Meat Science 218 (2024) 109631

Contents lists available at ScienceDirect

Meat Science

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

# Consumer eating quality and physicochemical traits of pork *Longissimus* and *Semimembranosus* differed between genetic lines

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ARTICLE INFO

*Keywords:*
Collagen
Intramuscular fat (IMF)
pH
Sensory evaluation
Check-all-that-apply (CATA)
Biometrics

ABSTRACT

Pork eating quality is affected by various factors. In this study, *Longissimus thoracis et lumborum* (LTL) and *Semimembranosus* (SM) muscles from seven genetic lines (PM-LR – Pure maternal, Landrace-type; PM-LW – Pure maternal, Large White-type; PM-D – Pure maternal, Duroc-type; PT-D – Pure terminal, Duroc-type; PT-LW – Pure terminal, Large White-type; PT-LR - Pure Terminal, Landrace-type; Comp-P × LW × D - Composite Terminal – Pietran × Large white × Duroc) were analyzed for pH, intramuscular fat (IMF) content, and collagen content and solubility. A consumer sensory test using check-all-that-apply (CATA) and biometric approaches was also conducted. The results showed that the IMF content of line PM-D was the highest ($P = 0.004$), while line PT-LW received the highest score in tenderness, liking of flavor, purchase intent, and quality grading ($P < 0.05$). Line PM-LR and PT-LR showed the lowest IMF content and were least preferred by consumers. Compared to LTL, SM showed higher pH, collagen solubility, and sensory scores in tenderness, juiciness, liking of flavor, and overall liking ($P < 0.05$). Different muscles and lines were associated with different CATA terms but not with differences in consumer emotional responses. pH positively influenced tenderness, juiciness, and overall liking ($P < 0.05$), but IMF and collagen had little effect. The flavor was the most important sensory attribute contributing to overall liking, followed by tenderness. Genetic line and muscle affected pork chemical properties and eating quality. The findings are important for the Australian pork industry to improve the eating quality of their products.

## 1. Introduction

The Australian pork industry has been putting efforts into improving pork eating quality over the past few decades. They have been implementing on-farm management strategies, enhancing their breeding strategies, and adopting new technologies in the production and processing sectors (Channon, D'Souza, & Dunshea, 2017). However, efficient production of pork, which meets market demand for leanness, has driven genetic selection for lean growth, resulting in adverse effects on pork eating quality (Schwab, Baas, Stalder, & Mabry, 2006). Therefore, it is crucial to survey the meat and eating quality traits of the commercial genetic lines currently in use to help the pork industry identify and improve its breeding strategies regarding eating quality.

Genetics can affect muscle physicochemical traits, which then affect pork eating quality. Connective tissue and intramuscular fat (IMF) are two essential muscle components that impact meat quality. Connective tissue is considered to affect the "background toughness" of meat (Purslow, 2018). However, some studies showed that collagen content and solubility significantly influenced meat tenderness, while others showed no effect (Ngapo et al., 2002; Rhee, Wheeler, Shackelford, & Koohmaraie, 2004; Roy, Das, Aalhus, & Bruce, 2021). Similarly, IMF was reported to affect the juiciness and flavor of meat (Czarniecka-Skubina, Przybylski, Jaworska, Kajak-Siemaszko, & Wachowicz, 2010; Fortin, Robertson, & Tong, 2005), but there were contradictory results

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https://doi.org/10.1016/j.meatsci.2024.109631
Received 23 June 2024; Received in revised form 4 August 2024; Accepted 14 August 2024
Available online 20 August 2024

for tenderness (Channon, D'Souza, & Dunshea, 2018; Gondret, Lefaucheur, Juin, Louveau, & Lebret, 2006). A previous meta-analysis showed that collagen content and solubility were correlated with beef sensory tenderness scores, but correlation coefficients differed between muscles (Li, Ha, Warner, & Dunshea, 2022a). Also, there were few studies on pork; therefore, it was not possible to conduct a similar meta-analysis for pork. Thus, more studies need to be undertaken to determine the contribution of connective tissue and IMF to pork eating quality under different conditions.

In Australia, Meat Standard Australia (MSA) has established a standard protocol for sensory evaluation of beef and lamb to measure eating experience consistently (Watson, Gee, Polkinghorne, & Porter, 2008). However, there is no standard specifically for pork. Pork's sensory properties differ from beef and lamb, and there may be better approaches than adopting MSA for pork (Channon et al., 2018). Identifying the critical sensory attributes contributing to consumer evaluation of Australian pork and suitable sensory evaluation methods for pork is necessary. Check-all-that-apply (CATA) is a sensory evaluation method recently applied to understand processed meat quality (Torrico et al., 2018). The CATA is a rapid profiling tool where consumers are asked to select all the terms that apply to the product from a pre-defined list of terms (Oliver, Cicerale, Pang, & Keast, 2018). Besides CATA, biometrics are another powerful tool in the sensory evaluation of food, such as meat (Fuentes, Gonzalez Viejo, Torrico, & Dunshea, 2018; Mena et al., 2023; Torrico et al., 2018). Physiological responses complement self-reported sensory responses, which allow a deeper understanding of consumers' unconscious emotional responses towards food products. Testing whether CATA and biometrics can differentiate between line or muscle will inform the development of sensory evaluation questionnaires specific to Australian pork.

Therefore, this study aimed to 1) compare the carcass traits, chemical properties, and eating quality of pork from different lines and muscles; 2) determine the effects of pH, collagen characteristics, and IMF on pork eating quality; and 3) find the most important sensory attributes contributing to consumer evaluation of Australian pork. It is hypothesized that: 1) lines from the Duroc breed will have higher IMF content and will be preferred by consumers; 2) the *Longissimus thoracis et lumborum* (LTL) will show similar pH, lower collagen content, and higher sensory scores than the *Semimembranosus* (SM); 3) collagen solubility and IMF content will be positively related to sensory attributes, while collagen content will be negatively related to sensory attributes; 4) biometrics and CATA can differentiate between lines and muscles; 5) flavor will be the most important sensory attribute contributing to overall liking.

## 2. Materials and methods

### 2.1. Animals

Seventy-eight female pigs from seven genetic lines were used (information on the genetic company was proprietary): PM-LR – Pure maternal, Landrace-type ($n = 12$, 7 sires); PM-LW – Pure maternal, Large White-type (n = 12, 4 sires); PM-D – Pure maternal, Duroc-type (n = 12, 6 sires); PT-D – Pure terminal, Duroc-type ($n = 11$, 7 sires); PT-LW – Pure terminal, Large White-type (n = 12, 7 sires); PT-LR - Pure Terminal, Landrace-type ($n = 6$, 4 sires); Comp-P × LW × D - Composite Terminal – Pietran × Large white × Duroc ($n = 13$, 8 sires). Line type was defined as a maternal or terminal line. All pigs were raised on a large commercial piggery. They were fed ad libitum to commercial pelleted diets. They were housed indoors with slatted floors. Pigs were slaughtered at 22 weeks of age. The live weight of the pigs was measured before slaughter. All pigs were slaughtered under normal commercial conditions in a commercial abattoir for two days (SunPork Group, Kingaroy, QLD Australia), and the measurement of carcass traits (hot carcass weight, cold carcass weight, P2 fat depth, and the dressing percentage) followed the method described previously (Li et al., 2024). At 24 h post-mortem, *Longissimus thoracis et lumborum* (LTL) and *Semimembranosus* (SM) were excised from the loin and leg primal of each carcass. Individual muscles were vacuum packed and frozen at 48 h post-mortem and transported to the University of Melbourne under an Animal Ethics Committee scavenged tissue license (Ethics ID #22011). The samples were stored frozen (−18 °C) until analysis.

### 2.2. Sample preparation

Meat samples were cut from frozen using a hand-held saw. For LTL, a 13.5 cm long block was cut from the center of the muscle for sensory evaluation. One 60 g-sample was cut from the anterior part of the muscle adjacent to the sensory evaluation sample for freeze-drying. For the SM, the muscle was cut in half (across the skin); the lateral part was used for sensory evaluation, and the medial part was used to remove a 60 g sample for freeze-drying. The location of the sample on each muscle for sensory evaluation was fixed. Samples for sensory evaluation were vacuum-packed and kept frozen until analysis. Small pieces for freeze-drying were placed in sample jars and freeze-dried for 120 h for collagen and intramuscular fat (IMF) analyses. Weights of all samples and jars were recorded to calculate water content. All samples were kept frozen before analysis.

### 2.3. Intramuscular fat (IMF) content

Intramuscular fat content was determined by AOAC method 991.36 (AOAC, 1995) with some modifications (Li, Ha, Warner, & Dunshea, 2022b). Briefly, freeze-dried samples were powdered with a coffee blender. Duplicates of 3.5 g of meat powder were wrapped in No.1 Whatman filter paper and subjected to Soxhlet extraction. The extraction solvent was diethyl ether. IMF content was calculated gravimetrically and expressed as a percentage of fresh meat.

### 2.4. Collagen content and solubility

Collagen content and solubility were determined using a colorimetric AOAC method 990.26 (Kolar, 1990) to determine hydroxyproline content as described by Li et al. (2022b). Total and soluble collagen content were calculated with a conversion factor of 7.25. Collagen content was expressed as mg/g fresh meat, and collagen solubility was expressed as the percentage of soluble collagen divided by total collagen content.

### 2.5. Sensory evaluation

#### 2.5.1. Consumers

Sensory evaluation was conducted in the sensory research facility at the University of Melbourne. This project has been approved by The University of Melbourne Human Ethics Committee (Ethics ID: 21857). A total of 229 consumers were recruited at the University of Melbourne by putting up posters, and posting on online notice boards and the School newsletters. There was a maximum of 18 consumers per sensory evaluation session, and the sensory evaluation sessions were conducted over four days with three or four sessions daily. One session lasted for approximately 45 min.

All consumers attended a briefing session before they started the evaluation. At the briefing, they confirmed that they were all above the age of 18, had consumed pork in the past three months, were willing to consume pork, consented to video recording, did not have strong-tasting food or coffee one hour before the test, and did not wear strong perfume. During the briefing session, consumers also filled out the demographic questionnaire (see supplementary material); the demographics of consumers are shown in Supplementary Table S1. Participants' ages ranged from 18 to above 70 years old. A majority of participants were Asian and around two-third of them were female. The demographics represented the population of young people living in the urban area and also the student population. The participants were also informed that they could withdraw anytime, and their responses would be kept confidential.

All participating consumers sign a consent form before sensory evaluation commenced. They confirmed their informed consent by signing, "I consent to participate in this project, the details of which have been explained to me, and I have been provided with a written plain language statement to keep". Upon completion of the briefing, consumers were directed to individual sensory booths. Each consumer was given a fork, napkin, and a cup of 10% apple juice (apple juice: water 1:9) and crackers to cleanse their palate between samples. Each consumer was served seven samples. The first serving was the "Link" sample (the first sample all consumers tasted, results not recorded) so they could familiarize themselves with the questionnaire. Consumers answered the questionnaire on the tablet using the Bio-Sensory application (App: The University of Melbourne, Parkville, VIC, Australia) (Fuentes et al., 2018). This App was set to record videos while consumers evaluated samples to get their initial reaction, when they assessed liking of odor. The videos were 10–30 s long.

#### 2.5.2. Sensory samples

The LTL from a previous project was selected as the "Link" sample, which consisted of a commercial product from the same company, aged two days and frozen for ten months. Samples for sensory evaluation were thawed at 2 °C for 24 h. The thawed muscle sample was cut perpendicular to the muscle fiber direction into three steaks of 2.5 cm thickness, which were then further cut into sensory samples of 5.0 × 5.0 × 2.5 $cm^3$. All samples were free of subcutaneous fat and connective tissue. After fabrication of the sensory samples, the pH and temperature of the remaining muscle were measured with a portable pH/temperature meter (TPS WP-80, TPS, Brendale QLD, Australia) equipped with an electrode (model TPS-121234, TPS, Brendale QLD, Australia). The pH meter was calibrated with pH 4.01 and 7.01 buffers. All steaks were randomized across sessions within a day. After cutting, six sensory samples for one round were placed on laminated A4 paper with their sample ID and random number code. Steaks and the A4 paper were 50% vacuum packed (50% of air taken out) and stored at 2 °C overnight before cooking.

The next day, steaks for the same session were transported to the kitchen in a Styrofoam box 10 min before the session started. The clamshell grill (Silex S-Tronic Single Grill, Silex, Marrickville NSW, Australia) was turned on two hours before the session began to pre-heat, and the temperature was set at 160 °C on both sides. The steaks were cooked to an internal temperature of 70 °C and rested for 30s. After resting, the final internal temperature of the steaks was around 72 °C. A set of starter samples was cooked to determine the cooking time with a thermocouple inserted in one steak. The cooking time was from 4 min 45 s to 5 min. After resting, steaks were cut into four pieces, from which three pieces were randomly chosen to be served to consumers in plastic sauce containers (70 ml, Genfac Plastics, Melbourne VIC, Australia). The fourth piece was discarded. All sauce containers were covered with aluminum foil to maintain the aroma. Each muscle was served to nine consumers, and each consumer tasted six samples, excluding the "Link".

#### 2.5.3. Sensory evaluation

The questionnaire consisted of three parts. In the first part, consumers assessed sensory attributes on hedonic scales from 0 to 100. The scale was 15 cm long and the results were converted to 100-point basis. The wording on the two extremes of the scale was: Liking of appearance – 0 (dislike extremely) and 100 (like extremely); liking of odor – 0 (dislike extremely) and 100 (like extremely); tenderness – 0 (not tender) and 100 (very tender); juiciness – 0 (not juicy) and 100 (very juicy); liking of flavor – 0 (dislike extremely) and 100 (like extremely); overall liking – 0 (dislike extremely) and 100 (like extremely).

In the second part, consumers answered whether they detected any off-flavor ("Yes" or "No") and their purchase intent (1 – "I would definitely not buy it", 2 – "I would probably not buy it", 3 – "I might buy it", 4 – "I would probably buy it" or 5 – "I would definitely buy it"). Success was defined as consumers selecting 4 and 5. They were also asked to assess the quality grading of the sample on a hedonic scale with the following phrases marked on the scale: "Unsatisfactory", "Good everyday", "Better than good everyday" and "Premium".

The third part was check-all-that-apply (CATA), where consumers selected all the words that best described the sample. There were 32 CATA terms, including 11 odor terms "fecal odor", "sweet odor", "roasted odor", "oily odor", "mushroom odor", "metallic odor", "earthy odor", "sour odor", "fruity odor", "familiar odor", and "porky odor"; 15 flavor terms "mushroom flavor", "buttery flavor", "clean flavor", "earthy flavor", "fecal flavor", "familiar flavor", "fatty flavor", "metallic flavor", "porky flavor", "roasted flavor", "sweet taste", "sour taste", "fruity flavor", "savory flavor" and "flavorless"; and six texture terms "chewy", "dry", "fibrous", "juicy", "soft" and "tender". These terms were determined with modifications da Silva et al. (2023). Due to the maximum number of options to display in the App for CATA questions, odor and texture terms were displayed on one page, flavor terms were on another page, and all terms were in a fixed order.

### 2.6. Data analysis

Carcass traits and chemical data were analyzed using a linear mixed model restricted maximum likelihood (REML) generalized linear mixed model in GenStat (22nd edition, VSN International, UK). For carcass traits, the fixed factor = line or line type, and the random factor = kill day. Two LTL samples with extremely high pH values (pH > 6.80) were eliminated from chemical and sensory data analysis. For chemical data (pH, IMF, collagen content, and solubility), the fixed model = line (line type) + muscle + line (line type) × muscle, and the random model = kill day.

The sensory evaluation results were analyzed using R (R Core Team, 2021) in RStudio (Posit, PBC, Boston, US). The line scale questions were analyzed using a linear mixed-effects model with packages "lme4", "jtools" and "emmeans". The fixed model = muscle + line + muscle × line, and the random model = carcass + participant + session. The predicted means, standard errors of the mean, and *P* values were recorded. The probability of regular (no off-flavor), the propability of success in purchase intent, and CATA data were analyzed by a generalized linear mixed-effects model with logarithmic transformation for the probability and binomial distribution. The fixed model = muscle + line + muscle × line, and the random model = carcass + participant + session. CATA data was also visualized using correspondence analysis (CA) using the "FactoMineR" and "factoextra" packages in RStudio. The CATA terms which had cumulative contribution <3.60 to Factor 1 and 2 were excluded from analysis. A linear mixed-effects model analyzed the predictions of overall liking, probability of success (purchase intent), and quality grading from individual sensory attributes (liking of flavor, tenderness, juiciness, odor, and appearance). The fixed model = liking of appearance + liking of odor + tenderness + juiciness + liking of flavor, and the random model = carcass + participant + session + muscle + line. The prediction of sensory attributes with chemical measurements was analyzed using the same method, and the fixed model = pH + IMF + collagen content + collagen solubility + muscle + line + muscle × line. A penalty-lift analysis was conducted on individual CATA terms to analyze the difference in the overall liking of a CATA term versus when it was not selected. The result of the penalty-lift analysis was visualized using a bar plot.

Facial expression data was analyzed according to the method described by Gonzalez Viejo et al. (2023). Videos were recorded and screened manually for data quality to ensure they showed the whole face of the participants. Selected videos were then translated to emotion responses using an automated software developed by the Digital Agriculture, Food and Wine Sciences Group from The University of Melbourne based on the histogram-oriented gradient and support vector machine algorithms from the Affectiva software development kit (SDK;

Affectiva, Boston, MA, USA). The variables obtained from this software were described by Gupta et al. (2022). Variables chosen for analysis were joy, relaxed, anger, rage, sadness, smirk, contempt, and valence because they best described emotions and contributed significantly to variations. Emotion variables were visualized by principal component analysis (PCA) in RStudio using packages "FactoMineR" and "factoextra".

## 3. Results

Carcass traits and chemical properties differed between lines. Line PT-D had the highest IMF content (0.959%), while lines from the Landrace breed had the lowest IMF content (PM-LR = 0.667% and PT-LR = 0.650%, $P$ = 0.004, Table 1). However, P2 fat depth was the highest in line PM-LW and lowest in line PT-D (Supplementary Table S2). Also, the maternal line showed higher P2 fat depth than the terminal line (Supplementary Table S3), but they did not differ in chemical properties (Supplementary Table S4).

Muscles differed in pH and collagen solubility (Table 1). The SM showed higher pH (5.70 vs 5.64, $P < 0.001$) and higher collagen solubility than the LTL (13.0 vs 9.90%, $P < 0.001$). There was no difference in IMF or collagen content between muscles.

For the sensory evaluation results (Table 2), line PT-LW showed the highest tenderness score, while line PT-LR showed the lowest (59.6 vs 45.4, $P$ = 0.005). The liking of flavor score was also the highest in samples from line PT-LW, with the lowest score in line PM-LR (60.8 vs 54.1, $P$ = 0.039). A similar trend was observed for the probability of success for purchase intent (0.361 vs 0.205, $P$ = 0.005) and quality grading (44.5 vs 36.9, $P$ = 0.041).

The LTL exhibited higher scores in liking of appearance (65.9 vs 62.9, $P$ = 0.001) (Table 2) and odor (66.1 vs 64.0, $P$ = 0.019) and probability of no off-flavor than the SM (0.986 vs 0.975, $P$ = 0.016). The SM showed higher scores in tenderness (58.4 vs 48.7, $P < 0.001$), juiciness (62.3 vs 54.1, $P < 0.001$), liking of flavor (59.9 vs 56.0, $P < 0.001$), and overall liking (60.3 vs 54.0, $P < 0.001$). The SM also showed a higher probability of success for purchase intent (0.353 vs 0.214, $P <$ 0.001) and higher quality grading than LTL (44.0 vs 36.8, $P < 0.001$).

In terms of interactions, LTL from line Comp-P × LW × D showed higher scores in liking of appearance than SM from line PM-D, PT-D, and Comp-P × LW × D (Table 2). Within the LTL, pork from line Comp-P × LW × D showed higher tenderness than those from lines PM-LW and PT-LR. Line PT-LW received the highest tenderness score within the SM, while line PT-LR received the lowest. Similarly, the SM from line PT-LW showed the highest probability of success for purchase intent, while LTL from line PT-LR showed the lowest.

The LTL was perceived as chewy, dry, and flavorless for the CATA results. The SM was tender, soft, juicy, and rich in porky odor, fatty flavor, porky flavor, and metallic flavor (Table 3). From the CA, Factor 1 explained 38.5% variations and the most contributing variable was tender, while Factor 2 explained 23.9% variations and the most contributing variable was sour odor (Fig. 1). Seven lines fell into four origin sections. Line PT-LR was flavorless with an oily odor. Line PM-LR and Comp-P × LW × D were chewy and fibrous. Line PT-D had a fatty flavor, while line PM-D was tender, soft and had a sweet odor. Line PT-LW and PM-LW were juicy and sweet.

Figs. 2 and 3 are PCA biplots of emotions. PC 1 explained 34.6% of variations, while PC2 explained 26.9% of variations. PC1 was mostly contributed by positive emotions valence, joy and relaxed. PC2 was mostly contributed by negative emotions anger, rage and sadness. All the positive emotions were on the right side and negative emotions were on the left. Individual sample points scattered along joy and relaxed or anger, rage, sadness, smirk and contempt. The mean points of the seven lines clustered around the origin and had no difference in emotions. Similarly, there was no difference between muscles in consumers' emotional responses.

Table 4 shows the contribution of chemical properties to sensory attributes. pH positively contributed to tenderness, juiciness, and overall liking. The slope of juiciness for IMF was close to significant ($P$ = 0.066). Collagen content and collagen solubility did not significantly affect sensory attributes.

Table 5 shows the prediction of overall liking, probability of success (purchase intent) and quality grading using individual sensory attributes. The prediction equation for overall liking was:

$$\text{Overall liking} = 0.65\ (\pm 0.02)\text{flavor} + 0.23\ (\pm 0.01)\ \text{tenderness} + 0.10\ (\pm 0.02)\ \text{juiciness} + 0.08\ (\pm 0.02)\ \text{appearance}$$

The prediction equation for the probability of success in purchase intent was:

$$\text{Probability of success (purchase intent)} = 0.11\ (\pm 0.01)\ \text{flavor} + 0.04\ (\pm 0.01)\ \text{tenderness} + 0.03\ (\pm 0.01)\ \text{juiciness}$$

The prediction equation for quality grading was:

$$\text{Quality grading} = 0.53\ (\pm 0.02)\ \text{flavor} + 0.24\ (\pm 0.02)\ \text{tenderness} + 0.11\ (\pm 0.02)\ \text{juiciness} + 0.10\ (\pm 0.02)\ \text{odor} + 0.05\ (\pm 0.02)\ \text{appearance}$$

**Table 1**
The effect of line (L), muscle (M) and the interaction of line and muscle (L × M) on the chemical properties of pork.

| | Muscle[a] | Line[b] | | | | | | | SED[c] | P-value[d] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | PM-LR | PM-LW | PM-D | PT-D | PT-LW | PT-LR | Comp-P × LW × D | | L | M | L × M |
| N | LTL | 12 | 12 | 12 | 11 | 12 | 6 | 11 | | | | |
| | SM | 12 | 12 | 12 | 11 | 12 | 6 | 13 | | | | |
| pH | LTL | 5.62 | 5.60 | 5.67 | 5.67 | 5.59 | 5.67 | 5.66 | 0.034 | 0.063 | **<0.001** | 0.50 |
| | SM | 5.69 | 5.71 | 5.69 | 5.70 | 5.66 | 5.73 | 5.70 | | | | |
| IMF (%)[e] | LTL | 0.558 | 0.794 | 0.894 | 0.920 | 0.798 | 0.666 | 0.927 | 0.1309 | **0.004** | 0.33 | 0.46 |
| | SM | 0.776 | 0.928 | 1.02 | 0.836 | 0.707 | 0.634 | 0.915 | | | | |
| Collagen content (mg/g) | LTL | 4.07 | 4.45 | 4.13 | 4.37 | 4.61 | 4.25 | 4.16 | 0.300 | 0.32 | 0.15 | 0.17 |
| | SM | 4.31 | 4.52 | 4.53 | 4.64 | 4.26 | 3.81 | 4.77 | | | | |
| Collagen solubility (%) | LTL | 9.96 | 11.0 | 10.3 | 9.94 | 9.11 | 9.74 | 9.29 | 1.063 | 0.058 | **<0.001** | 0.23 |
| | SM | 12.9 | 12.5 | 14.1 | 12.2 | 12.3 | 15.6 | 11.7 | | | | |

[a] LTL = *Longissimus thoracis et lumborum*, SM = *Semimembranosus.*
[b] PM-LR – Pure maternal, Landrace-type; PM-LW – Pure maternal, Large White-type; PM-D – Pure maternal, Duroc-type; PT-D – Pure terminal, Duroc-type; PT-LW – Pure terminal, Large White-type; PT-LR - Pure Terminal, Landrace-type; Comp-P × LW × D - Composite Terminal – Pietran × Large white × Duroc.
[c] SED = average standard error of difference of the interaction.
[d] Data was analyzed by generalized linear mixed-effect model in GenStat. Fixed factors = line + muscle + line × muscle; Random factor = kill day. Data is expressed as mean ± standard error of mean. L = line, M = muscle, L × M = line and muscle interaction.
[e] IMF = intramuscular fat.

**Table 2**
The effect of line (L), muscle (M) and the interaction of line and muscle (L × M) on the sensory attributes of pork.

| | Muscle[1] | Line[2] | | | | | | | SED[3] | P-value[4] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | PM-LR | PM-LW | PM-D | PT-D | PT-LW | PT-LR | Comp-P × LW × D | | L | M | L × M |
| N | LTL | 104 | 104 | 106 | 99 | 107 | 54 | 95 | | | | |
| | SM | 107 | 103 | 105 | 97 | 105 | 54 | 116 | | | | |
| Liking of appearance | LTL | 63.7[ab] | 64.4[ab] | 63.7[ab] | 67.8[ab] | 66.1[ab] | 65.3[ab] | 69.9[a] | 2.54 | 0.17 | **0.001** | **0.027** |
| | SM | 62.3[ab] | 64.7[ab] | 60.7[b] | 59.9[b] | 67.1[ab] | 64.3[ab] | 61.4[b] | | | | |
| Liking of odor | LTL | 62.9 | 65.2 | 64.9 | 68.0 | 66.8 | 68.6 | 66.0 | 2.46 | 0.23 | **0.019** | 0.79 |
| | SM | 62.1 | 63.7 | 64.7 | 63.1 | 66.0 | 65.6 | 62.8 | | | | |
| Tenderness | LTL | 47.2[cd] | 43.5[d] | 51.9[bcd] | 52.4[bcd] | 50.4[bcd] | 40.8[d] | 54.7[bc] | 4.26 | **0.005** | **<0.001** | **0.036** |
| | SM | 56.4[abcd] | 56.4[abc] | 59.4[abc] | 55.5[abc] | 68.7[a] | 50.0[bcd] | 62.4[ab] | | | | |
| Juiciness | LTL | 56.0 | 52.2 | 57.1 | 52.1 | 52.9 | 52.9 | 55.6 | 3.51 | 0.43 | **<0.001** | 0.92 |
| | SM | 62.6 | 62.0 | 66.0 | 59.3 | 63.9 | 59.4 | 63.1 | | | | |
| Liking of flavor | LTL | 52.8 | 55.8 | 56.2 | 57.5 | 58.3 | 51.7 | 59.6 | 2.98 | **0.039** | **<0.001** | 0.51 |
| | SM | 55.4 | 61.3 | 60.4 | 57.6 | 63.3 | 60.0 | 61.3 | | | | |
| Overall liking | LTL | 52.0 | 51.9 | 56.1 | 58.3 | 55.0 | 48.0 | 56.7 | 3.39 | 0.076 | **<0.001** | 0.16 |
| | SM | 56.6 | 61.5 | 60.6 | 58.9 | 65.8 | 56.6 | 62.2 | | | | |
| Probability of no off-flavor | LTL | 0.983 | 0.974 | 0.974 | 0.998 | 0.989 | 0.974 | 0.988 | 0.0224 | 0.075 | **0.016** | 0.37 |
| | SM | 0.948 | 0.983 | 0.965 | 0.982 | 0.982 | 0.965 | 0.983 | | | | |
| Probability of success (purchase intent)[5] | LTL | 0.182[c] | 0.151[c] | 0.281[abc] | 0.295[abc] | 0.229[bc] | 0.148[c] | 0.373[abc] | 0.0840 | **0.005** | **<0.001** | **0.010** |
| | SM | 0.244[bc] | 0.359[abc] | 0.477[ab] | 0.240[b] | 0.525[a] | 0.302[abc] | 0.387[abc] | | | | |
| Quality grading[6] | LTL | 33.6 | 35.0 | 39.4 | 39.5 | 38.6 | 32.4 | 39.2 | 3.30 | **0.041** | **<0.001** | 0.16 |
| | SM | 40.2 | 43.9 | 45.7 | 40.7 | 50.4 | 42.2 | 45.2 | | | | |

a, b,c,d Data with different superscripts differ significantly ($P < 0.05$) between line and muscles.
[1] LTL = *Longissimus thoracis et lumborum*, SM = *Semimembranosus.*
[2] PM-LR – Pure maternal, Landrace-type; PM-LW – Pure maternal, Large White-type; PM-D – Pure maternal, Duroc-type; PT-D – Pure terminal, Duroc-type; PT-LW – Pure terminal, Large White-type; PT-LR - Pure Terminal, Landrace-type; Comp-P × LW × D - Composite Terminal – Pietran × Large white × Duroc.
[3] SED = average standard error of difference.
[4] Data was analyzed by generalized linear mixed-effect model in RStudio. Fixed factors = line + muscle + line × muscle; Random factor = participant + carcass + session. Data is expressed as mean ± standard error of mean. Line scale ranged from 0 to 100.
[5] Success = participants selected 4 (I would probably buy it) and 5 (I would definitely buy it).
[6] Quality grading was on a line scale labeled unsatisfactory, good everyday, better than good everyday and premium at fixed intervals.

**Table 3**
Probability of selected (mean ± standard error of mean) check-all-that-apply (CATA) terms of *Longissimus thoracis et lumborum* (LTL) and *Semimembranosus* (SM).

| | Muscle | | *P*-value[a] |
|---|---|---|---|
| | LTL | SM | Muscle |
| Tender | 0.216[y] ± 0.0295 | 0.388[x] ± 0.0382 | **<0.001** |
| Chewy | 0.591[x] ± 0.0278 | 0.520[y] ± 0.0283 | **0.022** |
| Dry | 0.318[x] ± 0.0259 | 0.167[y] ± 0.0091 | **<0.001** |
| Soft | 0.117[y] ± 0.0207 | 0.230[x] ± 0.0304 | **<0.001** |
| Juicy | 0.332[y] ± 0.0250 | 0.458[x] ± 0.0267 | **<0.001** |
| Porky odor | 0.432[y] ± 0.0389 | 0.521[x] ± 0.0393 | **0.010** |
| Fatty flavor | 0.0060[y] ± 0.00431 | 0.0112[x] ± 0.00750 | **0.020** |
| Flavorless | 0.108[x] ± 0.0186 | 0.0582[y] ± 0.0120 | **<0.001** |
| Porky flavor | 0.467[y] ± 0.0392 | 0.609[x] ± 0.0375 | **<0.001** |
| Sour taste | 0.110[x] ± 0.0248 | 0.0707[y] ± 0.0177 | **0.006** |
| Metallic flavor | 0.0300[y] ± 0.0091 | 0.0544[x] ± 0.0145 | **0.003** |
| Fibrous | 0.345 ± 0.0319 | 0.308 ± 0.0302 | 0.22 |
| Sweet odor | 0.0500 ± 0.0120 | 0.0579 ± 0.0131 | 0.46 |
| Roasted odor | 0.343 ± 0.0348 | 0.291 ± 0.0322 | 0.080 |
| Oily odor | 0.0014 ± 0.0012 | 0.0020 ± 0.0017 | 0.15 |
| Earthy odor | 0.0323 ± 0.0093 | 0.0353 ± 0.0010 | 0.68 |
| Sour odor | 0.0443 ± 0.0121 | 0.0492 ± 0.0130 | 0.63 |
| Fruity odor | 0.0001 ± 0.1165 | 0.0007 ± 0.0004 | 0.99 |
| Familiar odor | 0.155 ± 0.0252 | 0.162 ± 0.0257 | 0.76 |
| Roasted flavor | 0.310 ± 0.0346 | 0.328 ± 0.0354 | 0.56 |
| Earthy flavor | 0.0395 ± 0.0116 | 0.0315 ± 0.0097 | 0.26 |
| Fruity flavor | 0.0016 ± 0.0016 | 0.0013 ± 0.0014 | 0.61 |
| Mushroom flavor | 0.0001 ± 0.0001 | 0.0002 ± 0.0002 | 0.60 |
| Clean flavor | 0.226 ± 0.0261 | 0.222 ± 0.0256 | 0.87 |
| Familiar flavor | 0.160 ± 0.0236 | 0.185 ± 0.0257 | 0.30 |
| Savory flavor | 0.137 ± 0.0241 | 0.140 ± 0.0245 | 0.91 |

x, y Data with different superscripts differ significantly ($P < 0.05$) between muscles.
[a] Data was analyzed by generalized linear mixed-effect model in RStudio. Fixed factors = line + muscle + line × muscle; Random factor = participant + carcass + session. Data is expressed as mean ± standard error of mean.

Fig. 4 shows the results of the penalty-lift analysis. The top five drivers for positive overall liking scores were "tender", "soft", "juicy", "buttery flavor" and "sweet taste". The top five CATA terms which negatively affected overall liking scores were "dry", "flavorless", "metallic odor", "fecal flavor" and "fecal odor".

## 4. Discussion

The significant findings of this study were: 1) line PM-D had the highest IMF content; 2) line PT-LW was most preferred by consumers and lines of Landrace breed were the least preferred; 3) the SM received higher sensory scores than the LTL, with higher pH and collagen solubility; 4) CATA could differentiate between lines and muscles, but biometrics could not; 5) pH positively contributed to tenderness, juiciness and overall liking; 6) flavor is the most important sensory attribute contributing to overall liking, followed by tenderness. Therefore, hypothesis 5) was accepted, while hypotheses 1), 2), and 4) were partly accepted, and hypothesis 3) was rejected.

Different lines showed different IMF content and sensory properties. In the present study, line PM-D showed the highest IMF content. This result was similar to previous studies, where pork from purebred Duroc pigs had higher IMF content than Landrace and Large White (Cameron, Warriss, Porter, & Enser, 1990; Smith & Pearson, 1986). However, the results of sensory evaluation varied in the literature. Wood et al. (2004) reported that LTL from Large White received a higher tenderness score than Duroc. Cameron et al. (1990) found that consumers considered LTL from Duroc to be more juicy but less tender and had less acceptable flavor than LTL from Landrace, while Lo, McLaren, McKeith, Fernando, and Novakofski (1992) reported that the sensory properties of LTL from Duroc and Landrace did not differ. The IMF content of pork in this study was lower than in previous studies (Cameron et al., 1990; Lo et al., 1992) but consistent with more recent studies in Australia (Li et al., 2024). Due to differences in genetic selection between countries, meat quality could also vary within the same breed. In addition, different farms have

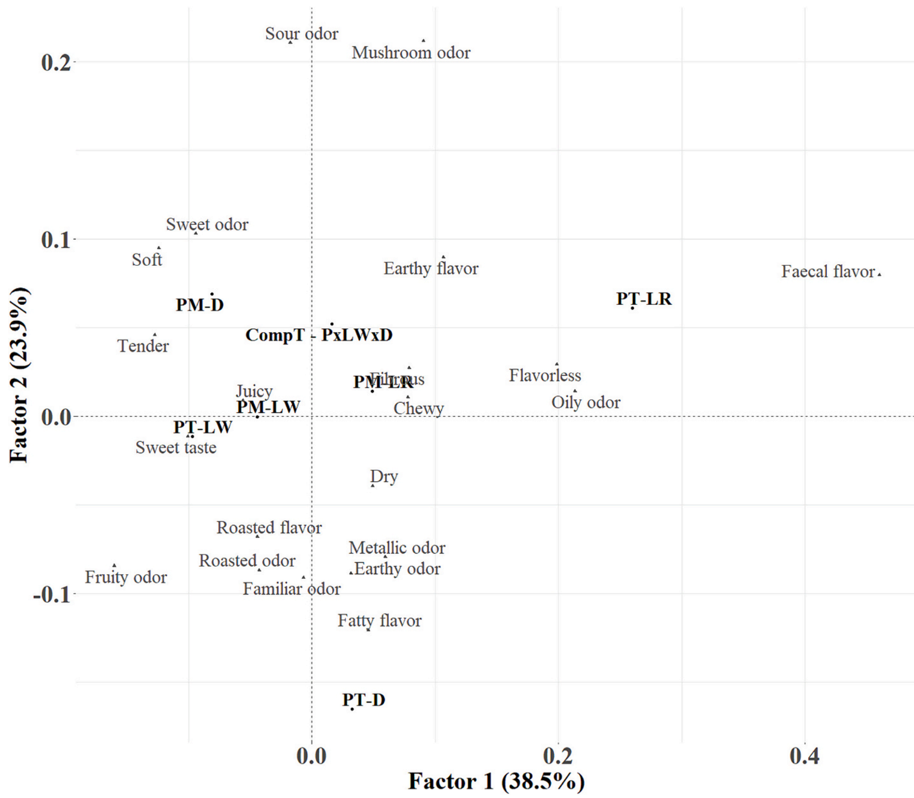


**Fig. 1.** Correspondence analysis biplot of check-all-that-apply result on different lines without outliers. PM-LR – Pure maternal, Landrace-type; PM-LW – Pure maternal, Large White-type; PM-D – Pure maternal, Duroc-type; PT-D – Pure terminal, Duroc-type; PT-LW – Pure terminal, Large White-type; PT-LR - Pure Terminal, Landrace-type; Comp-P × LW × D - Composite Terminal – Pietran × Large white × Duroc.

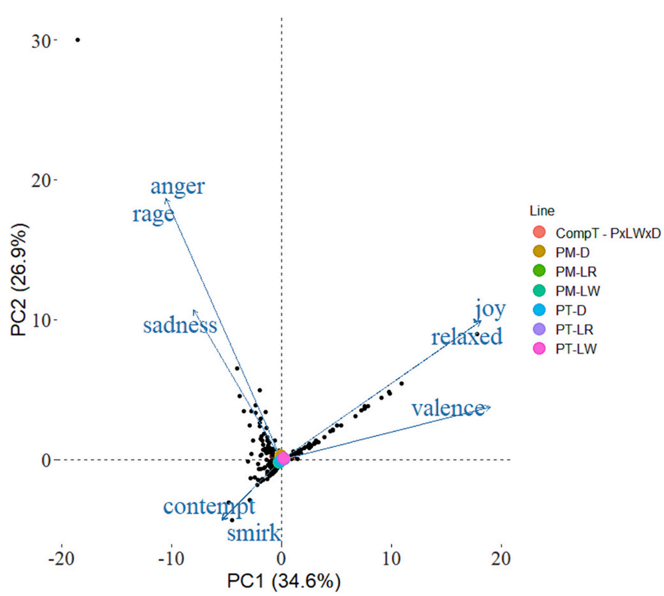


**Fig. 2.** Principal component analysis biplot of emotion of seven lines (PM-LR – Pure maternal, Landrace-type; PM-LW – Pure maternal, Large White-type; PM-D – Pure maternal, Duroc-type; PT-D – Pure terminal, Duroc-type; PT-LW – Pure terminal, Large White-type; PT-LR - Pure Terminal, Landrace-type; Comp-P × LW × D - Composite Terminal – Pietran × Large white × Duroc). Colored points represented mean points of each line.

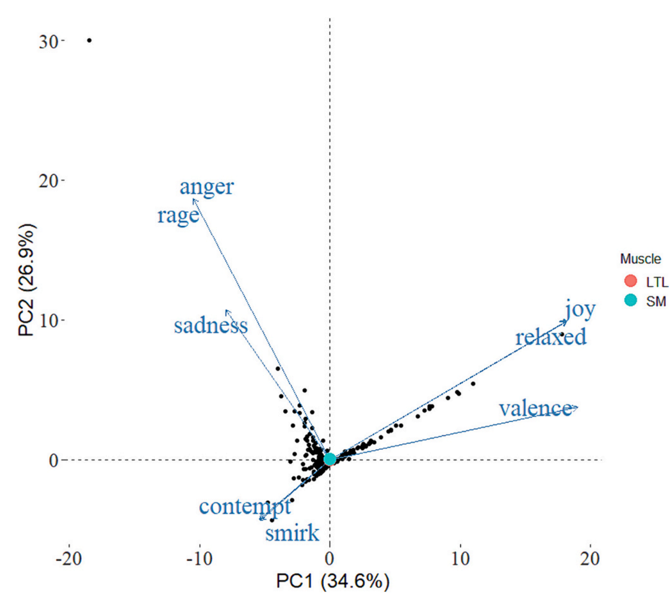


**Fig. 3.** Principle component analysis biplot of sensory attributes and emotion of *Longissimus thoracis et lumborum* (LTL) and *Semimembranosus* (SM). Colored points represented mean points of each line.

different rearing systems, leading to differences in growth rate and maturity and thus, pork eating quality among studies.

Apart from the difference between breeds, genetic selection also changed meat quality. In our previous study, which included five similar lines, line PM-LW had the lowest hardness (most tender) and was lower than that of PT-D (Li et al., 2024). In addition, all lines had higher IMF content than the present study (Li et al., 2024). Pork chemical components and eating quality changed with genetic selection. Selection for leanness could reduce IMF and tenderness (Lonergan, Huff-Lonergan,

**Table 4**
Slopes (mean ± standard error of mean) and *P*-values of sensory attributes vs chemical measurements.

| | Tenderness | | Juiciness | | Liking of flavor | | Overall liking | |
|---|---|---|---|---|---|---|---|---|
| | Slope[a] | *P*-value | Slope | *P*-value | Slope | *P*-value | Slope | *P*-value |
| pH | 28.1 ± 10.86 | **0.010** | 25.1 ± 8.89 | **0.005** | 7.59 ± 7.68 | 0.32 | 17.1 ± 8.59 | **0.048** |
| IMF (%)[b] | 2.92 ± 3.03 | 0.34 | 4.54 ± 2.45 | 0.066 | 3.09 ± 2.10 | 0.14 | 3.46 ± 2.37 | 0.15 |
| Collagen content (mg/g) | −0.72 ± 1.26 | 0.57 | −0.49 ± 1.04 | 0.64 | 1.25 ± 0.91 | 0.17 | 1.82 ± 1.01 | 0.071 |
| Collagen solubility (%) | −0.01 ± 0.33 | 0.98 | −0.04 ± 0.27 | 0.89 | 0.19 ± 0.24 | 0.43 | 0.14 ± 0.27 | 0.59 |

[a] Data was analyzed by generalized linear mixed-effect model in RStudio. Fixed factors = line + muscle + pH + IMF + collagen content + collagen solubility; Random factor = participant + carcass + session+ line + muscle.
[b] IMF = intramuscular fat.

**Table 5**
Slopes (mean ± standard error of mean) and P-values of overall liking and quality grading vs individual sensory attributes.

| | Liking of appearance | | Liking of odor | | Tenderness | | Juiciness | | Liking of flavor | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Slope[a] | *P*-value | Slope | *P*-value | Slope | *P*-value | Slope | *P*-value | Slope | *P*-value |
| Overall liking | 0.08 ± 0.02 | **<0.001** | 0.01 ± 0.02 | 0.74 | 0.23 ± 0.01 | **<0.001** | 0.10 ± 0.02 | **<0.001** | 0.65 ± 0.02 | **<0.001** |
| Probability of success (purchase intent)[b] | 0.01 ± 0.01 | 0.43 | 0.01 ± 0.01 | 0.10 | 0.04 ± 0.01 | **<0.001** | 0.03 ± 0.01 | **<0.001** | 0.11 ± 0.01 | **<0.001** |
| Quality grading[c] | 0.05 ± 0.02 | **0.029** | 0.10 ± 0.02 | **<0.001** | 0.24 ± 0.02 | **<0.001** | 0.11 ± 0.02 | **<0.001** | 0.53 ± 0.02 | **<0.001** |

[a] Data was analyzed by generalized linear mixed-effect model in RStudio. Fixed factors = appearance + odor + tenderness + juiciness + liking of flavor; Random factor = participant + carcass + session+ line + muscle.
[b] Success = participants selected 4 (I would probably buy it) and 5 (I would definitely buy it).
[c] Quality grading was on a line scale labeled unsatisfactory, good everyday, better than good everyday and premium at fixed intervals.

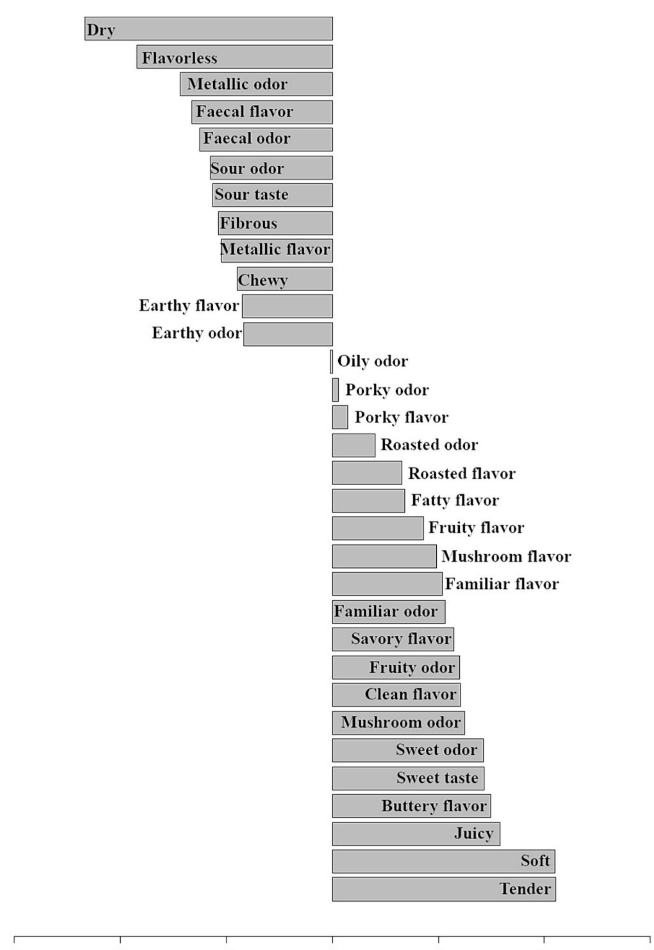


**Fig. 4.** Penalty lift analysis of check-all-that-apply terms. The unit change in overall liking scores when a CATA term is selected.

Rowe, Kuhlers, & Jungst, 2001). In addition, Schwab et al. (2006) reported that heritage Duroc pigs produced pork with higher IMF content, more pork flavor, and less off-flavor compared to contemporary pigs Contemporary Duroc pigs had been selected for increased carcass leanness to meet market and packer demands in the past decades, but meat quality and consumer acceptance was reduced. Therefore, selection for leanness is at the expense of pork quality.

In the present study, SM showed higher pH and collagen solubility than LTL, and consumers preferred it. However, the difference in pH was slight. Generally, pork LTL and SM had little difference in pH (Tomovic et al., 2014). Voutila, Mullen, Ruusunen, Troy, and Puolanne (2007) reported that collagen solubility did not differ between pork LTL and SM. This study's higher collagen solubility in SM may be related to a higher collagen turnover rate (Voutila et al., 2007). As pigs are slaughtered at a relatively young age in Australia, it is possible that muscle growth is still ongoing, and the growth rate of SM is faster than that of LTL. In addition to collagen solubility, sensory evaluation results differed from a previous study where the authors found that SM was less tender than LTL (Wheeler, Shackelford, & Koohmaraie, 2000). In this study, the LTL received higher scores in appearance and odor, likely because consumers were more familiar with this muscle. The SM was scored as more tender and juicy than the LTL, and LTL was perceived as dry, as shown in CATA. In our previous study, the SM had higher cooking loss than LTL (Li et al., 2024), leading to lower juiciness in LTL. The perception of meat juiciness and tenderness are interrelated (Liu et al., 2020). Lower scores of LTL in juiciness results in lower scores in tenderness. In addition, the SM was more flavorful than LTL. It might be caused by the higher polyunsaturated fatty acid in SM, which improves the flavor profile of pork (Purchas, Morel, Janz, & Wilkinson, 2009). Also, consumers preferred the sour taste in LTL less. Therefore, consumers preferred SM over LTL.

In the present study, pH was positively related to tenderness, juiciness, and overall liking. This result agreed with previous studies (Guignot, Touraille, Ouali, Renerre, & Monin, 1994; Richardson, Fields, Dilger, & Boler, 2018; J. A. Silva, Patarata, & Martins, 1999). One of the mechanisms for the pH effect on tenderness is that pH affects the activity of proteases, which contribute to post-mortem proteolysis (Lomiwes, Farouk, Wu, & Young, 2014). In addition, the degree of doneness is lower for meat with higher pH when cooked at the same temperature (Bouton, Harris, & Shorthose, 1971; Brewer & Novakofski, 1999). pH also affects water-holding capacity. When the pH is higher than the isoelectric point of proteins (~5.2), myofibrillar proteins have a predominance of negative charges and repel each other, allowing more water to remain in the intermyofibrillar space (Huff-Lonergan & Lonergan, 2005). Therefore, pH affects pork eating quality.

Opposite to the hypothesis, IMF and collagen had little effect on pork sensory attributes. Previous studies reported no effect (Rincker, Killefer, Ellis, Brewer, & McKeith, 2008; Wheeler, Shackelford, & Koohmaraie, 2002) or significant effects (Huff-Lonergan et al., 2002) of IMF and collagen on pork sensory attributes. The insignificant effect of IMF in the present study could be due to its low concentration in the muscle, as it was lower than that of many studies (Fernandez, Monin, Talmant, Mourot, & Lebret, 1999; Huff-Lonergan et al., 2002), possibly because we were investigating superior terminal lines, concerning carcass leanness, that are the grandparents of most market animals. Other muscle components, such as myofibrillar proteins, are more important in influencing eating quality. Therefore, IMF had little influence on eating quality in this study. For collagen, perimysium's strength decreases when cooked to above 50 °C (Christensen, Purslow, & Larsen, 2000). In the present study, the final temperature of the muscles was around 72 °C, at which the strength of myofibrillar protein was at its maximum (Christensen et al., 2000). Meat is a complex matrix. Its components can behave differently when their concentration and environment change. Therefore, more studies are needed to understand the effects of IMF and collagen on pork eating quality under different conditions.

Flavor, tenderness, and juiciness are the key sensory attributes for consumer evaluation of Australian pork. Among them, flavor is the most important sensory attributes contributing to overall liking in the present study, followed by tenderness. Similarly, Channon, D'Souza, and Dunshea (2016) reported that the slope for the liking of flavor was 0.618 and that for tenderness was 0.235 in predicting the overall liking of pork LTL, *Triceps Brachii* and *Biceps femoris*. Moeller et al. (2010) conducted a correlation analysis between sensory attributes of pork *Longissimus*, and they found that overall liking was most strongly correlated with liking flavor ($r = 0.79$), followed by tenderness liking ($r = 0.73$). Together with the results of penalty-lift analysis, it can be concluded that if the pork flavor is acceptable and pleasant, consumers will be concerned about tenderness. Appearance and odor are less important than other attributes in this study, as the cooking temperature was controlled. In contrast to pork, tenderness is the primary driver of liking in beef, while flavor is also the most important attribute in lamb, similar to pork (Miller, 2020). This also confirms that the MSA protocol is not applicable to pork. However, one limitation of this study was that there were a large portion of consumers with Asian cultural heritage, although they were all consumers of Australian pork. It will be worth to investigate the opinions of British-Australian and indigenous Australian towards Australian pork.

In this study, CATA effectively differentiated muscles and lines, whereas biometrics did not. The CATA method is a rapid and reliable method to characterize food products, and it has some applications in meat and meat products (Henrique, Deliza and Rosenthal, 2015; Jorge et al., 2015). da Silva et al. (2023) differentiated and characterized pork from pigs fed with different oil supplements using CATA. CATA can be included in future sensory evaluation of pork for the pork industry. In contrast to CATA, emotion results did not differ between muscles or lines. Torrico et al. (2018) reported a beef consumer test in which the facially expressed emotions could discriminate *Biceps femoris* (BF) stored in high oxygen modified atmosphere packaging from BF and *Psoas major* in vacuum packaging. Similarly, Mena et al. (2023) found that emotional analysis of consumers eating beef patties differentiated between younger and older consumers, and soft and hard beef patties beef patties with or without added sauce. In the present study, videos were taken when most consumers assessed odor, which had fewer differences between samples as shown by CATA (Table 3). It is recommended that consumers' emotional responses should be recorded when they are evaluating tenderness.

## 5. Conclusion

Genetic line and muscle affect pH, collagen characteristics, IMF, and pork eating quality. Line PM-D showed the highest IMF content, but consumers preferred line PT-LW. Lines from the Landrace breed received the lowest sensory scores. The SM had higher ratings in sensory evaluation than LTL, partly because of its higher pH and collagen solubility. However, collagen characteristics and IMF had little influence on pork eating quality. Flavor was the most important sensory attribute in consumer evaluation of Australian pork, followed by tenderness. The CATA method effectively differentiated between muscle and line, but the biometric approach showed a slight advantage, possibly due to the time the data was collected. Future studies can focus on breeding strategies or nutrition interventions to improve pork flavor.

## Funding

This project was funded by Australasian Pork Research Institute Limited (5A-108). Xiying Li received Dr. Albert Shimmins Fund from The University of Melbourne for writing up this manuscript.

## Author contribution

X. Li: Methodology, Data curation, Formal analysis, Writing-Original draft preparation; M. Hastie: Methodology, Validation, Writing-Reviewing and Editing; R. Warner: Validation, Writing-Reviewing and Editing; R. Hewitt: Methodology, Data curation, Formal analysis; D. D'Souza: Conceptualization, Writing- Reviewing and Editing; C. Gonzalez Viejo: Data curation, Formal analysis, Writing-Reviewing and Editing; S. Fuentes: Validation, Writing-Reviewing and Editing; M. Ha: Validation, Writing-Reviewing and Editing; F. Dunshea: Conceptualization, Writing- Reviewing and Editing.

## Consent form

Human ethics approval was obtained for the sensory studies as listed in the text, and all consumers were provided with a plain language statement and gave their information before participating in the study.

## CRediT authorship contribution statement

**Xiying Li:** Writing – original draft, Methodology, Formal analysis, Data curation. **Melindee Hastie:** Writing – review & editing, Validation, Methodology. **Robyn D. Warner:** Writing – review & editing, Validation. **Robert J.E. Hewitt:** Methodology, Formal analysis, Data curation. **Darryl N. D'Souza:** Writing – review & editing, Conceptualization. **Claudia Gonzalez Viejo:** Writing – review & editing, Formal analysis, Data curation. **Sigfredo Fuentes:** Writing – review & editing, Validation. **Minh Ha:** Writing – review & editing, Validation. **Frank R. Dunshea:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare no conflict of interest.

## Data availability

The data that has been used is confidential.

## Acknowledgment

The authors appreciate the help of Dr. Christian Davey and Dr. Graham Hepworth from the Melbourne Statistical Platform on data analysis. X. Li would like to thank Archana Abhijith, Brodie Peace, Guanqiu Huang, Huiling Huang, Huu Hieu Le, Kieren Watkins, Michelle

Le Master, Wei Gu and Yi Xu for their help in the experiments.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.meatsci.2024.109631.

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