and sensory properties. The quality of pork belly is influenced by various factors, such as sex, genetic parameters, carcass weight, and diet. A more diverse approach is required to comprehensively understand the quality traits and impact factors of pork bellies.

Keywords: pork, pork belly, quality, endogenous factor, exogenous factor

Introduction

Meat is an important source of protein and several essential nutrients in the human diet. Pork is one of the most preferred meats worldwide and its consumption has steadily increased (Godfray et al., 2018; Jeon et al., 2024). Among the primal cuts of pork, the pork belly is one of the most valuable cuts that is preferred in many countries (Jo et al., 2022; Jeong et al., 2024).

Consumer interest in food safety, quality, and healthy diets is increasing, and these changes influence meat consumption and meat industry. While factors, such as individual income and product price, are expected to have less impact on meat consumption, the importance of meat quality is anticipated to increase (Henchion et al., 2014; Kim et al., 2023). Pork belly is composed of multiple muscles and intermuscular fat layers, making it more challenging to assess meat quality than single-muscle cuts such as pork loin (Jo et al., 2024). To determine the quality of pork belly, the quality of both the muscle and fat layers must be considered. Additionally, pork bellies are consumed differently in different countries. In Western countries, pork belly is primarily consumed as bacon after curing, whereas in some countries, such as South Korea, consumers prefer grilled pork belly (Choe et al., 2015; Kang et al., 2015). These varying consumption preferences lead to different expectations regarding the quality of pork belly. Therefore, to prepare pork belly that satisfies consumer preferences, it is necessary to understand the quality traits of pork belly and factors that influence them. This study systematically reviewed and summarized previously published literature on pork belly quality. In particular, we reviewed only the fresh pork belly quality, excluding processing effects such as curing, aging, and freezing. Therefore, this review aimed to clarify the quality properties of pork belly and identify the factors affecting the quality properties.

Literature selection

This study aimed to systematically search and summarize the previous literature to identify the quality properties of fresh pork belly and the factors that influence belly quality. The literature was selected following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines (Page et al., 2021). The search was conducted using the Web of Science and SCOPUS databases with no restrictions on the year of publication.

We used a combination of the terms ‘meat’, ‘quality’, ‘pork’, and ‘belly’ to search the literature in Web of Science and SCOPUS. The criteria for selecting studies were as follows: (1) written in English and published in journals and (2) research studies on the quality of fresh pork belly or influencing factor to belly quality. The pork belly is a major cut of pork carcass; therefore, it is common to analyze belly quality together with other cuts to describe the overall quality of pork carcasses. Among these studies, we selected those that allocated at least one section to the description of pork belly quality to select literature with sufficient consideration for pork belly quality. In addition, studies that analyzed the quality of fresh pork belly after processing, such as heating, storage, and aging, were excluded.

A total of 735 studies were obtained from the literature search of the database, and some studies were excluded based on the process of selection and eligibility evaluation (Fig 1). A total of 150 studies were excluded due to duplication. Studies were excluded if they did not fit the topic based on the title and abstract, or if the full text was unavailable. The remaining 184 articles were reviewed in full and those meeting the above-mentioned criteria were excluded. Finally, 55 articles were selected, and the key data were summarized and organized in this review.

Quality traits of fresh pork belly

The pork belly is a cut obtained from the central part after removing the shoulder, leg, and loin of the half carcass. The cut of pork belly from the carcass varies from countries. In

South Korea, pork belly is defined as the abdominal muscle from the 5^{th} or 6^{th} rib to the hind leg (the 7^{th} lumbar vertebrae) with the loin removed. The United Nations Economic Commission for Europe (UNECE) and the United States Department of Agriculture (USDA) specify that the pork belly contains 10 to 13 ribs (USDA requiring a minimum of 11 ribs), depending on the extent of shoulder part removed, and be square or rectangular in shape with neither side of the belly more than 5 cm longer than the opposite side (UNECE, 2006; USDA, 2014). The pork belly consists of multiple muscle and fat layers, requiring a comprehensive assessment of both muscle and fat conditions to evaluate the overall belly quality. We identified and classified the quality traits of the pork belly reported in the selected studies (Fig 2).

The most frequently measured quality trait of pork belly was the pork belly yield from carcasses. This trait was investigated in 46 of the 55 articles. Pork belly yield includes the weight of the belly, its proportion within the carcass, dimensions (length, width, and thickness), and the muscle-to-fat ratio . The pork belly yield is an important commercial attribute that leads to profits from the producer’s perspective (Choe et al., 2015). Processors prefer heavy and thick pork bellies because of their higher processing yields (Soladoye et al., 2015). However, increased belly weight is generally associated with higher fat content (Albano-Gaglio et al., 2024; Hoa et al., 2021) which consumers may not prefer, given the growing concerns about high-fat diets. Therefore, there is a need to achieve a balance between producer profitability and consumer preferences regarding pork belly yield.

Firmness was the second most commonly evaluated quality trait, as referenced in 37 of 55 articles. The firmness of pork belly is an important property that influences its processing efficiency, yield, and consumer acceptability. It has been reported that soft pork belly is difficult to process, has a poor appearance owing to the separation of fat layers, and has a short shelf life with low oxidation stability (Soladoye et al., 2017; Zomeño et al., 2024).

Firmness is affected by multiple factors, including the dimensions, thickness, fat content, and fat saturation of pork belly (Soladoye et al., 2017). The methods used to assess belly firmness include flop distance and angle analysis, instrumental texture measurement, and finger-press firmness. Flop distance and angle analyses measure the distance between two dropped endpoints and the angle at the bend point by placing the pork belly on a horizontal bar with the skin side up or down (Font-i-Furnols et al., 2023). A greater flop distance and angle indicated a firmer pork belly. Instrumental texture measurement determines firmness by measuring the force required to compress the central part of the pork belly using a texture analyzer (Apple et al., 2011; Font-i-Furnols et al., 2023). Finger-press firmness evaluates belly firmness on a 5-point scale by applying pressure on the belly with a finger and assessing the degree to which the finger press mark remains (Soladoye et al., 2017; Zomeño et al., 2024).

Fatty acid composition analysis was also extensively performed to determine pork belly quality, representing 52.73% of the selected articles. The fatty acid composition includes the proportions of saturated fatty acids (SFA), such as palmitic acid and steric acid; monounsaturated fatty acids (MUFA), such as oleic acid; polyunsaturated fatty acids (PUFA), such as linoleic acid, linolenic acid, and arachidonic acid; PUFA/SFA ratio; and n-6/n-3 ratio. Fatty acid composition is affected by various factors such as sex, growth rate, and diet (Browne et al., 2013; Correa et al., 2008; Kellenr et al., 2015). The fatty acid composition reflects fat accumulation, with higher growth rates and greater fat accumulation leading to increased fat saturation (Corre et al., 2008). In general, the fatty acid composition of fresh pork belly was reported to be a PUFA/SFA ratio of 0.48 and an n-6/n-3 ratio of 17.98 (Choe et al., 2015). However, many countries, including the United States and Europe, recommend decreasing the consumption of SFA and the n-6/n-3 ratio and increasing the PUFA/SFA ratio in the diet (Choe et al., 2015; Soladoye et al., 2017). In the United Kingdom, the PUFA/SFA ratio and n-6/n-3 ratio have been recommended to be greater than 0.4 and less than 4.0 respectively (Soladoye et al., 2017). Therefore, it is important to produce pork bellies with a balanced fatty acid composition considering both belly productivity and consumer health. The iodine value (IV), which reflects the degree of fat unsaturation, has also been investigated as a quality trait in pork belly. IV is calculated as the amount of iodine bound of unsaturated fat because iodine react with the π-electrons of the double bonds (Gatlin et al., 2003). IV is associated with UFA content, including oleic acid, linoleic acid, linolenic acid, and pork belly firmness (Font-i-Furnols et al., 2023).

Other quality traits of pork belly include physicochemical properties that are typically measured to assess meat quality, such as color, pH, proximate composition, and water-holding capacity. Color is an important factor for consumers when judging meat quality at the point of purchase. Consumers use meat color as an indicator of freshness. Bright red meat and white fat are preferred as good quality meat (Font-i-Furnols & Guerrero, 2014; Hugo & Roodt, 2007). Among the 55 studies, 13 confirmed the color of the pork belly. Some studies have confirmed the color of specific muscles, such as the rectus abdominis muscle, external abdominal oblique muscle, or fat, rather than the color of the entire surface of the meat because pork belly consists of layers of muscle and fat (Apple et al., 2007; Engel et al., 2001). Other studies have assessed the subjective visual color of the muscle fat in pork belly (Browne et al., 2013; Jeong et al., 2011). Additionally, physicochemical properties, such as pH and proximate composition, were measured by grinding the pork belly or measuring the pH in the muscle area using solid-state probes (Hoa et al., 2021; Hoa et al., 2023; Jeong et al., 2011). The pH of pork belly was measured in 5 studies, and the measured pork belly pH ranges from 5.70 to 5.95 (COSTA E SILVA et al., 2017; Hoa et al., 2023; Lim et al., 2013; Lim et al., 2014; Jeong et al., 2011). Other quality traits reported in the literature to confirm the oxidative stability of pork belly fat include cooking loss, volatile compound composition, sensory properties, and malondialdehyde content (Albano-Gaglio et al., 2024; Hoa et al., 2021; Lim et al., 2013).

Factors affecting the pork belly quality

Meat quality is affected by multiple factors, including endogenous factors such as sex, genetic effect, and breed, as well as exogenous factors such as feeding and slaughter methods. Additionally, post-slaughter processes such as chilling, storage, and aging significantly impact meat quality. This review divided the factors affecting pork belly quality, as described in 55 articles, into endogenous and exogenous factors. To maintain a focus on the fresh pork belly quality, the effects of processing methods such as storage, freezing, and aging after slaughter were not addressed.

Endogenous factor

Sex effect and castration methods

Animal sex affects various carcass properties such as weight, lean meat yield, and fat content, which can change the quality of pork belly. Several studies have investigated the effects of sex on pork belly quality (Table 1). Male pigs are generally castrated to prevent boar taint caused by androstenone and skatole and to reduce aggressive and sexual behavior, thereby improving growth performance (Prunier et al., 2006). Barrows (catrated male pig) are generally heavier than gilts, increasing the proportion of pork belly in the carcass (Bahelka et al., 2011; Correa et al., 2008; Duziński et al., 2015; Lee et al., 2013; Overholt et al., 2016; Stupka et al., 2004). Barrows also tend to have a higher fat deposition in the pork belly, whereas gilts have a higher proportion of lean meat in the belly (Bahelka et al., 2011; Stupka et al., 2004). These results were reported because barrows require less energy to deposition lean tissue than gilts and excess energy is accumulated as fat (Overholt et al., 2016). Additionally, the fatty acid composition of belly fat can be affected by sex (Correa et al., 2008; Lee et al., 2013). Correa et al. (2008) found that compared to barrows, gilts had lower SFA content and higher linoleic acid and PUFA contents in belly fat. Lee et al. (2013) reported similar results, with barrows having a higher palmitic acid content, the SFA, and lower linoleic acid, the PUFA in belly fat than that in gilts. Overall, compared to barrows, gilts have a higher degree of belly fat unsaturation and a higher iodine value. Therefore, barrows produce firmer pork bellies with the higher proportion of SFA than the pork bellies of gilts.

Immunocastration is emerging as an alternative to traditional surgical castration, and the effects of different castration methods on pork belly quality have been widely studied (Costa e silva et al., 2017; Font-i-Furnols et al., 2023; Jeong et al., 2011; Kyle et al., 2014; Lowe et al., 2016; Tavárez et al., 2014). Most studies indicate that immunocastration produces softer pork belly with lower fat content, higher PUFA content, and higher iodine value than pork belly obtained from surgically castrated pigs (Costa et al., 2017; Font-i-Furnols et al., 2023; Kyle et al., 2014; Lowe et al., 2016). Jeong et al. (2011) reported the sensory properties of pork belly based on different castration methods. They reported that pork belly obtained from immunocastrated pigs had higher visual evaluation traits than the pork belly obtained from surgically castrated pig, although the former did not significantly affect taste, tenderness, and overall acceptability (Jeong et al., 2011). In addition, there have been studies on examining the effects of supplementing ractopamine hydrochloride (RAC) in combination with immunological castration (Costa e silva et al., 2017; Kyle et al., 2014; Lowe et al., 2016). RAC, a β-adrenergic agonist, is known to improve feed efficiency and increase lean meat content (Leick et al., 2010). Kyle et al. (2014) reported that immunologically castrated barrows fed a diet supplemented with RAC produced a wider and softer pork belly with a significantly higher percentage of PUFA in pbelly fat. In contrast, Costa et al. (2017) and Lowe et al. (2016) found no significant effects of RAC supplementation on pork belly quality in immunocastrated barrows. Harris et al. (2018) and Tavárez et al. (2014) reported changes in pork belly quality based on time interval between administration of the second dose of Improvest (GnRF analog diphtheria toxoid conjugate) for immunocastration and slaughter. In a study by Harris et al. (2018), the thickness of pork belly increased as the time interval increased, and the PUFA percentage and IV increased as the time interval decreased. Therefore, additional studies are necessary to determine the optimal combination of immunocastration with other treatments.

Genetic effect

Genetic factors, including genotype and breed, are key determinants of meat quality. Understanding genetic factors is important to improve the quality of pork belly effectively. Studies have investigated the heritability and genetic correlations between pork belly quality traits (Hermesch, 2008; Kang et al., 2015; Lee et al., 2023a). In their study, the heritability of traits such as belly weight, dimensions, fat content, and muscle area of pork belly had a moderate heritability ranging from 0.2 to 0.5 (Hermesch, 2008; Kang et al., 2015; Lee et al., 2023a). In particular, studies by Kang et al. (2015) and Lee et al. (2023a) identified genetic parameters of several individual muscles of pork belly. These estimated genetic parameters suggest that pork belly traits can be improved through genetic selection. Additionally, Lee et al. (2023b) predicted key genes associated with pork belly traits, including transcription factors. They determined the traits related to pork belly yield and three muscle areas (cutaneous trunci muscle, rectus abdominis muscle, and external abdominal oblique muscle) in pork belly slices, and identified related genetic factors. The results confirmed that adipogenesis-associated transcription factors affected pork belly composition.

Various studies have been conducted on genotypes associated with pork quality to improve pig genetics (Table 1). Halothane is a well-known gene that influences pork quality traits. Halothane gene is associated with a pale, soft, and exudative (PSE) meat. Pigs carrying the halothane gene have increased lean meat content, but have significantly negative effects on water-holding capacity and the color of meat (Swan et al., 2001). Swan et al. (2001) investigated pork belly quality based on genotype by comparing pigs without the halothane gene and pigs heterozygous or homozygous recessive for the halothane gene. Consistent with the known effects of the halothane gene, pigs lacking the halothane gene showed increased fat accumulation and pork belly firmness. The IGF2 (insulin like growth factor 2) is a gene involved in myogenesis. The A/G mutation at position 3072 within intron 3 of IGF2 affects up to 30% of the variation in muscle mass and up to 20% of backfat thickness (Clark et al., 2014). The quality of pork belly obtained from pigs heterozygous (AG) or homozygous (AA) for IGF2 mutation has been investigated (Clark et al., 2014). Thicker and firmer pork bellies were obtained from pigs that were heterozygous (AG) for the IGF2 mutation. The CRTC family regulates mitochondrial metabolic activity, and of the genes of this family, *CRTC3* has been reported to play an important role in controlling obesity development and energy metabolism (Lee et al., 2018). Lee et al. (2018) genotyped 360 Yorkshire pigs and identified the p.V515F mutation in exon 16 of 40 single-nucleotide polymorphisms. The p.V515F mutation in *CRTC3* gene significantly affected intermuscular fat thickness, total muscle area, and total fat percentage in the belly.

Pig breeds have continuously improved production capacity and meat quality. Commercial breeds of pigs include many different breeds such as Duroc, Yorkshire, Hampshire, and Landrace. Commercial purebred pig breeds include many different breeds, including the Duroc, Yorkshire, Hampshire, and Landrace. Duroc has excellent growth and muscle quality attributes and is used as a terminal sire (NSR, 2015). Yorkshire and Landrace have excellent litter size and birth and weaning weight and are used as parent-stock females (NSR, 2015). The difference in pig breed traits can ultimately affect the meat quality. Studies have been conducted on the influence of pig breeds on meat quality, investigating the differences between breeds, such as single breeds, crossbreeds, or novel breeds (Bahelka et al., 2011; Lim et al., 2013; Lim et al., 2014; Lowell et al., 2019; Hoa et al., 2023). Lim et al. (2014, 2015) investigated the differences in the quality traits of pork belly from two- and three-way crossbreeds of Yorkshire, Berkshire, Chester White, Landrace, and Duroc pigs, which are widely used Korean commercial pigs. Yorkshire × Berkshire pigs showed the lowest moisture content and cooking loss. Yorkshire × Landrace pigs have a high MUFA composition, whereas Yorkshire × Chester White pigs have a high PUFA composition and high sensory evaluation results (Lim et al., 2013). On the other hand, in three-way crossbred pigs, there were no significant differences in most quality traits except for high moisture content in Yorkshire×Chester White×Yorkshire pigs and high sensory evaluation results in Yorkshire×Landrace×Duroc (Lim et al., 2014). Lowell et al. (2019) investigated the effects of breed type (Pietrain or Duroc) on pork quality traits by controlling inherent and environmental factors. These results confirmed that thicker and firmer pork bellies were obtained from Duroc sired pigs. This was consistent with the expectations that the Duroc breed had fast growth rate and higher intramuscular fat content and that the Pietrain breed had lean meat yield. Studies on crossbreeding between local and commercial breeds to improve meat quality have also been reported. The difference in pork belly quality was confirmed between a novel breed (Woori Heukdon, WHD) which crossbreeding between Duroc sow with Korean native black pig sire and a commercial breed (Landrace×Yorkshire×Duroc, LYD) (Hoa et al., 2023). The fat content and cooking loss increased in the WHD group. Additionally, WHD belly had a higher volatile aroma associated with a fatty odor, whereas LYD belly had a higher compound with a roasty odor (Hoa et al., 2023). There are various studies on crossbreeding with local breeds, but most studies deal with growth performance or overall carcass traits rather than pork belly quality (Pugliese & Sirtori, 2012). To enhance pork belly quality, further studies are needed on pork belly traits across various breeds, including commercial breeds, crossbreeds, and novel breeds. Saikia et al. (2024) reported the effectiveness of genetic improvement based on the estimated feed conversion ratio breeding value. The effects of the genetic line (sire or dam) and feed efficiency groups (low, intermediate, or high) on breeding value were investigated. Belly weight and belly thickness was highest in the high-efficiency group of the sire line. Pork belly quality is influenced by various genetic parameters. Therefore, further research is needed to identify the genetic factors that can improve quality to meet the needs of producers and consumers.

Growth performance

Many studies have reported that the growth performance of pigs, such as carcass weight and fat content, is significantly related to the quality of the pork belly (Correa et al., 2008; Harsh et al., 2017; Hoa et al.,2021; Lee et al., 2023a; Vališ et al., 2005). In a study by Lee et al. (2023a), carcass weight had a strong positive genetic correlation with belly weight, total belly volume, and several muscle areas of the pork belly. Similar results have been reported by Correa et al. (2008) and Harsh et al. (2017). They reported that a thicker and firmer pork belly was obtained from heavier carcasses, and a higher proportion of SFA was observed in the group with a faster growth rate.

Hoe et al. (2021) and Albano-Gaglio et al. (2024) studied the relationship between fat content and pork belly quality. The high fat content of the carcass increased the yield of pork belly, reduces cooking loss, and decreased the proportion of PUFAs in the pork belly fat (Hoe et al., 2021). Additionally, the content of oleic acid-derived compounds associated with fatty and oily flavors increases, which can improve the sensory properties. Albano-Gaglio et al. (2024) reported similar results for fat content. However, these effects may differ depending on the breed, even if the fat content is similar. In that study (Albano-Gaglio et al., 2024), although the groups had similar amount of fat content, Iberian×Duroc barrows produced lower width and firmer bellies compared to Duroc pigs. In conclusion, heavier pigs have a higher pork belly yield. However, increased carcass weight may increase fat accumulation in the pork belly, which should be considered because it affects consumer preferences.

Exogenous factors

Diet

Dietary components can be readily transferred from feed to the muscle and fat tissues of pigs, thereby affecting pork quality (Soladoye et al., 2015). Changes in pork belly quality according to diet are summarized in Table 2.

Numerous studies have been conducted to improve the quality of pork belly fat and fatty acid composition by supplementing it with dietary fat. The fat sources used varied from vegetable oils, such as corn, flaxseed, and sunflower oil, to animal fats, such as poultry fat and beef tallow. Many studies have confirmed that the supply of fat significantly affects the fatty acid composition of pork bellies (Apple et al., 2007; Eggert et al., 2001; Gatlin et al., 2003; Kellner et al., 2014). Supplementing the diet with conjugated linoleic acid oil (CLA) increased the total CLA and SFA proportions in pork belly fat, decreased IV, and resulted in a firmer pork belly (Eggert et al., 2001). Eggert et al. (2001) noted that CLA functions as an anticarcinogen and antiatherogen in animals and can improve the fat properties of pork belly without significantly affecting lean meat properties. Varying the IV of pig feed changed the physical characteristics and fatty acid composition of the pork belly (Gatlin et al., 2003). In a study by Gatlin et al. (2003), the thickness of the pork belly decreased and its length increased with an increase in IV in pig feed. Additionally, the linoleic acid content in pork belly fat increased, while palmitic acid and stearic acid content decreased with variations in IV levels in pig feed. Supplying an animal fat source to pig feed can increase the SFA proportion in pork belly, decrease IV levels, and produce a firmer pork belly (Apple et al., 2007; Kellner et al., 2014). Kellner et al. (2015) investigated whether feeding unsaturated fat followed by a withdrawal period could prevent quality deterioration in pork belly but found that the withdrawal period did not lead to improvement in the quality of pork belly. On the other hand, in some studies, the supply of dietary fat did not have a clear effect on the quality of pork belly fat (Engel et al., 2001; Huang et al,2019; Swan et al., 2001). This may result from differences in genetic factors, the energy state of animals, or experimental conditions. Further studies under various conditions are needed to clarify the effect of dietary fat sources on pork belly quality.

Many studies have investigated the effects of feed supplementation with dried distiller grains with solubles (DDGS). DDGS is a by-product of ethanol production from grains, and extensive research has been conducted on its feeding value (Stein & Shurson, 2009). Researchers have conducted studies on DDGS, investigating the effects of treatments such as DDGS dosage (Overholt et al., 2016; Whitney et al., 2006), supplementation duration (Harris et al., 2018; Tavárez et al., 2014; Xu et al., 2010), or combination with other dietary sources (Browne et al., 2013; Davis et al., 2015; Gaffield et al., 2022; Lee et al., 2013; Villela et al., 2017), on pork belly quality. DDGS contains many unsaturated fatty acids, especially linoleic acid. Thus, feeding pigs a diet containing DDGS generally increases the IV levels. (Stein and Shurson, 2009). Whitney et al. (2006) and Overholt et al. (2016) reported similar results, that state increasing the DDGS content in pig diets increased the IV of pork belly fat, resulting in a thin and softer pork belly. The authors concluded that the optimal DDGS content in grower-finisher pig diets, which were formulated based on the total amino acid content, was less than 20% (Whitney et al., 2006). Overholt et al. (2016) also investigated the effect of a diet supplemented with DDGS and found that pellet-fed pigs had heavier bellies with higher IV. Several studies have considered feeding strategies that included DDGS, followed by a withdrawal period or a gradual reduction in DDGS (Harris et al., 2018; Tavárez et al., 2014; Xu et al., 2010). The increased IV and tenderness found in pork belly supplemented with DDGS were significantly reduced by including a withdrawal period for DDGS (Harris et al., 2018; Tavárez et al., 2014; Xu et al., 2010). Lee et al. (2012) investigated the characteristics of pigs fed DDGS and corn germ and found that the pork belly firmness in these pigs decreased regardless of the DDGS supply. Several studies have been conducted to reduce the negative effects of DDGS by supplying additional fat sources (beef tallow, palm kernel oil, glycerol, cottonseed oil, or yellow grease) to pig diets. However, most dietary fat sources did not reduce the decrease in pork belly firmness (Browne et al., 2013; Davis et al., 2015; Lee et al., 2013; Villela et al., 2017). Meanwhile, in a study where researchers addedhigh-oleic soybean oil (HOSO) to diets with DDGS, it was found that the HOSO supplementation increased the proportion of MUFAs in pork belly fat and improved the physical properties and firmness (Gaffield et al., 2022).

Other dietary treatments for pigs have also been considered. In a study by Apple et al. (2011), the addition of carnitinewith a fat source changed the fatty acid composition but did not significantly affect the dimensions or firmness of pork belly. Zhu et al. (2021) found that adding camelina press cake to pig diets decreased the thickness of pork belly but had no significant effect on firmness. The effect of supplying antioxidants to pig diets on pork belly quality has been previously investigated (An et al., 2019; Lu et al., 2014). Lu et al. (2014) investigated the effects of supplying antioxidants to a high-oxidant diet. Pigs fed oxidized diets had softer pork belly, and the addition of antioxidants tended to slightly improve firmness; however, the effect was not significant. An et al. (2019) reported that effects of supplying lycopene and tomato paste as antioxidants to pigs. There was no significant difference in the belly yield and lipid properties; however, the malondialdehyde content was reduced, which improved the oxidative stability. With the ban on the use of antibiotics in livestock diets, Lowell et al. (2018) investigated the effect of antibiotic use on pork belly quality, and found no significant differences in pork belly quality between pigs fed antibiotic-free, natural antimicrobials, or antibiotics. Methionine (Met), an essential amino acid, is commonly added as a supplement to growing-finishing pig diets because it is the second most limiting amino acid in pigs. Remole et al. (2024) found that differences in Met source did not significantly affect pork belly quality. Therefore, diets with various ingredients and treatments can significantly affect pork belly quality, and further research should be conducted to produce high-quality pork belly.

Others

Pork belly quality is influenced by factors other than feed intake. Bryan et al. (2020) reported that infection with porcine reproductive and respiratory syndrome viruses (PRRSV) reduced pork belly firmness. Zomeño et al. (2024) investigated the effect of the boning processing method (hot or cold) on pork belly quality. They reported that the hot-boned belly (cut immediately postmortem) was shorter, wider, thicker, and firmer than the cold-boned belly (cut at 24 h postmortem) due to intense shortening and hardening. These results confirm that disease and carcass handling can affect pork belly quality. However, since studies addressing pork belly quality are insufficient, further research on various influencing factors is necessary.

Conclusion

This review identified the quality traits of pork belly and the factors that affect them based on previous studies. Pork belly quality was assessed based on belly yield, dimensions (length, width, and thickness), firmness, and fatty acid composition. Factors affecting pork belly quality include endogenous factors such as sex, breed, and carcass weight, and exogenous factors such as diet. Many studies have focused on improving the fatty acid composition and firmness of pork bellies in the context of dietary effects. The yield and fat deposition of pork belly were higher in barrow than in gilt and immunocastration had lower fat content and softer pork belly. The adipogenesis-associated transcription factors and genes involved in growth affected the pork belly quality. It was confirmed that the pork belly quality traits differ with various pig breeds. Dietary fat sources can be used to improve the fat quality and fatty acid composition of pork belly.

However, there is still a need for discussion on good-quality pork belly owing to the differences in perspectives between producers and consumers regarding pork belly quality. Particularly, discussions are necessary to balance the health aspects with the economic and sensory attributes according to the fatty acid composition and fat content of pork belly. In addition, studies focusing only on pork belly quality are significantly lacking. Most studies considered pork belly quality to be a part of the carcass quality change and often not addressed as a major issue. Therefore, to clarify the appropriate pork belly quality according to changing consumption patterns, research focusing on pork belly quality should be continuously conducted.

Conflicts of interest

The authors declare no potential conflicts of interest.

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Ethics Approval

This article does not require IRB/IACUC approval because there are no human an animal participants.

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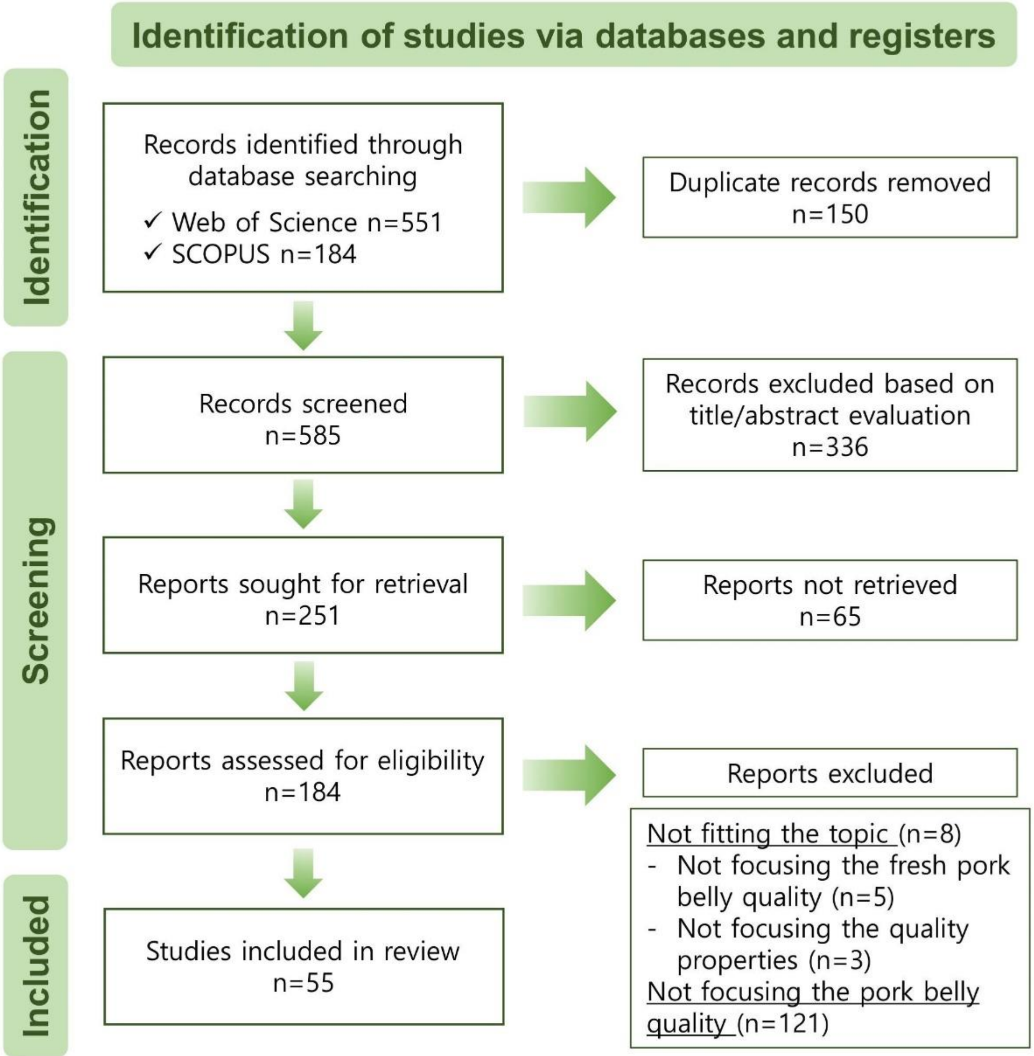
Figure legend.

Figure 1. Pork belly quality PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram.

Figure 2. Quality traits of pork belly evaluated in 55 selected literature

[1] The number of literature mentioning the quality traits among the total 55 literature



657

658 **Figure 1.**

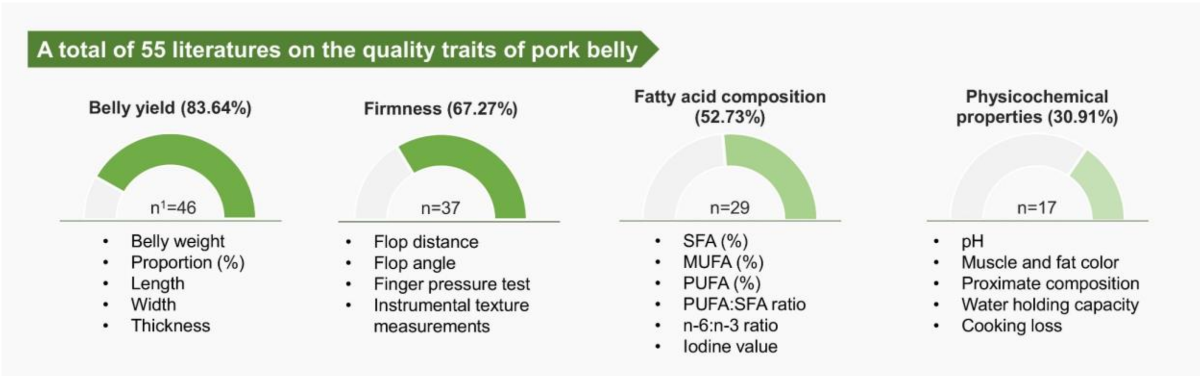

A total of 55 literatures on the quality traits of pork belly
Belly yield (83.64%)
n1=46
Belly weight
Proportion (%)
Length
Width
Thickness
Firmness (67.27%)
n=37
Flop distance
Flop angle
Finger pressure test
Instrumental texture measurements
Fatty acid composition (52.73%)
n=29
SFA (%)
MUFA (%)
PUFA (%)
PUFA:SFA ratio
n-6:n-3 ratio
Iodine value
Physicochemical properties (30.91%)
n=17
pH
Muscle and fat color
Proximate composition
Water holding capacity
Cooking loss

Figure 2.

Table 1. Summary of effect of endogenous factors on pork belly quality

Treatment	Effects on pork belly quality	Reference
Sex effect		
Gilt or barrow	· Belly proportion in the carcass: higher in barrow · Lean meat proportion in belly: higher in gilt	Stupka et al., 2004
Gilt or barrow	· Back fat thickness: higher in barrow · Firmness: softer in gilt · Fatty acid composition - ↓ SFA and ↑ linoleic acid and PUFA in gilt - ↑ iodine value (IV) in gilt	Correa et al., 2008
Gilt or barrow	· Belly proportion in the carcass: higher in barrow · Meat and fat in the belly (%) - Higher meat proportion in gilt belly - Higher content of fat in barrow belly	Bahelka et al., 2011
Gilt or barrow	· Belly weight: heavier belly in barrow · Firmness: softer in gilt · Fatty acid composition - ↑ palmitic acid and ↓ linolenic acid in barrow - ↑ IV in gilt	Lee et al., 2013
Gilt or barrow	· Weight, width, and thickness: heavier, wider, and thicker belly in barrows · Firmness: firmer belly in barrows	Overholt et al., 2016
Castrated methods		
Immunocastrated males (IC), surgically castrated males (SC), intact males (IM), or females (FE)	· pH: IC > SC and FE · Color of IC: ↓ L* value than SC and ↑ a* value than SC and FE · Water holding capacity: IC < SC · Cooking loss: FE ≥ SC ≥ IC = EM · Fat content: highest in SC and lowest in EM belly · Visual evaluation: higher score in IC and FE belly · Sensory evaluations - Tenderness: lower in EM - Juiciness: higher in SC - Overall acceptability: higher in SC and lower in EM	Jeong et al., 2011
Physically castrated (SC), immunologically castrated barrow (IC), intact male (IM), or gilt	· Width: widest belly in IC barrows fed ractopamine hydrochloride · Thickness: thicker belly in SC barrow than IM · Firmness - Highest flop distances in belly of SC barrow - No differences between IC fed ractopamine and gilts - Lowest flop distance in belly of IM · Fatty acid composition - ↑ IV in IM and no difference between IC and	Kyle et al., 2014

	gilt - ↓ SFA and MUFA and ↑ PUFA in IM	
Physically castrated (SC) or immunologically castrated (IC) and ractopamine hydrochloride diet	· Thickness: thicker belly in SC · Firmness (flop): softer belly in IC	Lowe et al., 2016
Gilt, immunocastrated (IC), or barrow (surgically castrated, SC)	· Proximate content: ↑ protein content and ↓ lipid content in IC than SC · Color: ↑ a* value in gilt belly meat · Backfat thickness: higher in IC than gilt · Fatty acid composition - ↑ PUFA, omega-3, and omega-6 in IC than SC - ↓ SFA in gilt than SC - ↑ IV in gilt and IC	Costa e silva et al., 2017
Surgically castrated males (SCM), entire females (FE), immunocastrated females (ICF)	· Belly proportion (%): highest in SCM · Firmness: firmer belly in SCM · Proximate content: ↑ dry matter and fat and ↓ moisture and protein in SCM · Fatty acid composition - SFA and MUFA were not significantly different between sexual types - ↑ linoleic acid and PUFA in FE and ICF - IV: FE ≥ ICF ≥ SCM	Font-i-Furnols et al., 2023
Immunocastrated males (ICM) or entire males	· Belly length: longer belly in ICM · Firmness: Firmer belly in ICM · Fatty acid composition - ↑ SFA and ↓ PUFA, PUFA/SFA ratio, and IV in ICM	Font-i-Furnols et al., 2023
Physically castrated (SC) or immunologically castrated (IC) barrow	· Width: wider belly in IC · Thickness: thicker belly in SC · Firmness (flop): tended to firmer belly in SC	Tavárez et al., 2014
Time intervals between second Improvest® dose and slaughter · 9, 7, or 5 week before slaughter	· Thickness: increases linearly as time interval increase · Fatty acid composition - ↑ PUFA and IV as time interval decrease	Harris et al., 2018
Genetic effect, Genotype		
Stress genotype · Negative = NN (halothane-free), carrier = Nn, or positive = nn	· Firmness: increased in stress-negative genotype · Proximate content: ↓ moisture and protein and ↑ lipid in stress-negative genotype	Swan et al., 2001

(homozygous recessive for the halothane gene)		
Genotype, IGF2-G3072A mutation ・ Heterozygous (AG) or homozygous (AA)	・ Thickness: thicker belly in AG pigs than AA pigs ・ Firmness: firmer belly in AG pigs ・ IV: tended to higher IV in AA pigs	Clark et al., 2014
Genotype, CRTC3-p.V515F mutation ・ GG, TG, or TT	・ Intermuscular fat thickness: thinner in pigs with the TT genotype ・ Total muscle area: greater in pigs with heterozygous genotype (GG and TT) ・ Total fat percentage: TG>GG>TT	Lee et al., 2018
Genetic effect, Breed		
Sire line ・ Hampshire (HA)×Pietrain (PN), Landrace (LA), or Yorkshire (YO)×PN	・ Belly proportion in the carcass: LA>HA×PN>YO×PN ・ Meat and fat in the belly (%) - HA×PN: highest percentage of meat - YO×PN: highest percentage of fat, skin, and bones	Bahelka et al., 2011
Two-way crossbreeds ・ Yorkshire×Landrace (YL), Yorkshire×Berkshire (YB), or Yorkshire×Chester White (YC)	・ pH: lowest in YC ・ Proximate content: ↓ moisture content in YB belly ・ Cooking loss: lower in YB ・ TBARS values: higher in YB at 14 d ・ Fatty acid composition - YL: ↑ stearic acid, oleic acid, and MUFA - YB and YC: ↑ myristic acid, linoleic acid, linolenic acid, and n-6 fatty acids - YC: ↑ PUFA ・ Free amino acid composition: ↑ concentrations of most free amino acids in YB ・ Sensory evaluation: higher score in YC	Lim et al., 2013
Three-way crossbreeds ・ Yorkshire × Landrace × Duroc (YLD), Yorkshire × Chester White × Yorkshire (YCY), and Yorkshire × Berkshire × Duroc (YBD)	・ Proximate content: highest moisture content in YCY belly ・ Sensory evaluation: higher score in YLD	Lim et al., 2014
Sire line ・ Pietrain or Duroc ancestry	・ Thickness: thicker belly in Duroc sired pigs ・ Firmness: greater flop distance in Duroc sired pigs	Lowell et al., 2019

Breed ・ LYD (Landrace× Yorkshire ×Duroc) or novel pig breed (Woori Heukdon, WHD)	・ Belly yield (%): higher in WHD ・ Proximate composition: ↑ fat content and ↓ moisture, protein, and collagen in WHD ・ Cooking loss: lower in WHD ・ Color: ↓ L* value and ↑ a* value in WHD ・ Fatty acid composition - ↑ MUFA and UFA and ↓ SFA in WHD ・ Volatile aroma composition - ↑ compounds associated with fatty odor in WHD - ↑ compounds associated with rosty ordor in LYD	Hoa et al., 2023
Genetic line effect ・ Sire or dam line Estimated breeding value ・ Feed efficiency: low, intermediate, or high	・ Belly weight: heaviest belly in sire high efficiency group ・ Thickness: thickest belly in sire high efficiency group	Saikia et al., 2024
Growth performance		
Growth rate Slaughter weight	・ Back fat thickness: higher with weight increase ・ Fatty acid composition - ↑ PUFA:SFA ratios and n-6:n-3 ratios in slow growing - ↑ stearic fatty acid and SFA proportions in fast growing	Correa et al., 2008
Carcass weight	・ Thickness: thicker belly with increase carcass weight ・ Firmness: firmer belly with increase carcass weight ・ IV: decreased IV with increase carcass weight	Harsh et al., 2017
Fat levels	・ Belly yield: higher yield with increased fat level ・ Proximate composition: ↑ fat and ↓ moisture, protein, and collagen in high fat level ・ Color: ↑ b* value in high fat level ・ Cooking loss: decreased with increased fat level ・ Fatty acid composition - ↑ oleic acid and ↓ PUFA in high fat level ・ Volatile aroma composition - ↑ Maillard reaction-derived flavor compound (meaty and roasty flavors) in low fat level group - ↑ oleic acid-derived compounds (fatty and oily flavors) in high fat level group ・ Sensory properties: higher score in high fat level group	Hoa et al., 2021
Fatness and genetic effect ・ F1: 12.3-25.9%, F2: 26.0-33.9%, and F3:	・ Belly weight: heaviest in F5 and lightest in F1 pigs ・ Belly proportion: lowest in F5 and no significant difference between commercial pigs (F1-3) ・ Length: increased across the bellies from F1 to F4	Albano-Gaglio et al., 2024

34.0-47.1% of fat content from commercial pigs · F4: 36.4-56.3% of fat content from Duroc pigs · F5: 55.0-69.1% of fat content from Iberian×Duroc barrows	· Width: lowest in F5 and no significant difference between F1-F4 · Firmness: firmer belly in F5 and softer belly in F1 · Proximate composition: ↑ lipid content and ↓ moisture, protein, and ash content with increased fatness · Fatty acid composition - ↑ SFA and MUFA and ↓ PUFA with increased fatness in commercial pigs - ↑ oleic acid and ↓ linoleic acid in F5 · IV: F1>F2>F3>F4>F5

Table 2. Summary of effect of diets on pork belly quality

Treatment	Effects on pork belly quality	Reference
Dietary fat source		
Conjugated linoleic acid (CLA) · Control or 0.75% CLA	· Proximate content: ↑ moisture and protein content and ↓ lipid content	Swan et al., 2001
Dietary fat source · Choice white grease or poultry fat · Level: 2, 4, or 6%	· Color of belly lean or fat: no effect · Firmness: no effect	Engel et al., 2001
Conjugated linoleic acid · 1% CLA oil, 1% sunflower oil, or fed the sunflower oil-supplemented diet restricted to the amount consumed by pigs fed the CLA diet	· Firmness: increased in the CLA group · Fatty acid composition: - ↑ total CLA and SFA and ↓ MUFA and UFA in the CLA group - IV: lower in the CLA group	Eggert et al., 2001
Hydrogenated dietary fat · Supplement with 5% choice white grease to IV of 20, 40, 60, or 80	· Thickness: decreased with increasing IV of diet · Length: increased with increasing IV of diet · Fatty acid composition - ↑ IV with increasing IV of diet - ↑ linoleic acid and ↓ palmitic acid and steric acid with increasing IV of diet	Gatlin et al., 2003
Dietary fat source · 5% Beef tallow (BT) or soybean oil (SBO)	· Firmness: firmer belly in BT group · Color of belly fat: lighter and redder in BT group · Fatty acid composition - ↓ PUFA and ↑ SFA and MUFA in BT group	Apple et al., 2007
Dietary fat source 3 or 6% of choice white grease (CWG), corn oil (CO), or beef tallow (TAL)	· Weight: increased in pigs fed dietary fat source · Firmness: firmer belly in pigs fed beef tallow · IV: increased in pigs fed corn oil	Kellner et al., 2014

Dietary fat source · 0 or 1% flaxseed oil + 1,3, or 5% poultry fat Vitamin E · 11 or 220 IU/kg Dietary fat withdrawal times · 21, 42, or 63 d before slaughter	· Width and thickness: ↑ width and thickness with ↑ dietary lipids	Huang et al., 2019
Dietary fat unsaturation loads 5% corn oil (HIGH), 5% animal-vegetable blend (MED), or 2.5% corn oil (LOW)	· Belly weight and thickness: no effect · Firmness: ↓ belly firmness with increasing the dietary fat unsaturation loads	Kellner et al., 2015
Dried distillers grains with solubles (DDGS)		
DDGS · 0, 10, 20, or 30%	· Thickness: ↓ thickness with ↑ DDGS concentration · Firmness: ↓ firmness with ↑ DDGS concentration · IV: increased with increased DDGS concentration	Whitney et al., 2006
DDGS with withdrawal period · DDGS: 0, 15, or 30% · Withdrawal: 0, 3, 6, or 9 week	· Firmness: Softer belly with feeding 30% DDGS without withdrawal period · Fatty acid composition - ↑ PUFA and IV and ↓ SFA and MUFA with ↑ DDGS - ↓ IV with ↑ DDGS withdrawal period	Xu et al., 2010
DDGS · 0 or 30% Corn germ · 0, 10, 20, or 30%	· Weight: tend to decreased with feeding DDGS · Length: decreased with increase corn germ in diet without DDGS · Firmness - ↓ flop distance in feeding DDGS - ↓ flop distance with corn germ without DDGS supplement	Lee et al., 2012
DDGS + Dietary fat source · Beef tallow (BT, 5%) or yellow grease (YG, 4.7%) · 5 feeding phases	· Firmness: softer belly in YG fed during all 5 feeding phases than BT · Fat color: ↓ b* value as time fed BT increased · Fatty acid composition - ↑ SFA and MUFA concentrations in belly fat with BT fed during all 5 feeding phases - ↑ PUFA and IV in belly fat with YG fed during all 5 feeding phases	Browne et al., 2013

DDGS · DDGS: 0 or 30% Dietary treatment · Corn germ, beef tallow, palm kernel oil, or glycerol	· Firmness: ↑ flop distance in pigs fed DDGS · Fatty acid composition - ↑ oleic acid content in control group than pigs fed DDGS except pigs fed beef tallow - ↑ MUFA in control group than pigs fed DDGS or corn germ - ↑ MUFA in pigs fed beef tallow than pigs fed DDGS	Lee et al., 2013
DDGS · 0%, 30% DDGS with withdrawal, or 30% DDGS without withdrawal	· Width: tended to wider belly with fed DDGS · Firmness: softer belly with fed DDGS · IV: increased with fed DDGS without withdrawal	Tavárez et al., 2014
DDGS · 0 or 30% Tallow · 0 or 5%	· Thickness: tend to be thicker in tallow fed pigs · Length: decreased in tallow fed pigs · Firmness: softer belly in DDGS fed pigs and tend to decreased of flop angle in tallow fed pigs · Fatty acid composition - ↓ oleic acid, MUFA, and SFA and ↑ PUFA in DDGS fed pigs - ↑ oleic acid and MUFA and ↓ SFA in tallow fed pigs · IV: increased in DDGS fed pigs and decreased when tallow added to diets with DDGS · Fat color: ↓ L*, a*, and b* value in pigs fed DDGS	Davis et al., 2015
Diet form · Meal or pelleted DDGS · 0 or 30%	· Belly weigh: heavier belly in pellet-fed pigs · Thickness: reduced in 30 % DDGS-fed pigs · Firmness: ↓ flop distance in 30% DDGS-fed pigs · Fatty acid composition - ↑ PUFA and ↓ MUFA and SFA in pellet-fed pigs and 30% DDGS-fed pigs - ↑ IV in pellet-fed pigs and 30% DDGS-fed pigs	Overholt et al., 2016
40% DDGS and dietary treatment · Cottonseed oil or crude glycerol	· Thickness: highest in pig fed cottonseed oil · Firmness - Compression force tended to be less in pigs fed glycerol than 40% DDGS · Fatty acid composition - ↑ SFA, PUFA, and IV and ↓ MUFA in pigs fed cottonseed oil	Villela et al., 2017
DDGS feeding strategies · Corn-soybean meal with 0% DDGS (PCon) · Progressive reduction in	· Belly percentage: lowest in NCon and highest in PCon · Thickness: thinner belly in NCon and similar thickness in PCon and WD · Firmness: flop distance, PCon> SD>WD>NCon, softer belly in PCon · Color of belly fat: ↓ L* value in NCon · Fatty acid composition	Harris et al., 2018

DDGS supply (SD) · DDGS 40% with withdrawal period (WD) · DDGS 40% in all phase (NCon)	- ↓ SFA and MUFA and ↑ PUFA in NCon - IV: NCon>WD=SD>PCon	
High oleic soybean oil (HOSO) · 25% DDGS or HOSO (2, 4, or 6%)	· Width: higher in DDGS fed pigs and lower in 2 and 4% HOSO fed pigs · Thickness: Thicker belly in HOSO fed pigs · Firmness: firmer belly in HOSO fed pigs · Fatty acid composition - ↓ SFA with increasing HOSO levels in pig diet - ↑ MUFA with increasing HOSO levels in pig diet - ↑ PUFA in DDGS fed pigs - IV: highest in 6% HOSO fed pigs and lowest in 2% HOSO fed pigs	Gaffield et al., 2022
Others		
L-carnitine (CARN) · 0 or 100 mg/kg Corn oil · 0, 2, or 4%	· Firmness: decrease linearly with corn oil content in diet · Fatty acid composition - CARN supplement: ↑ SFA in the intermuscular fat layer, ↑ MUFA in the lean layers, and ↓ PUFA in the intermuscular fat and *cutaneous trunci* muscle - Corn oil: ↓ SFA and MUFA composition and ↑ PUFA content	Apple et al., 2011
Antioxidant · High oxidant diet, 11 IU/kg vitamin E, antioxidant blend, vitamin E + antioxidant blend, and standard corn-soy control diet	· Length: decreased belly length in pigs fed high oxidant diet and vitamin E · Width: lowest in pigs fed high oxidant diet · Firmness: firmer belly in pigs fed corn-soy diet and softer belly in vitamin E pigs	Lu et al., 2014
Antibiotic or antimicrobial · Antibiotic free, natural antimicrobial (0.025% oregano), or antibiotic (40	No significant effect	Lowell et al., 2018

mg/kg tylosin phosphate)		
Lycopene, tomato paste, or both	• MDA content: lower MDA concentrations in feeding lycopene or tomato paste • Fatty acid composition: no effect	An et al., 2019
Camelina press cake (CPC) 0, 5, 10, or 15%	• Thickness: decreased thickness with increased CPC level • Firmness: no effect	Zhu et al., 2021
Methionine (Met) source L-Met, DL-Met, or calcium salt of DL-Met hydroxyl analog	No significant effect	Remole et al., 2024