









Carcass and meat traits from Moura pigs raised under rotational grazing in southern Brazil

Sebastião Ferreira Magagnin¹ , Meire Luiza Wirth¹ , Kaline Alessandra Lima de Sá² , Luara Karina Maccari¹ , Luana Burake² , Sandra Regina Souza Teixeira de Carvalho³ , Geisson Marcos Nardi⁴ , Juliana Sperotto Brum⁵ , Teresinha Marisa Bertol⁶ , Lucélia Hauptli³ , Marson Bruck Warpechowski^{2*} , Giustino Tribuzi⁷ 

¹ Universidade Federal de Santa Catarina, Programa de Pós-Graduação em Ciências dos Alimentos, Florianópolis, SC, Brasil.

² Universidade Federal do Paraná, Departamento de Zootecnia, Curitiba, PR, Brasil.

³ Universidade Federal de Santa Catarina, Departamento de Zootecnia e Desenvolvimento Rural, Florianópolis, SC, Brasil.

⁴ Universidade Federal de Santa Catarina, Departamento de Ciências Morfológicas, Florianópolis, SC, Brasil.

⁵ Universidade Federal do Paraná, Departamento de Medicina Veterinária, Curitiba, PR, Brasil.

⁶ EMBRAPA, Centro Nacional de Pesquisa de Suínos e Aves, Concórdia, SC, Brasil.

⁷ Universidade Federal de Santa Catarina, Departamento de Ciência e Tecnologia de Alimentos, Florianópolis, SC, Brasil.

ABSTRACT - This study aimed to characterize carcass, meat quality, sensory and textural parameters, as well as muscle fiber types from 16 Moura pigs, as a local pig raised in outdoor production system, and evaluate differences with 16 conventional commercial (CC) pigs, raised intensively, representing the principal pork type, widely available in national market. Carcass measurements, liquid loss and cooked pork texture tests, proximal composition analysis of pork and backfat, and sensory evaluations with 104 pork consumers were carried out. The statistical arrangement used was bifactorial blocks: pork type and sex (2 × 2) in two blocks. Moura pigs had greater carcass lipid deposition and intramuscular fat (IMF) (3.51 vs 1.91 g/100 g) than CC pigs (P<0.01), while CC pigs had greater lean tissue deposition and drip loss (6.44 vs. 2.88%) (P<0.01). Moura pork backfat presented a higher luminosity and lipid content and lower moisture content, and red and yellow values than CC backfat (P<0.03), while Moura pork was darker and redder than CC pork (P<0.01). Moura pork had larger relative areas of oxidative (Ia) (11.19 vs. 7.32%) and intermediate (IIa) (22.81 vs 11.70%) muscle fibers, while CC pork had higher glycolytic fibers (80.98 vs 66.00%) relative areas (P<0.01). Hardness, gumminess, and chewiness parameters from CC cooked pork had higher values than moura pork (P<0.01). Panelists preferred cooked Moura pork (72 vs. 28%) to CC pork (P<0.01). Differences in backfat characteristics between CC and Moura pork are attributed to greater lipid backfat content in Moura pork. The greater proportion of Ia and IIa muscle fibers contribute to Moura pork color, combined with a greater IMF content and less liquid loss, contributing to greater tenderness and juiciness Moura pork, preferred by consumers.

Keywords: intramuscular fat, instrumental texture, muscle fibers, sensory panel, water loss

*Corresponding author:
marson@ufpr.br

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1. Introduction

Moura pig is a lard type pig locally adapted to Southern Brazil climate and dietary conditions (Figueiredo et al., 2022). Records indicate Moura pig population growth in southern Brazil during the early 20th century, but by the late century, numbers had declined extremely (Fávero et al., 2007). The herd had reserves in research institutions and small subsistence farms. After intensive rescue efforts last decade, in 2024, there were 470 Moura pigs in reproduction herds, distributed in 64 farms, all in southern Brazil, 78% in Paraná state (Sá, 2024).

This pig is characterized by marbling, meat quality, low performance and feed efficiency (Bertol et al., 2010) and exhibits genetic differences from other local Brazilian breeds, presenting ancestry with other European pig breeds, such as Mangalitza, not only with Iberian breeds (Souza et al., 2009). The rescue and valorization of local pig breeds raised in outdoor production systems aim to supply raw materials to produce high-value-added meat products (Pugliese et al., 2013).

These breeds exhibit higher carcass fat deposition, meat marbling, and proportion of muscle fibers with oxidative metabolism compared with lean pig breeds (Huff-Lonergan et al., 2002; Lefaucheur, 2010), influencing meat physical and qualitative traits, technological aspects, and organoleptic properties (Wojtysiak and Połtowicz, 2014).

In southern Brazil, high quality pork can be produced using Moura pigs in outdoor silvopastoral grazing production areas, which feature native fruits and forage species, as well as other nutritious foods that can be produced on small farms.

A few papers (Bertol et al., 2013; Oliveira, 2016; Luz, 2019; Figueiredo et al., 2022) reported information about performance parameters, feed intake, carcass, and quality of Moura pork and their hybrids. However, there is no information on physical or technological characteristics complementary to Moura pork, such as muscle fiber types, instrumental textural profiles, and sensory assessment.

On the other hand, conventional commercial pork raised under intensive conditions is extensively sampled and studied regarding their physico-chemical characteristics and pork quality and is also widely available in the Brazilian market. For this reason, conventional commercial pork was used as a reference to evaluate carcass and meat traits from Moura pigs raised in an outdoor silvopastoral system with rotational grazing. Both porks are result of their pig breed and production system combination.

The study aimed to characterize the carcass and quality of Moura pork from animals raised in a silvopastoral production system with rotational grazing. For this, we performed a carcass characterization, pork and backfat proximal composition, muscle fiber typing, cooked pork textural profiles, sensory acceptability, and consumer preferences using as a reference conventional commercial pork, from animals raised in an intensive production system.

2. Material and methods

The animal ethics committee of the Universidade Federal do Paraná (UFPR), protocol 032/2022, approved the pig evaluations. Ethics committee for research with human beings at Universidade Federal de Santa Catarina (UFSC) approved the sensory analysis test (number 5999423).

2.1. Animals, production systems characteristics, and feed proximal composition

Thirty-two pigs were evaluated and divided into two distinct groups according to the genotype and breeding system. They were classified as pork types.

Moura pork type was from 16 purebred Moura pigs, which were raised from 15.00 kg to 140.14±10.31 kg body weight (BW) and 394.31±28.48 days at slaughter, in silvopastoral outdoor system with rotational grazing, installed at the Centro de Criação de Suínos da Raça Moura (Moura Pig Breeding Center) at the Canguiri Experimental Farm of UFPR.

The Moura pigs were rotated in the paddocks in four animals of same sex groups, with three days of occupancy time in 12.50 × 25.00 m paddocks and 30 days for re-entry. However, the experimental unit for carcass and meat traits in this study was the individual animal (n = 16 Moura pigs), 50% of them barrows and 50% gilts, slaughtered in two lots.

Two months pre-slaughter, animals consumed 2.50 kg commercial feed daily, along with fresh forage available in homogeneously cultivated pasture. The relative availability of forage species in paddocks consisted of: 88.00% Ryegrass (*Lolium multiflorum*), 5.00% Forage Turnip (*Raphanus sativus*), 5.00% Kikuyu (*Pennisetum clandestinum*), and 2.00% other forages.

Conventional commercial (CC) pork type was from 16 animals, slaughtered in the same commercial slaughterhouse as Moura porks, divided into eight animals lots of 50% gilts (n = 4) and 50% barrows (n = 4).

The pigs' genetics is composed of hybrid commercial sow (50% Landrace and 50% Large White) and commercial boars semen pool (44.92% Large White, 29.69% Pietrain; 23.44% Duroc, and 1.95% Landrace), and animals come from an intensive commercial conventional pig farm, housed indoor from 20.00 kg BW, with daily feeding of 2.50 kg of commercial feed for finishing pigs, in the pre-slaughter phase, from 90.00 kg to 115.00 kg of live weight at slaughter.

The feed formulations offered to Moura and CC pigs are shown in Table 1.

Table 1 - Animal feed formulations (in g/100 g of natural matter) offered to conventional commercial and Moura pigs

Feed raw material	Conventional commercial	Moura
Milled corn, 8.1% crude protein (CP)	80.187	81.760
Soybean meal, 45.3% CP	15.335	9.200
Meat meal, 56.1% CP	0.000	4.400
Wheat bran, 14.8% CP	0.000	2.900
L-lysine 77%	0.437	0.510
Mineral and vitamin premix ¹	3.000	0.400
Salt	0.395	0.340
Sanitizer additive ²	0.000	0.300
Mycotoxin adsorbent ³	0.000	0.100
DL-methionine 99%	0.082	0.090
Soy oil	0.564	-
Total	100.000	100.000

¹ Commercial mineral and vitamin premix provided to finishing Moura pigs with guarantee levels: vitamin A (min.), 1,667,500 IU/kg; vitamin D3 (min.), 300,000 IU/kg; vitamin E (min.), 8,750 IU/kg; vitamin K3 (min.), 131 mg/kg; vitamin B1 (min.), 250 mg/kg; vitamin B2 (min.), 1,125 mg/kg; vitamin B6 (min.), 125 mg/kg; vitamin B12 (min.), 4250 mcg/kg; folic acid (min.), 750 mg/kg; calcium pantothenate (min.), 1,850 mg/kg; choline (min.), 60 g/kg; copper (min.), 31.25 g/kg; iron (min.), 25 g/kg; manganese (min.), 10 g/kg; zinc (min.), 25 g/kg; iodine (min.), 226 mg/kg; selenium (min.), 88 mg/kg; cobalt (min.), 128 mg/kg; biotin (min.), 50 mg/kg; niacin (min.), 2,500 mg/kg; BHT, 3,750 mg/kg; BHA, 245 mg/kg.

Commercial mineral and vitamin premix provided for finishing conventional commercial pigs with guarantee levels: calcium (min.), 158 g/kg; calcium (max), 166.66 g/kg; phosphorus (min.), 15 g/kg; sodium (min.), 65 g/kg; vitamin A (min.), 126,666.6 IU/kg; vitamin D3 (min.), 36,000 IU/kg; vitamin E (min.), 500 IU/kg; vitamin K3 (min.), 35 mg/kg; vitamin B1 (min.), 23.33 mg/kg; vitamin B2 (min.), 66.66 mg/kg; vitamin B6 (min.), 33.33 mg/kg; vitamin B12 (min.), 466.66 mcg/kg; folic acid (min.), 11 mg/kg; pantothenic acid (min.), 200 mg/kg; copper (min.), 2 g/kg; iron (min.), 2 g/kg; manganese (min.), 1 g/kg; zinc (min.), 2.5 g/kg; iodine (min.), 26 mg/kg; selenium (min.), 6.6 mg/kg; biotin (min.), 2.2 mg/kg; niacin (min.), 650 mg/kg; virginiamycin, 366.66 mg/kg; phytase (min.), 16,666.66 IU/kg.

² Liquid propionic acid (7%); formaldehyde (30%); ammonia solution (5%), and water (63%).

³ Heat-treated calcium montmorillonite.

In the pre-slaughter phase, Moura and CC pigs were kept fasting for 14 hours in the slaughterhouse waiting area. Carcass and muscle samples were accessed for both pork groups 45 minutes after slaughter, and carcass, meat, and backfat were accessed 24 h after. Sampling design is presented in Figure 1.

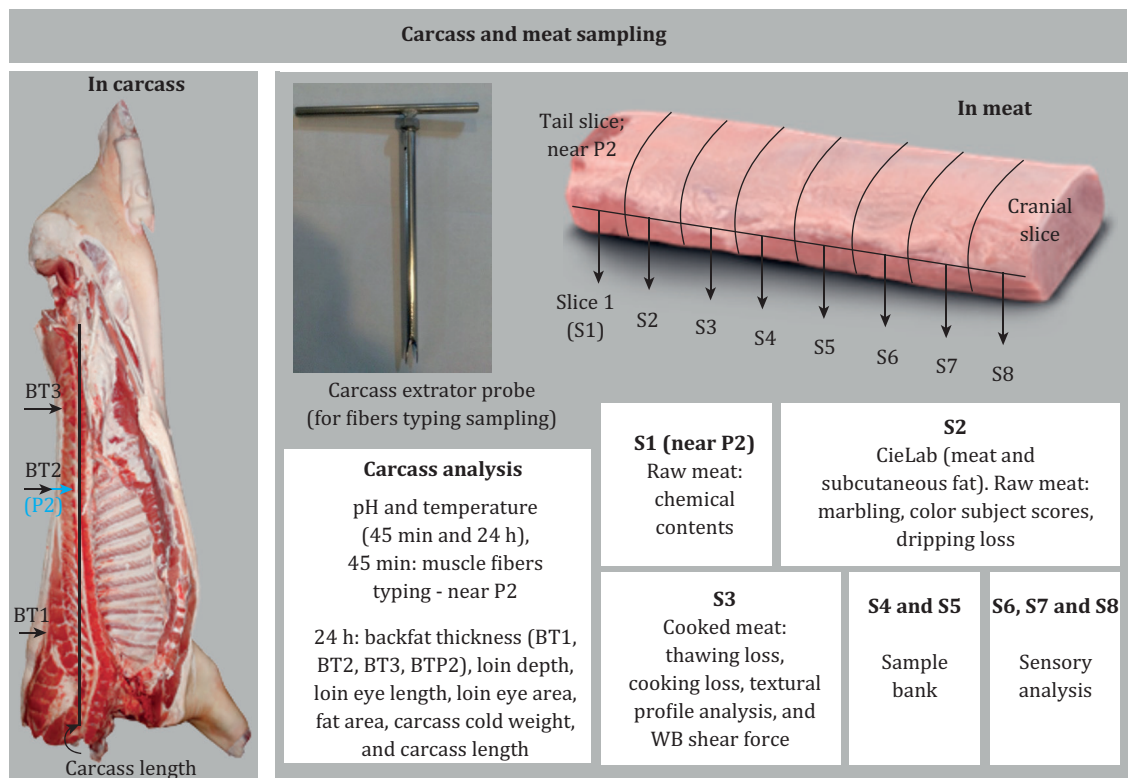


Figure 1 - Design sampling carried out in carcass and meat slices (25 mm thick). Original half carcass photography by Saudali Foods (2024).

2.2. Left half carcass measurements

The carcass parameters, measured after slaughter, are described below, based on the Brazilian carcass typification method (ABCS, 1973) and described by Bridi and Silva (2009). More information about the parameters measured in the carcass is presented in Supplementary material S1.

A pH meter (HI 99163, Hanna Instruments, Smithfield, RI, USA) was used, at 45 minutes post-slaughter, to measure pH (pH45min) and temperature (T45min) in the *Longissimus thoracis* muscle. Measurements were taken between the last thoracic rib and the first lumbar rib at a distance of 65 mm from midline, specifically at point P2. At 24 hours after slaughter, pH (pH24h) and temperature (T24h) were measured at point P2. Carcass length and backfat thickness (BT) at points 1 (BT1), 2 (BT2), and 3 (BT3) were also measured (ABCS, 1979; Luz, 2019).

After a left half carcass transverse cut was made at the junction between the last thoracic and first lumbar vertebrae, measurements were taken for BT at point P2 (BTP2), loin depth, loin eye length, and cold carcass weight (CCW). Loin eye area (LEA) and fat area were determined using a 13-megapixel cell phone camera (Samsung Galaxy A01, Samsung Electronics, Suwon, South Korea) positioned 30 cm above and parallel to the loin eye plane. A ruler in the photograph was used to establish the photo scale. Areas were delineated and measured using AutoCAD software (AutoDesk Inc., California, USA).

2.3. Meat and backfat proximal composition

The proximal composition parameters were assessed in pork: moisture (ISO 1442:1997), protein (Kjeldahl; ISO 1871:2009), ash (ISO 936:1998), and total lipids (acid hydrolysis; ISO 1443:1973); and in backfat: moisture and total lipids.

2.4. Color, shear force, textural profile analysis, and water loss measurements

A slice of the *Longissimus thoracis* (25 mm thick) was exposed for 20 minutes for color measurement using a colorimeter (Camera Minolta Ltd., Japan; D65 illuminant; 0° viewing angle; 8 mm measuring area; 11 mm diameter illumination area) based on the CIELAB system, with luminosity (L^*), red (a^*), and yellow (b^*) coordinates. Color and marbling scores were also obtained from this slice according to the NPPC (1999) graphic scale of 1-6. The slice was also used for the drip loss test on raw whole pork slice. A minimum slice weight from 80 to 100 g was suspended by an S type hook in a bottle and refrigerated from 24 to 48 hours post-slaughter, following the methodology adapted from Honikel (1997).

A slice of *Longissimus thoracis* from each animal was used to measure meat water loss during thawing and cooking. Slices were thawed for 24 hours at 4 °C, then cooked in a preheated oven (FISCHER, model 9741-15718, Brusque, SC, Brazil) at 180 °C until the center reached 70 °C, without added NaCl.

The Warner-Bratzler shear force analysis for cooked pork was performed using four replicates of 1.5 × 1.5 × 2.5 cm. Following the procedure used by Bertol et al. (2013), the samples were placed perpendicular to the direction of the muscle fibers, in a Warner-Bratzler device (TA.HD.Plus, Stable Micro Systems, Godalming, UK), equipped with a 1-mm thick inverted “V” blade. The test was conducted with samples at room temperature (23 °C), as well as textural profile analysis test.

The textural profile analysis used four replicates of 1.5 × 1.5 × 1.5 cm of cooked pork, arranged in the direction of the muscle fibers perpendicular to the compression direction of the probe and compressed to 70% of their original height (Wojtysiak and Połtowicz, 2014); the parameters were calculated according to Ramírez and Cava (2007).

2.5. Muscle fiber typing

Longissimus lumborum samples for muscle fiber type analysis were collected 45 minutes after slaughter close to point P2. A cylindrical extractor, specifically developed for this study with an 8-mm internal diameter was used for sample collection (Figure 1). Samples were frozen immediately in liquid nitrogen at -180 °C. Cross-sections of the muscle fibers were obtained by cutting the muscles at a 10- μ m thickness using a cryostat (Thermo Scientific® HM525 NX®, Walldorf, Germany). The slices were incubated at 37 °C for 40 min in a solution containing 0.08% [wt/vol] reduced nicotinamide adenine dinucleotide (NADH⁺) and 0.1% [wt/vol] nitrobluetetrazolium (Dubowitz and Brooke, 1973).

The visualization of histological sections was carried out using an Olympus BX-41 optical microscope (Evident, Tokyo, Japan) at 100X magnification, with each sample capturing four fields of 1051 × 1402 μ m. The classification of muscle fibers was based on differences in color, with red oxidative fibers (Ia) presented in dark blue, white glycolytic fibers (IIb) in light color and intermediate-metabolism fibers (IIa) intermediately in light blue. Each muscle fiber type quantity and area were determined by direct counting within each photo field (1.47 mm²), using AutoCAD 2020 software (AutoDesk Inc. California, USA). More information about how muscle fiber measurements were performed is presented in Supplementary material S2.

2.6. Meat sensory evaluation by consumer panelists

Three *Longissimus thoracis* slices were thawed for 24 hours at 4 °C, cut into cubes measuring 2.5 × 2.5 × 2.5 cm, added with 0.5% NaCl, and baked as described in item 2.4. The 104 voluntary untrained panelists reported consuming pork or pork products at least twice a week.

The sensory evaluation was conducted according to ABNT NBR ISO 8589, 2015, and ABNT NBR ISO 11136, 2016. Samples were subjected to preference and sensory acceptability tests. In the acceptability test, the samples were presented monadically, two samples, one from Moura and the other from CC pork per panelist, and evaluated using a 9-point hedonic scale with scores from 1 (extremely disliked) to 9 (extremely liked), about the following characteristics: appearance, color, aroma, flavor, texture, and

general acceptability. For the preference and purchase intention tests, the analysts chose their preferred sample and indicated their purchase intention on a 5-point scale: 1 (certainly I wouldn't purchase it) to 5 (I would certainly purchase it).

2.7. Statistical analysis

The experimental statistical model adopted in this work is a bifactorial block arrangement ($2 \times 2 \times 2 \times 4$). The two blocks consisted of slaughter lots (I and II) and different laboratory runs, which were used to enhance result accuracy. Factor A comprises the two pork types (Moura and CC), factor B comprises two sexes (barrows and gilts), and the third factor is the interaction between the two previous factors ($A \times B$), with four repetitions within each level of interaction within each block.

Moura pigs were expected to have a higher final BW, close to 140 kg, compared with CC pigs, which were expected to have around 115 kg FBW. Therefore, cold carcass weight (CCW) was included as a covariate in the data analysis to control errors in results from differences in BW of pork types. Below is the linear model description, for significative CCW covariate (Eq. 1).

$$y_{klj} = m + b_j + A_k + B_l + (AB)_{kl} + c(CCW_{klj} - \overline{CCW}) + e_{klj} \quad (1)$$

In the model, the general average of observations is denoted by m , b_j is the block effect, A_k is the effect of factor A, B_l is the effect of factor B, and $(AB)_{kl}$ is the $A \times B$ interaction effect. The linear coefficient of the covariate CCW is denoted by c , and $(CCW_{klj} - \overline{CCW})$ represents the difference between the observed value and the average CCW value; the covariate was considered in the model only in variables in which covariate weight was significant. The error is represented by e_{klj} .

Bifactor analyses were performed using the general linear model (GLM) of Statgraphic Centurion XV® 15.2.05 (Statpoint, Inc., Warrenton, VA, USA). In this software, correlation data was also obtained between the variables, and the data from the sensory panel parameters were analyzed using statistics based on the paired T Test, indicated by the ABNT NBR ISO 11136, 2016 norm.

The principal component analysis (PCA) (Statistica® 13.5.0.17, TIBCO Software Inc, Palo Alto, CA, USA) was also performed. The variables factor loadings coordinates ($x = PC1$; $y = PC2$) were unrotated and normalized for variables ($n = 15$) and supplementary variables: MO, CC, B and G. Score data (animals, $n = 32$) were also plotted. Parameters with correlation ($r > 0.50$) with pork types MO or CC were included in plotted confidence ellipses corresponding to 95% normality.

3. Results

3.1. Carcass traits and meat and backfat proximal content of Moura and CC pigs

Moura pork presented T24h value higher than CC pork ($P = 0.01$; Table 2). The values of Moura pork protein content, IMF, and marbling score were higher than those of CC pork ($P < 0.01$). The meat moisture content was higher in CC than in Moura pork ($P < 0.01$; Table 2).

Moura pork had lower moisture content in backfat than CC pork, as well as higher lipid content ($P < 0.01$) (Table 2). This result also occurred among gilts and barrows, showing that barrows had lower moisture content ($P = 0.01$) and higher lipid content ($P = 0.02$).

The values of parameters related to lipid deposition (BFT at point (1, 2, 3, and P2), fat area, marbling score, and IMF), were higher in Moura pork ($P < 0.01$) than in CC pork. The values of the parameters related to lean tissue deposition: (loin depth, loin eye length, and LEA) were higher in CC ($P < 0.01$) than in Moura pork (Table 2; Figure 2). The parameters related to lipid deposition presented correlations among themselves in the range $0.98 > r > 0.55$ ($P < 0.01$), and the parameters related to lean tissue deposition presented correlations in the range $0.92 > r > 0.47$ ($P < 0.01$), and there was a negative correlation between the lipid and lean deposition parameters in the range $-0.89 < r < -0.36$ ($P < 0.05$).

Barrows presented lower values in parameters associated with lean tissue deposition compared with gilts, mainly LEA ($P = 0.01$). However, barrows presented higher values in lipid parameters than gilts: BTP2 ($P < 0.01$), fat area ($P = 0.04$), and marbling score ($P = 0.04$) (Table 2; Figure 2).

In carcass parameters, BTP2 showed a significant interaction ($P < 0.01$), following the classification: Moura barrows (38.69 mm, A), Moura gilts (30.23 mm, B), CC barrows (8.06 mm, C), and CC gilts (8.02 mm, C).

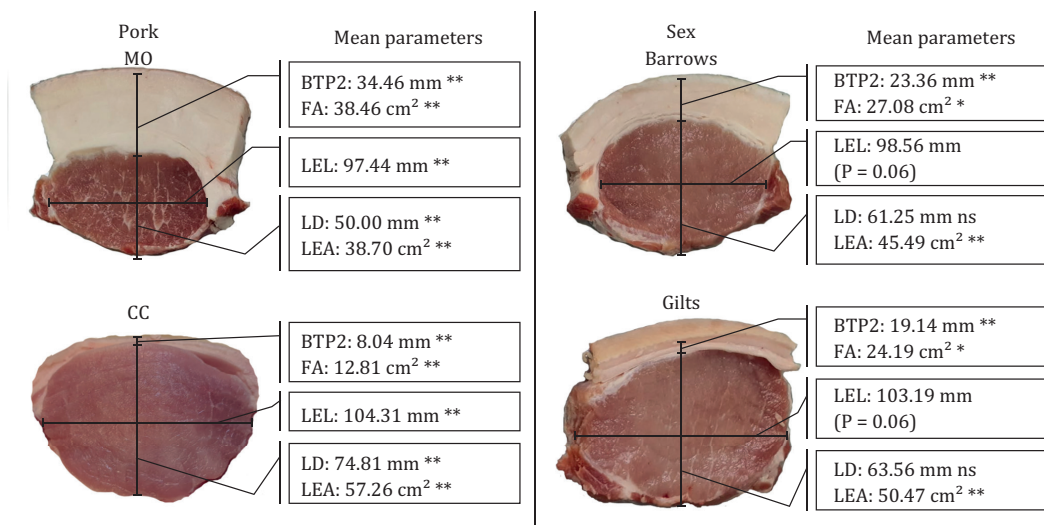
Table 2 - Least Square Means corrected by cold carcass weight (CCW) as a covariate in significant model and means of pork and carcass traits of Moura and conventional commercial (CC) pork

Parameter	Pork		Sex		RMSE	Significance ²			CCW
	CC	Moura	Gilts	Barrows		Pork (P)	Sex (S)	P × S	
pH45min	6.26	6.42	6.31	6.37	0.33	0.20	0.57	0.42	
T45min (°C)	26.37	25.58	25.91	26.04	1.18	0.07	0.77	0.12	
pH24h	5.80	5.87	5.83	5.85	0.11	0.09	0.65	0.94	
T24h (°C)	11.92	12.76	12.67	12.01	0.89	0.01*	0.04*	0.64	
CL (cm)	104.59	100.67	103.05	102.21	2.96	0.33	0.45	0.29	<0.01*
BT1 (mm) ¹	29.76	52.55	39.78	42.53	5.77	<0.01*	0.18	0.76	<0.01*
BT2 (mm) ¹	19.56	35.94	27.40	28.10	6.53	<0.01*	0.75	0.56	
BT3 (mm) ¹	8.31	38.19	22.94	23.56	5.76	<0.01*	0.76	0.90	
Marbling score ¹	1.63	2.66	1.87	2.42	0.74	<0.01*	0.04*	0.44	
Meat proximal content (g/100 g)									
Moisture	74.03	71.17	72.93	72.27	1.18	<0.01*	0.13	0.05	
Lipids-IMF ¹	1.91	3.51	2.44	2.98	0.98	<0.01*	0.14	0.34	
Minerals	1.13	1.15	1.14	1.14	0.06	0.47	0.84	0.80	
Proteins	23.33	23.77	23.50	23.60	0.85	<0.01*	0.90	0.36	0.01*
Backfat proximal content (g/100 g)									
Moisture	19.69	6.20	14.06	11.82	1.94	<0.01*	0.01*	0.28	
Lipids	69.96	91.49	79.56	81.90	2.45	<0.01*	0.02*	0.64	

CL - carcass length; BT1, BT2, and BT3 - backfat thicknesses on the mesial line of the carcass at points BT1 (on the mesial portion of the first thoracic vertebra), BT2 (between the last thoracic rib and the first lumbar rib), and BT3 (between the penultimate and last lumbar vertebra); IMF - intramuscular fat; CCW - average cold carcass weight (102.99 kg); RMSE - root mean square error.

¹ Fat parameter.

² Statistical significance: * $P < 0.05$ (significant).



CC - conventional commercial; MO - Moura.

* $P < 0.05$; ** $P < 0.01$.

Figure 2 - Graphical representation of *Longissimus thoracis* cross section at level of last rib of different pigs (Moura and CC) and sexes (barrows and gilts), with statistical information on muscle and fat deposition parameters.

3.2. Muscle fiber types, meat, and backfat color parameters

In backfat color, Moura pork presented lower yellow (b^*) and red (a^*) values compared with CC pork ($P < 0.01$), but higher luminosity (L^*) values ($P = 0.03$) (Table 3). Moura pork was darker, according to L^* value and color score, and redder than that from CC pork ($P < 0.01$).

Moura pork present greater relative quantities of intermediate muscle fibers and relative areas of oxidative and intermediate muscle fibers and lower relative quantities and areas of glycolytic muscle fibers than CC pork ($P < 0.01$; Figure 3).

A positive correlation was observed between L^* values with the quantitative proportion of glycolytic fiber (%IIb) ($r = 0.45$; $P < 0.01$) and relative proportion of glycolytic fiber area (%AIIb) ($r = 0.61$; $P < 0.01$).

In Moura pork, the cross-sectional area values for oxidative and intermediate muscle fibers were significantly higher than in CC pork ($P < 0.01$), but the cross-sectional area of glycolytic muscle fiber was not affected by pork type (Table 3). The cross-sectional area of Ia and IIa fibers presented a positive correlation with lipid deposition parameters (BTP2, fat area and IMF ($0.56 > r > 0.37$; $P < 0.04$)) and relative area of IIb fiber correlated with lean tissue parameters (loin depth, loin eye length, and LEA ($0.74 > r > 0.48$; $P < 0.01$)).

The oxidative and intermediary muscle fibers were organized in clusters between glycolytic muscle fibers (Figure 3). However, the quantity of Ia fibers/cluster ($P = 0.04$) and IIa fibers/cluster ($P < 0.01$) were higher in Moura than in CC pork.

Therefore, Moura pork presented a significantly higher total oxidative and intermediary fibers per clusters than CC pork ($P < 0.01$). Thus, the relative quantity of IIa/ mm^2 was greater in Moura pork (Figure 3).

Table 3 - Means of backfat and pork color parameters and muscle fiber typing of Moura and conventional commercial (CC) pork

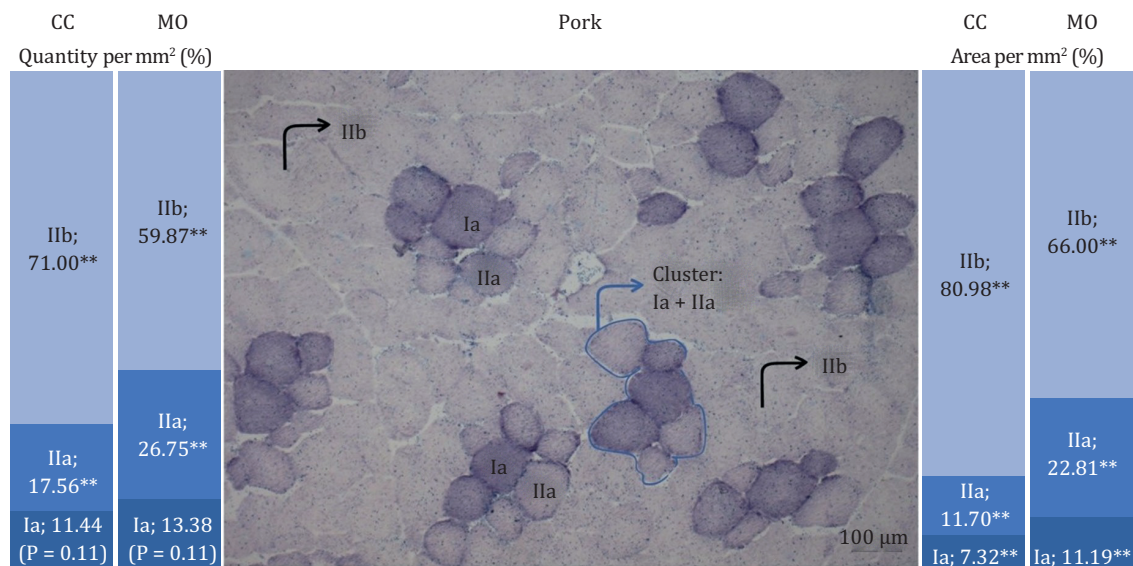
Parameter	Pork		Sex		RMSE	Significance ¹		
	CC	Moura	Gilts	Barrows		Pork (P)	Sex (S)	P × S
	Backfat							
L^*	78.73	79.37	79.62	78.48	1.44	0.03*	0.36	0.45
a^*	2.29	-0.05	0.96	1.28	0.62	<0.01*	0.56	0.05
b^*	10.47	6.63	8.64	8.46	0.90	<0.01*	0.16	0.32
	Pork							
L^*	57.34	51.33	53.99	54.68	2.98	<0.01*	0.52	0.10
a^*	1.49	3.87	2.59	2.77	1.24	<0.01*	0.68	0.33
b^*	9.75	9.41	9.41	9.75	1.22	0.43	0.44	0.25
Color score	2.52	4.24	3.42	3.34	0.50	<0.01*	0.65	0.61
	Cross-sectional area of fiber (μm^2)							
Ia (μm^2)	2709	3785	3132	3375	1055	<0.01*	0.50	0.60
IIa (μm^2)	2828	3884	3287	3425	875	<0.01*	0.66	0.99
IIb (μm^2)	4832	4954	4892	4894	1047	0.74	1.00	0.53
	Quantity per mm^2							
Fibers	245.51	231.71	237.28	239.94	46.42	0.41	0.88	0.68
Clusters	9.45	9.14	8.97	9.62	2.23	0.70	0.44	0.72
(Ia+IIa)/Cluster	7.51	10.22	8.88	8.85	1.55	<0.01*	0.94	0.26
	Muscle fibers quantity in loin eye area (n; × 1000)							
Ia	162	120	141	141	57	0.04*	0.99	0.72
IIa	245	242	243	244	79	0.93	0.98	0.25
IIb	998	532	818	712	185	<0.01*	0.12	0.38

Ia - red oxidative fiber; IIa - intermediate metabolism (oxidative-glycolytic) fiber; IIb - white glycolytic fiber; clusters - Ia and IIa fibers aggregate into clusters between fibers IIb; RMSE - root mean square error.

¹ Statistical significance: * $P < 0.05$ (significant).

On the other hand, CC pork had a higher total cluster quantity in the LEA due to their larger LEA than Moura pork ($P < 0.01$). In loin eye area, differences were observed in absolute amounts of oxidative ($P = 0.04$) and glycolytic ($P < 0.01$) muscle fibers.

Conventional commercial pork had a greater abundance of oxidative muscle fibers (+35.00%) (162,000 vs 120,000) and glycolytic muscle fibers (+87.59%) (1,007,000 vs 523,000) than Moura pork in LEA (Table 3). This agrees with the direct correlation between total oxidative ($r = 0.35$; $P = 0.04$) and glycolytic ($r = 0.83$; $P < 0.01$) muscle fibers amount in the muscle, considering LEA value.



CC - conventional commercial; MO - Moura.
** $P < 0.01$.

Figure 3 - Graphical representation of *Longissimus thoracis* muscle fibers typing and cross-section at level of last rib, with statistical information on proportions in quantity and area of oxidative (Ia), intermediate (IIa), and glycolytic (Iib) muscle fibers of pigs (Moura and CC) and statistical parameters.

3.3. Water loss and meat textural and sensory parameters

Parameters such as Warner-Bratzler shear force, hardness, cohesiveness, gumminess, and chewiness, which are indicators of texture in cooked meat, as well as drip, thawing, and cooking losses, exhibited lower values for Moura than for CC pork ($P < 0.02$) (Table 4). Regarding sex effect, on cooked meat, higher values were presented in the parameters hardness, cohesiveness, gumminess, and chewiness for gilts compared with barrows ($P < 0.02$; Table 4).

Significant and positive correlations were observed among these textural parameters (Warner-Bratzler shear force, hardness, cohesiveness, gumminess, and chewiness) in cooked meat ($0.99 > r > 0.51$; $P < 0.01$), and inverse correlations of these textural parameters with IMF ($-0.65 < r < -0.38$; $P < 0.03$). However, the correlation between IMF and cooked meat shear force ($r = -0.26$; $P = 0.14$) was not significant.

Drip loss showed a significant interaction ($P = 0.03$) with the following classification: CC barrows (7.38%, A), CC gilts (5.50%, AB), MO gilts (3.25%; AB), and Moura barrows (2.50%, B). Drip loss presented positive correlation with relative data of quantity and area of glycolytic muscle fibers (%Iib and A%Iib) and moisture content ($0.42 < r < 0.60$; $P < 0.02$) and inverse correlation with IMF, cross-sectional area of oxidative and intermediary muscle fibers, Ia relative area (%AIa), and IIa relative area (%AIIa) ($-0.58 < r < -0.34$; $P < 0.05$).

Consistent with these results, Moura pork showed lower drip loss, relative quantity and area of glycolytic muscle fibers, and moisture content than CC pork ($P < 0.01$). Considering the relationships of positive variables with drip loss and significant drip loss interaction, additionally CC barrow pork presented larger area of cross-sectional IIB fibers (+2.33%), higher moisture content (+5.29%), and lower pH24h (-1.13%) in relation to Moura barrow pork.

In cooked meat sensory analysis, the parameters texture, general acceptability ($P < 0.05$), appearance, color, purchase intention, and preference ($P < 0.01$) were statistically different. Moura pork presented higher mean scores in all hedonic scale scores than CC pork (Figure 4).

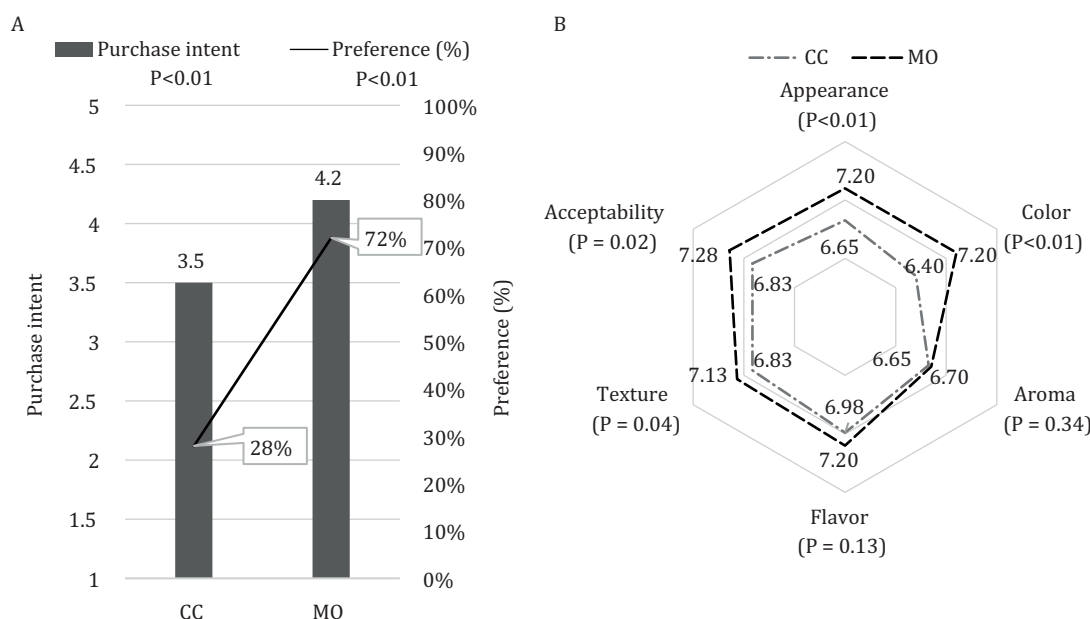
The scores for acceptability parameters, including appearance, color, aroma, flavor, texture, and general acceptability, showed positive correlations with each other ($0.87 > r > 0.40$; $P < 0.02$). Conversely,

Table 4 - Means of liquid loss parameters and textural profiles of Moura and conventional commercial (CC) pork

Parameter	Pork		Sex		RMSE	Significance ¹		
	CC	Moura	Gilts	Barrows		Pork (P)	Sex (S)	P × S
			Raw pork					
Drip loss (%)	6.44	2.88	4.38	4.94	1.59	<0.01*	0.32	0.03*
			Cooked pork					
Thawing loss (%)	8.80	5.38	7.69	6.85	2.08	<0.01*	0.26	0.66
Cooking loss (%)	41.40	38.91	40.43	39.88	1.81	<0.01*	0.40	0.53
WBSF (N)	62.55	49.04	56.59	55.01	12.31	<0.01*	0.72	0.41
Hardness (N)	327.40	239.88	313.87	253.42	59.76	<0.01*	<0.01*	1.00
Cohesiveness (%)	43.00	37.13	42.25	37.88	3.30	<0.01*	<0.01*	0.92
Springiness (%)	62.19	60.69	61.00	61.88	3.66	0.26	0.51	0.27
Gumminess (N)	143.50	92.12	133.80	101.82	31.47	<0.01*	<0.01*	0.90
Chewiness (N)	90.57	56.96	83.35	64.18	21.56	<0.01*	0.02*	0.89

WBSF - Warner-Bratzler shear force; RMSE - root mean square error.

¹ Statistical significance: * $P < 0.05$ (significant).



CC - conventional commercial; MO - Moura.

Acceptability test with sensory characteristics represented on a hedonic scale (1-9), purchase intention on a hedonic scale (1-5), and consumer preference expressed as a percentage.

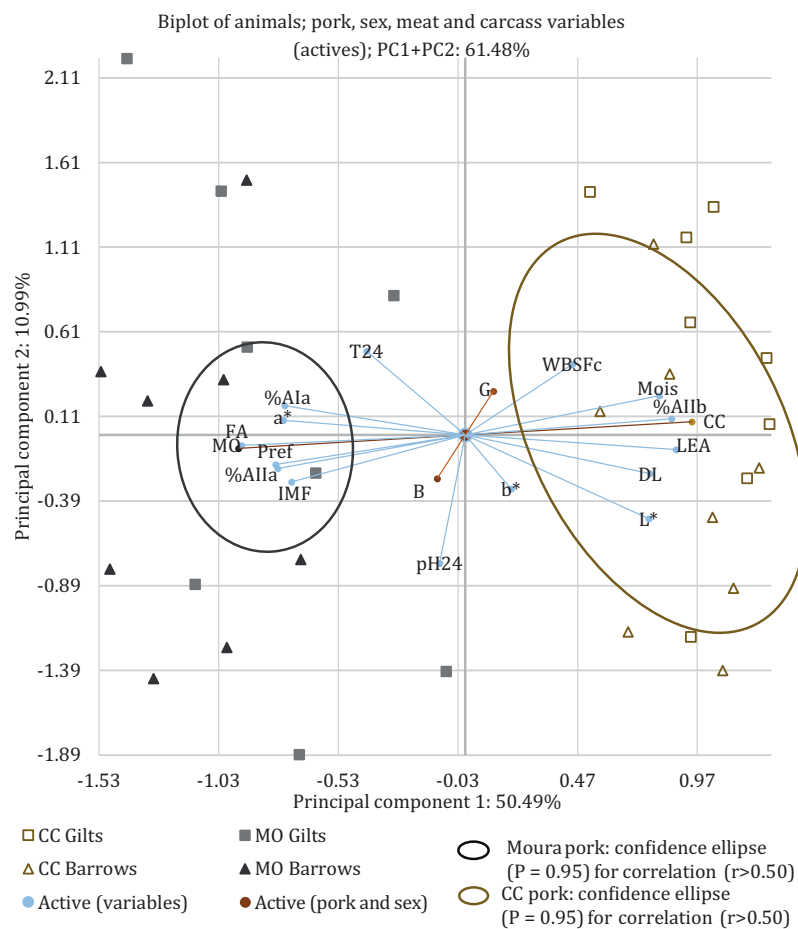
Figure 4 - Purchase intention, preference (A), and acceptability (B) sensory tests.

a negative correlation ($-0.54 < r < -0.50$; $P < 0.01$) was observed between purchase intention and preference data and textural profile analysis values such as hardness, cohesiveness, gumminess, and chewiness of cooked meat.

The sensory analysis of color evaluation is positively correlated with sum of the relative areas of oxidative and intermediary muscle fibers ($r = 0.39$; $P = 0.03$). Texture, general acceptability, and preference presented negative correlations with total quantity of glycolytic muscle fibers ($-0.68 < r < -0.4$; $P < 0.02$) and positive correlations with cross-sectional area of oxidative and intermediary muscle fibers ($0.45 > r > 0.27$; $P < 0.13$).

3.4. PCA analysis and principal correlations between pork parameters

In the PCA, two principal components (PC1 and PC2) explained 61.48% of the variation. Principal component 1 strongly and positively relates to parameters such as drip loss, moisture, relative area of glycolytic muscle fiber, cooked meat Warner-Bratzler shear force, LEA, luminosity, and the supplementary variable CC pork, while negatively relates to relative area of oxidative muscle fiber, relative area of intermediary muscle fiber, fat area, preference, a^* , IMF, and the supplementary variable MO pork. These variables form two distinct clusters, characterizing Moura and CC pork groups based on PC1, fitting in significance ellipses ($P = 0.95$) for correlations ($r > 0.5$) between the variables, aligning closely with each pork type group (Moura and CC pork; Figure 5). Additionally, the correlation values are expressed in Table 5.



CC - conventional commercial; MO - Moura.

The ellipses correspond to 95% confidence of variables correlated to pig type groups (Moura or conventional commercial; $r > 0.50$). On the plot: Case factor scores coordinates (animals = 32), variables ($n = 15$), factor coordinates and supplementary variables ($n = 4$). Pig type: Moura and CC; sex: barrows and gilts.

Figure 5 - Principal component analysis of carcass and meat characteristics.

Table 5 - Correlations among carcass parameters, pork quality, textural parameters, and panelist preference

	%AIa	%AIb	CCW	LEA	Fat area	L*	a*	IMF	Moisture	Drip loss	Thawing loss	Cooking loss	WBSFc	Hrdc	Preference
%AIa	0.57*	-0.77*	0.37*	-0.72*	0.65*	-0.62*	0.59*	0.44*	-0.51*	-0.58*	-0.51*	-0.39*	-0.31	-0.51*	0.44*
%AIb		-0.96*	0.46*	-0.57*	0.71*	-0.51*	0.67*	0.47*	-0.50*	-0.48*	-0.48*	-0.18	-0.31	-0.38*	0.55*
CCW			-0.46*	0.69*	-0.76*	0.61*	-0.71*	-0.51*	0.56*	0.57*	0.53*	0.26	0.34	0.45*	-0.57*
LEA				-0.40*	0.77*	-0.41*	0.35	0.41*	-0.68*	-0.53*	-0.48*	-0.49*	-0.23	-0.43*	0.53*
Fat area					-0.82*	0.62*	-0.62*	-0.63*	0.66*	0.65*	0.56*	0.61*	0.51*	0.54*	-0.73*
L*						-0.68*	0.69*	0.68*	-0.81*	-0.67*	-0.60*	-0.64*	-0.45*	-0.57*	0.78*
a*							-0.60*	-0.44*	0.53*	0.73*	0.47*	0.52*	0.06	0.18	-0.51*
IMF								0.48*	-0.55*	-0.45*	-0.31	-0.33	-0.25	-0.20	0.53*
Moisture									-0.82*	-0.47*	-0.22	-0.32	-0.26	-0.58*	0.61*
Drip loss										0.60*	0.46*	0.55*	0.35	0.60*	-0.72*
Thawing loss											0.58*	0.48*	0.28	0.29	-0.59*
Cooking loss												0.56*	0.46*	0.47*	-0.52*
WBSFc													0.42*	0.40*	-0.48*
Hrdc														0.72*	-0.39*
															-0.52*

%AIa - relative Ia fiber area/mm²; %AIb - relative Ib fiber area/mm²; %AIlb - relative lb fiber area/mm²; CCW - average cold carcass weight; LEA - loin eye area; L* - CIELab light; a* - CIELab redness; IMF - intramuscular fat; WBSFc - Warner-Bratzler shear force of cooked meat; Hrdc - hardness of cooked meat.

Statistical significance: * P<0.05 (significant).

4. Discussion

4.1. Carcass traits, backfat, and pork proximal content

Regarding pH_{24h}, the values obtained for Moura and CC pigs are within the normal range; according to Alonso et al. (2010), pH_{24h} for pale, soft and exudative (PSE) pork is <5.5, while for dark, firm and dry (DFD) pork it is >6.0. The values were close to those reported by Luz (2019), with 5.68 for CC pigs and ranging from 5.54 to 5.61 for Moura pigs ($P = 0.34$). In local Italian breeds, Pugliese et al. (2005) reported a pH_{24h} value of 5.78 for the Cinta Senese pig, while Fortina et al. (2005) reported 5.96 for Casertana pig and 6.15 for Mora Romagnola pig.

It was observed that Moura pork presented lower lean mass deposition and moisture tissues content, and higher overall fat deposition in carcass and fat tissue contents, such as IMF, than CC pork (Table 2), which is a typical characteristic of native pigs that contrasts with high-performance lean pigs (Franci et al., 2005; Wojtysiak and Poltowicz, 2014). This higher fat deposition resulted in a higher carcass temperature 24 h after slaughter, due to the thermal insulation effect of backfat layer, which delay carcass cooling (Savell et al., 2005).

Moura pigs presented higher meat protein content than CC pigs. Most authors have reported non-significant or lower protein content in local breeds meat compared with leaner breeds (Franci et al., 2005; Gan et al. (2019). However, in the study by Kasprzyk and Bogucka (2020), the local pig breed presented a higher protein content than commercial lean pig with a greater content of mitochondria and myoglobin protein (Fazarinc et al., 2020), showing that a variation exists within local pigs reflecting on pork quality parameters (Gan et al., 2019).

Barrows also presented lower values in carcass parameters associated with lean tissue deposition compared with gilts, as well as greater backfat thickness and higher fat content in subcutaneous tissue. This occurs because barrows do not produce testicular steroid hormones and potentially reducing muscle mass (Oliveira, 2016) and have higher feed intake (Latorre et al., 2003); thus, net energy was partitioned to increase overall lipid deposition and tissues fat content (Franci et al., 2005; Teye et al., 2006).

The BTP₂ presented significant interaction between pork type and sex. Conventional commercial pigs under restricted feeding management exhibited low and similar BTP₂ between the sexes, presenting standardized carcasses. When properly implemented with controlled energy intake and protein provision, the restricted feed management primarily restricts carcass lipid deposition (Teye et al., 2006), as the results of CC pigs in this study, indicating effective dietary restriction management.

Moura pigs' feed intake was not strictly controlled, as CC pigs. Moura pigs received 2.50 kg/day of formulated diet and had free access to pasture, leading to increased lipid deposition. This effect was particularly pronounced in barrows, which usually eat more than gilts and have less muscle deposition potential (Latorre et al., 2003; Bertol et al., 2013).

4.2. Muscle fibers types, meat and backfat color parameters

The backfat color presented by Moura pork presented higher L* value and had lower b* and a* values than CC pork. In studies by Pugliese et al. (2005) and Pugliese et al. (2013), similar results were obtained in Cinta Senese pigs raised outdoors and confined. Animals raised in outdoors system had lower a* and b* values and higher L* values than confined pigs fed a grain-based diet. Thus, the backfat color in confined pigs, characterized by higher a* and b* values, may be influenced by natural pigments present in their diet.

Martins et al. (2020) associated the backfat red color with a greater occurrence of blood microvessels. In the case of Moura pork, the lower a* value in relation to CC pigs may have resulted from the higher

amount of backfat, which could dilute red color of microvessels. Backfat L^* value is strongly linked to fat content and composition, mainly to the most abundant saturated fatty acids, such as C18:0 and C16:0 (Carrapiso and Garcia, 2005).

Moura pork was darker and redder than CC pork. Approximately 80 to 90% of meat color is attributed to the myoglobin content, which influences L^* and a^* values (Gan et al., 2019). Porks with higher L^* values are typically associated with leaner pigs that have a greater proportion of glycolytic muscle fibers. These porks contain less myoglobin and tend to have lower ultimate pH values, which promote the degradation of myofibrillar proteins and myoglobin. As a result, light absorption is reduced and L^* values increase (Huff-Lonergan et al., 2002).

The red color is directly associated with protein pigment, myoglobin, which binds oxygen to the heme group on the meat surface. Indigenous pigs typically have a higher content of myoglobin and oxidative metabolism fibers (Ia and IIa) than lean pigs (Wojtysiak and Poltowicz, 2014). According to this, Moura pork have relatively more oxidative and intermediate muscle fibers and relatively fewer glycolytic muscle fibers than CC pork. In this study, quantities and relative areas values of oxidative, intermediary, and glycolytic muscle fibers in CC pork were close to values obtained by Lebret et al. (2002) in loin muscle of lean pigs crossed with Landrace \times Large White. The relative quantity oxidative muscle fibers for Moura pork are slightly lower than the relative quantity of this muscle fiber type obtained in Bogucka et al. (2008) in loins of Duroc pigs (15.1%) and Duroc \times Wild boar crossbred (15.7%). In terms of intermediate muscle fibers, Moura pork showed values between those of Duroc (22.7%) and the Duroc \times Boar crossbreds (30.4%). Similarly, for glycolytic fibers, Moura pork also exhibited intermediate values compared with Duroc (62.2%) and Duroc \times Boar crossbreds (53.9%), as reported by Bogucka et al. (2008).

The cross-sectional area of fibers Ia and IIa were greater in Moura pork and presented a positive correlation with lipid deposition parameters. According to Lefaucheur (2010), the genetic factor is also correlated to diameter of muscle fibers, which can affect the IMF deposition, and is positively correlated with the general fat deposition. Intramuscular fat is also linked to a greater amount of relative oxidative fibers, since fat serves as a substrate for these fibers (Fazarinc et al., 2020; Fiedler et al., 2003). Other factors, such as age and production system, influence the diameter size of fibers (Ortiz et al., 2021).

Oxidative and intermediate muscle fibers are organized in clusters among glycolytic muscle fibers, as described by Zhang et al. (2017) and illustrated in Figure 3. Additionally, in this study, the total number of clusters per mm^2 and the total number of muscle fibers per mm^2 were similar across the different porks (Table 3). This structural similarity is important for muscle function, as vascularization occurs through blood capillaries located within these fiber clusters (Wojtysiak et al., 2016).

Therefore, the similar dispersion of these clusters between pork types is important to maintain muscle irrigation. Thus, the greater quantity/ mm^2 of intermediary muscle fibers in Moura pork occurs due to a greater quantity/cluster of intermediary muscle fibers.

A significantly higher proportion of glycolytic muscle fibers in LEA of CC pork, compared with that of Moura pork, supports the positive relation between relative glycolytic fiber area and lean tissue deposition. This reflects selection for leaner genotypes, which presents greater glycolytic fiber proportions and, consequently, increased carcass muscle mass (Wojtysiak and Poltowicz, 2014).

4.3. Water loss and meat textural and sensory parameters

Moura pork showed less fluid loss and greater tenderness than CC pork. The pork from lean pigs with a higher proportion of glycolytic muscle fibers usually presents lower pH_{24h} values, contributing to lower myofibril-related water retention in *rigor mortis* and greater overall water loss (Huff-Lonergan et al., 2002; Lefaucheur, 2010). These parameters also contributed to the significant interaction of the drip loss parameter, with a difference between pork from CC and MO barrows.

The post-mortem pH decline promotes sarcomere shortening and transverse myofibril shrinkage, increasing protein density and contributing to meat hardness. This compaction limits protease accessibility, thereby reducing proteolysis and impairing tenderness (Ertbjerg and Puolanne, 2017).

In addition to greater liquid loss, which affects textural parameters, lean pigs usually have low intramuscular fat levels, which also contributes to increased hardness and resistance to chewing, while IMF content helps chewing lubrication and meat tenderness (Huff-Lonergan et al., 2002; Lefaucheur, 2010). Alonso et al. (2010) observed positive correlations among the parameters shear force, hardness, cohesiveness, and chewiness ($0.81 > r > 0.53$; $P < 0.05$) of cooked pork.

The sex effect on parameters hardness, cohesiveness, gumminess, and chewiness presented lower values for barrows, which presented higher IMF content and lower drip and cooking losses, as reported by Faucitano et al. (2005), resulting in higher scores and meat tenderness.

In the sensory analysis of cooked meat, Moura pork presented higher mean scores in all hedonic scale scores than CC pork. The results are similar to those of Rodrigues and Teixeira (2014), who noted differences between black Alentejano pigs raised free-range and consuming nuts compared with commercial pigs fed a formulated diet, particularly in terms of texture, softness, and juiciness. The results were related IMF content.

The color evaluation in the sensory analysis was directly proportional to the sum of relative area of oxidative metabolism fibers (%AIa + %AIIa), which have a higher Myoglobin content than glycolytic muscle fibers (Lefaucheur, 2010). According to Suman et al. (2016), protein can interfere with the color or external appearance as a function of Maillard reaction, different states of Myoglobin, and its thermal stability during cooking. Mostly, it becomes brownish because of metmyoglobin (Lindahl et al., 2001).

4.4. Principal component analysis analysis and correlations among parameters

In the PCA, PC1 was aligned closely with each pork type (MO and CC), and significantly relationships were observed (Table 5), as previous described by Huff-Lonergan et al. (2002), in which drip loss had a significant correlation with L^* (0.33; $P < 0.01$), marbling content (-0.12 ; $P < 0.01$), and quantity of oxidative and intermediate fibers (-0.10 ; $P = 0.03$). Similar observations in pork quality were reported by Wojtysiak and Połtowicz (2014) for native pork, contrasting with lean pork.

In general, porks with higher moisture and lighter color usually lose more fluid during *rigor mortis*, due to a pH drop (Huff-Lonergan et al., 2002; Ortiz et al., 2021). During cooking, fluid loss increases as myofibrils shrink and sarcomeres shorten, leading to greater hardness (Ertbjerg and Puolanne, 2017). The consumer preference is related to IMF, which enhances flavor, chewing, tenderness, and the color is associated with oxidative fibers (Ortiz et al., 2021; Rodrigues and Teixeira, 2014).

Moura pork presents interesting quality attributes not only to be used for high added value products, but it can be used in crosses that aim to improve some meat quality characteristics, being a genetic material that deserves greater attention and importance, justifying its genetic and historical rescue.

5. Conclusions

The study reported important information about Moura pork from animals raised in an outdoor silvopastoral system with rotational grazing, regarding meat quality, muscle fiber types, raw and cooked meat texture, and consumer preferences. Moura pork presents reddish meat due to high muscle oxidative metabolism. The meat is marbled and loses little liquid, which contributes to its tenderness and greater sensory acceptance.

Moura and barrow pork presented more pronounced fat in carcass, in backfat composition, and intramuscular fat than conventional commercial and gilts pork. Moura pork has better meat quality, mainly attributed to higher quantity of intramuscular fat, oxidative and intermediate metabolism fibers, and lower drip loss, which provide more tender meat, leading to greater consumer preference over that from conventional commercial pork.

Supplementary material

The supplementary material of this article can be found online at: https://www.rbz.org.br/wp-content/uploads/articles_xml/1806-9290-rbz-54-e20240145/1806-9290-rbz-54-e20240145-suppl.zip

Data availability

The entire dataset supporting the results of this study is available upon request to the corresponding author.

Author contributions

Conceptualization: Magagnin, S. F.; Sá, K. A. L.; Carvalho, S. R. S. T.; Nardi, G. M.; Brum, J. S.; Bertol, T. M.; Hauptli, L.; Warpechowski, M. B. and Tribuzi, G. **Data curation:** Magagnin, S. F.; Wirth, M. L.; Burake, L.; Brum, J. S.; Bertol, T. M.; Hauptli, L.; Warpechowski, M. B. and Tribuzi, G. **Formal analysis:** Magagnin, S. F.; Wirth, M. L.; Sá, K. A. L.; Maccari, L. K.; Burake, L.; Brum, J. S.; Hauptli, L.; Warpechowski, M. B. and Tribuzi, G. **Funding acquisition:** Magagnin, S. F.; Warpechowski, M. B. and Tribuzi, G. **Investigation:** Magagnin, S. F.; Wirth, M. L.; Sá, K. A. L.; Maccari, L. K.; Burake, L.; Carvalho, S. R. S. T.; Nardi, G. M.; Brum, J. S.; Bertol, T. M.; Hauptli, L.; Warpechowski, M. B. and Tribuzi, G. **Methodology:** Magagnin, S. F.; Wirth, M. L.; Sá, K. A. L.; Maccari, L. K.; Burake, L.; Carvalho, S. R. S. T.; Nardi, G. M.; Brum, J. S.; Bertol, T. M.; Hauptli, L.; Warpechowski, M. B. and Tribuzi, G. **Project administration:** Magagnin, S. F.; Warpechowski, M. B. and Tribuzi, G. **Resources:** Magagnin, S. F.; Wirth, M. L.; Sá, K. A. L.; Maccari, L. K.; Burake, L.; Carvalho, S. R. S. T.; Nardi, G. M.; Brum, J. S.; Bertol, T. M.; Hauptli, L.; Warpechowski, M. B. and Tribuzi, G. **Software:** Magagnin, S. F.; Wirth, M. L.; Hauptli, L.; Warpechowski, M. B. and Tribuzi, G. **Supervision:** Magagnin, S. F.; Hauptli, L.; Warpechowski, M. B. and Tribuzi, G. **Validation:** Magagnin, S. F.; Wirth, M. L.; Sá, K. A. L.; Brum, J. S.; Bertol, T. M.; Hauptli, L.; Warpechowski, M. B. and Tribuzi, G. **Visualization:** Magagnin, S. F.; Wirth, M. L.; Sá, K. A. L.; Maccari, L. K.; Burake, L.; Carvalho, S. R. S. T.; Nardi, G. M.; Brum, J. S.; Bertol, T. M.; Hauptli, L.; Warpechowski, M. B. and Tribuzi, G. **Writing – original draft:** Magagnin, S. F.; Hauptli, L.; Warpechowski, M. B. and Tribuzi, G. **Writing – review & editing:** Magagnin, S. F.; Wirth, M. L.; Sá, K. A. L.; Maccari, L. K.; Burake, L.; Carvalho, S. R. S. T.; Nardi, G. M.; Brum, J. S.; Bertol, T. M.; Hauptli, L.; Warpechowski, M. B. and Tribuzi, G.

Conflict of interest

The authors declare no conflict of interest.

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Declaration of generative AI in scientific writing

An AI tool (Chat GPT Open AI) was used to improve the English language in some parts of the manuscript. However, the text was carefully revised to ensure that no errors were introduced by the use of the AI tool.

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