Agr. Nat. Resour. 60 (2026) 600108

AGRICULTURE AND
NATURAL RESOURCES

Journal homepage: http://anres.kasetsart.org

Research article

Qualitative characteristics of carcass, meat and subcutaneous fat of commercial heavy pigs raised indoors and outdoors

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Article Info

Article history:
Received 22 July 2025
Revised 24 November 2025
Accepted 21 December 2025
Available online 28 February 2026

Keywords:
Carcass,
Fatty acids,
Lard,
Meat,
Pig commercial hybrids

Abstract

Importance of the work: Usually, heavy commercial pigs are raised indoors, with limited information available on the meat and fat characteristics in such animals reared outdoors.

Objectives: To examine how the farming system (FS; outdoors versus indoors) and sex affect the carcass, meat and lard characteristics in heavy commercial pigs.

Materials and Methods: In total, 24 animals, 10 barrows and 14 gilts (Italian Duroc × TalentTopigs crossed with Landrace × Large White) were reared in two sex-balanced FS groups under a factorial experimental design (with FS and sex as fixed factors). The pigs were slaughtered when they had reached the standard hot carcass weight for heavy-pig production. Meat characteristics were assessed in the *longissimus lumborum* muscle and the lard was analyzed for its proximate and fatty acid (FA) profile.

Results: Rearing pigs outdoors resulted in slower growth than those raised indoors, with a lower percentage of lean carcass mass (48.8% versus 51.1%, respectively; $p = 0.05$) and a redder meat (3.66 versus 2.19, respectively; $p < 0.01$) which tended to be tougher (35.9 N versus. 31.2 N, respectively; $p = 0.06$), due to the lower soluble collagen content (34.0% versus 43.5%, respectively; $p = 0.03$). However, the lard of the outdoors pigs had a lower saturated FA content than for the indoor-raised pigs (41.13% versus 42.43%, respectively; $p = 0.04$). Gilts had loins and lard with higher polyunsaturated FA contents than the barrows (20.51% versus 19.11%, respectively; $p = 0.01$).

Main finding: Both sex and FS impacted the nutritional and technological characteristics of carcass, meat and lard of the pigs. Outdoor farming improved the lard nutritional quality but produced firmer, darker meat and a lower carcass yield. The lard analysis provided insights for developing niche markets, underlining the importance of the production method in meat and fat quality.

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https://doi.org/10.34044/j.anres.2026.60.1.08

Introduction

Heavy pig breeding is important for obtaining typical or Protected Designation of Origin (PDO) products in several European countries such as Italy, France and Poland; specifically, in Italy, 93% of slaughtered pigs have an average weight of 156 kg (ISTAT, 2024) and about 79% are heavy pigs for PDO production (Associazione nazionale allevatori suini, 2023). To meet the required quality characteristics, PDO cured hams come from females or barrows and meet specific requirements in terms of the pig live weight or a minimum subcutaneous fat thickness of the thighs (Vegni et al., 2023). The genetic improvement program of commercial breeds, such as Duroc, Large White, Landrace and especially their hybrids, has contributed to the achievement of high-quality standards of meat and cured ham (Pagliarini et al., 2015), so that today most of heavy pig herds are composed of these breeds (Schwalm et al., 2013).

Usually, intensive farming systems are adopted for heavy-pig production to optimize production and standardize fattening procedures (Salogni et al., 2022). However, consumers are becoming increasingly sensitive to issues, such as food safety, environmental impact and animal welfare, which are often associated with intensive production systems. Consequently, outdoor pig farming has begun to spread to meet consumer demand for meat quality and good animal welfare (Russo et al., 2007). Outdoor production not only improves animal welfare (EFSA, 2022) but also reduces antibiotic use (EFSA, 2021), thereby enhancing consumer acceptance. Indeed, Ludwiczak et al. (2023) reported a higher willingness to pay and greater hedonic liking for extensive production systems and welfare-labelled pork than for conventional products, even though extensification may face practical challenges. However, pork quality is a multifaceted concept, shaped by factors along the entire production chain and perceived differently depending on perspective. Consumers tend to focus on visual traits and sensory attributes, such as taste, tenderness and juiciness, which are closely linked to technological and scientific parameters such as pH, water-holding capacity, texture and colour (Edwards, 2005; Lebret et al., 2011). The results have been far from consistent from alternative rearing systems considering carcass and meat quality. For example, Stern et al. (2023) highlighted improvements in traits, such as lean meat content and shear force, whereas others have reported less favorable carcass characteristics and technological properties, including higher drip loss, darker color and increased shear force (Olsson et al., 2003; Edwards, 2005). Despite the often-contradictory results, many studies have been conducted on the effect of the rearing system on pork quality (Lebret et al., 2002; Heyer et al., 2006; Adbullah, 2023); however, few have considered heavy pigs and these focused mainly on rustic/local breeds (Trombetta et al., 2009; Ncogo Nchama et al., 2023). Therefore, although extensive farming systems are unlikely to meet global demand on their own, they may attract consumers concerned with sustainability, animal welfare and production efficiency, offering a promising market for meat products aligned with modern preferences and willingness to pay (Giannetto et al., 2023).

The hypothesis underlying the current study was that an outdoor production system could improve carcass characteristics, meat and lard quality in heavy pigs, taking into account the sex. Therefore, the purpose of this study was to investigate the effect of indoor and outdoor farming systems and sex on the carcass, meat and lard quality characteristics of heavy pigs belonging to a commercial hybrid.

Materials and Methods

Ethics Statement

The study was conducted in a commercial farm in Palmanova, Italy and in accordance with EU Directive 2010/63/EU. Since the procedures adopted were routine, no formal approval was required.

Animals, housing and feeding

In total, 24 (14 gilts and 10 barrows) commercial hybrid pigs (Italian Duroc × TalentTopigs crossed with Landrace × Large White) aged approximatively 7 mth and 115 kg live weight were assigned randomly to two farming systems (housed indoors = IN and outdoors = OUT) balanced by sex. The IN group was housed in slatted pens in a temperature-controlled environment, with 2 m^2 per pig and enrichment materials, while the OUT group was reared outdoors in a 2 ha paddock with 0.012 ha of shelter. The OUT trial took place April–October and the average temperature was 19°C. The diet for all the experimental pigs consisted of pelleted feed including hulled sunflower seed meal, wheat, wheat bran, hulled soybean meal, maize, wheat middling, sorghum, wheat bran, sugar cane molasses, calcium carbonate, animal fat (melting point< 40°C) and sodium chloride.

The chemical composition of the diet was: dry matter (DM; 87.3%); ashes 5.08% DM; neutral detergent fibre (NDF) 14.82% DM; ether extract 4.06% DM; crude protein 16.35% DM; and estimated digestible energy 13.1 MJ/kg. Animals had *ad libitum* access to feed and water, with all animals being slaughtered when they had reached a commercial live weight corresponding to 180 kg hot carcass weight.

Measurements and sampling

After a 12 hr fasting period, the animals were slaughtered in an EC-licensed slaughterhouse using electrical stunning. The slaughterhouse was located on the farm. At 45 min after slaughter, the pH values of *gluteus medius* m. and *semimembranous* m. were measured using an HI 8424 pH-meter (Hanna Instruments; Padovana, Italy) equipped with a pH 52-32 probe (Crison Instruments; Barcelona, Spain) and the hot carcass weight included the weight of the head, but not the offal. Carcass characteristics, such as thickness of the *gluteus medius* m. and subcutaneous fat and estimated lean meat, were assessed following the ZP (Zwei- Punkt) -measuring method as reported by Ncogo Nchama et al. (2023). Samples of *longissimus lumborum* m. and the corresponding subcutaneous fat (lard) were collected and stored at 4°C.

At 24 hr after slaughter, muscle and adipose tissues were separated and cleaned. The lard was divided into two parts (inner and outer), as reported by Ncogo Nchama et al. (2023). Subsequently, three samples were analyzed for each animal: loin, inner lard and outer lard. The ultimate pH (pHu) was measured in all samples, as described above. Color was measured on the muscle and fat after 30 min blooming (Commission International De l'Eclairage, 2018) in agreement with Ncogo Nchama et al. (2023), as well as drip loss, cooking loss and shear force. Samples intended for chemical composition, lipid oxidation in meat and gas-chromatographic analyses were frozen at –20°C.

The carcasses were stored at 4°C. Then, at 5 d after slaughter, samples of *longissimus lumborum* m. were collected to further evaluate the lipid oxidation in meat.

Chemical analysis

The methods of Association of Official Analytical Chemists (2016) were followed for the determination of DM, ashes, crude protein and ether extract using about 100 g of loin. DM, ashes and lipids were determined for the lard (inner and outer). The total hydroxyproline (HPro) content in muscle was determined using a Hydroxyproline Assay Kit (Cat. N. MAK008; Sigma-Aldrich; St. Luis, MO, USA). The total collagen content in the meat was estimated by multiplying the HPro content by a factor of 7.25 (Goll et al., 1963). The insoluble collagen was extracted according to Palka (1999). Lipid oxidation in the meat was determined based on measuring thiobarbituric acid and reactive substances (TBARS), following the method described by Siu and Draper (1978), with some modifications. In particular, loins were thawed overnight at 4 ± 2°C; then, 2.5 g of minced samples were homogenized (Ultra Turrax T-25; IKA Werkec; Taufkirchen, DE, EU) in a 50 mL centrifuge tube with 12.5 mL of distilled water, with the samples kept in an ice bath to avoid any further oxidation. Next, 12.5 mL of trichloroacetic acid (10%) was added to precipitate any proteins. Each sample was centrifuged (Mod. 6k-15; Sigma; Osterode am Harz, DE, EU) at 4°C and 2,000 revolutions per minute for 20 min. Then, the supernatant was passed through Whatman filter paper N°541, with 4 mL of the filtrate being pipetted into a 15 mL screw-capped Pyrex tube containing 1 mL of 2-thiobarbituric acid (TBA) 0.06 M. The solution was swirled and incubated for 90 min in hot water (80°C) for color development. Then, each sample was cooled under tap water and the absorbance was measured at 532 nm using an ultraviolet/visible spectrophotometer (Mod. UV-2501PC; Shimadzu; IL, USA. Each sample was analyzed in duplicate. For each trial, a couple of blanks were prepared with 2 mL of distilled water + 2 mL of 10% trichloroacetic acid+ 1 mL of TBA 0.06M. The milligrams of malonaldehyde (MDA) per kilogram of meat were calculated based on interpolation from the calibration line ($y = 3.4061x – 0.0174$) using 1,1,3,3,-tetraethoxypropane as the standard.

Lipid extraction and fatty acid (FA) analysis of the lard were performed as reported by Pianezze et al. (2021) and Ncogo Nchama et al. (2022), respectively. Briefly, FA methyl esters were obtained using methanolic HCl via the trans-esterification of triglycerides. The FA was quantified using gas chromatography-mass spectrometry analyses performed in EI mode (70 eV) using a 5977E MSD system with a nonpolar stationary phase (5%-phenyl) methylpolysiloxane and an HP-5ms column (length 30 m, inner diameter, film thickness 0.25 mm; Agilent Technologies; Santa Clara, CA, USA). C21:0 was used as the internal standard and the FAs were identified using the National Institute of Standards and Technologies Mass Spectral Library (https://www.nist.gov/).

Cholesterol analysis was performed based on direct saponification in KOH, as reported by Ncogo Nchama et al. (2023).

Statistical analysis

Data were analyzed using the SPSS software (version 17; SPSS Inc.; Chicago, IL, USA) and R (version 4.5.1; R Core Team, 2025). Data normality was assessed using the Shapiro-Wilk test. Data on carcass, meat composition and oxidative stability of the loin (analyzed within aging time) were processed using to a bi-factorial experimental design, evaluating the fixed effect of the "farming system" (outdoors versus indoors) and sex (gilts versus barrows). In addition, the interaction of farming system × sex was considered. Lard composition data were processed according to a general linear model for repeated measures, evaluating the effect of the "layer" factor (inner versus outer) as within subjects and the effects of farming system and sex as between subjects. All the interactions between factors were considered. If the interaction between two factors were significant, the main effects were not interpreted separately. *Post hoc* comparisons were conducted between the marginal means of experimental groups, with correction for multiple comparisons (Tukey's test). A similar model was also adopted for the *postmortem* pH, with $p \leq 0.05$ and $0.05 \leq p \leq 0.10$ were considered significant and as a tendency towards significance, respectively. Data were reported as estimated marginal mean ± SE values.

Results

The slaughter age was higher for the outdoor-farmed animals than for the indoor animals (13.5 ± 0.4 versus 11.3 ± 0.4 months; $p < 0.01$; Table 1). The carcass characteristics of the pigs are shown in Table 1. The estimated lean meat percentage was higher for IN than OUT pigs (51.1 ± 0.8 versus 48.9 ± 0.8; $p = 0.050$). In addition, there was a trend toward significance for the difference related to subcutaneous fat thickness, which was greater in the OUT than in the IN pigs (32 ± 1.6 versus 28 ± 1.6 mm; $p = 0.077$). In contrast, sex did not influence carcass characteristics ($p > 0.05$).

Table 1 Estimated marginal means of carcass and meat characteristics of pigs reared under outdoor (OUT) or indoor (IN) systems.

	Within pig factor (WPF)	Farming system (FS)		Sex		SE	*p* value						
		OUT	IN	Gilts	Barrows		FS	Sex	FS × Sex	WPF	FS × WPF	Sex × WPF	FS × Sex × WPF
Age (mth)		13.5	11.3	12.3	12.5	0.27	0.000	0.699	0.630				
Carcass characteristics (Zwei Punkten method)													
Subcutaneous fat thickness (mm)		32	28	28	31	1.14	0.077	0.241	0.409				
Muscle thickness (mm)		88	89	90	87	1.17	0.775	0.178	0.232				
Estimated lean meat *(%)		48.9	51.1	50.8	49.1	0.54	0.050	0.133	0.496				
pH *gluteus medius*	6.23	6.15	6.02	6.08	6.09	0.045	0.146	0.986	0.102	0.000	0.764	0.860	0.848
45min *semimembranousus*	5.94												
Longissimus lumborum													
pHu		5.36	5.36	5.36	5.35	0.021	0.943	0.819	0.519				
L*		49.89	50.00	49.61	50.28	1.019	0.957	0.746	0.117				
a*		3.66	2.19	3.02	2.83	0.203	0.002	0.645	0.459				
b*		13.55	12.89	13.18	13.26	0.264	0.224	0.886	0.225				
Drip loss (%)		7.01	6.97	7.29	6.70	0.396	0.963	0.466	0.904				
Cooking loss (%)		26.1	27.7	26.7	27.2	0.67	0.242	0.715	0.369				
WBSF (N)		35.9	31.2	34.8	32.3	1.19	0.058	0.306	0.534				
Water (%)		71.0	71.4	71.8	70.6	0.271	0.488	0.039	0.213				
Ash (%)		1.12	1.12	1.12	1.11	0.008	0.956	0.400	0.245				
Crude protein (%)		22.25	22.99	22.8	22.5	0.150	0.022	0.302	0.881				
Total collagen (mg/g)		3.21	2.92	3.02	3.11	0.065	0.034	0.510	0.102				
Soluble collagen (% total)		34.0	43.5	35.3	42.2	2.034	0.031	0.108	0.356				
Lipids (%)		4.75	3.99	3.54	5.20	0.315	0.245	0.016	0.309				
Cholesterol (mg/g)		0.750	0.822	0.778	0.794	0.01	0.000	0.366	0.043				

Estimated lean meat = 57.7975 - 0.5126 x1 + 0.0834 x2, where x1 = subcutaneous fat thickness, x2 = muscle thickness; pHu = pH after 24 hr; L* = lightness; a*, = red index; b* = yellow index; WBSF = Warner-Bratzler shear force.

$p \leq 0.05$ and $0.05 \leq p \leq 0.10$ considered significant and tendency toward significance, respectively.

The meat characteristics of the pigs are shown in Table 1. The pH at 45 min after slaughter was higher in the *gluteus medius* than in the *semimembranousus* m. (6.23 ± 0.06 versus 5.94 ± 0.05; $p < 0.001$; Table 1). The OUT group had higher redness (a*; 3.66 ± 0.29 versus 2.19 ± 0.29; $p = 0.002$) and tended to have a higher Warner-Bratzler shear force (WBSF) than the IN group (35.9 ± 1.9 versus 31.2 ± 1.9N; $p = 0.058$). The lipid content was similar between the IN and OUT groups ($p = 0.245$); however, the crude protein content was higher in the IN than the OUT group (22.99 ± 0.21 versus 22.25 ± 0.21%; $p = 0.022$). The total collagen (3.21 ± 0.09 versus 2.92 ± 0.09 mg/g; $p = 0.034$) and soluble collagen (34.0 ± 2.9 versus 43.5 ± 0.1%total; $p = 0.031$) contents of the loin were significantly higher and lower in the OUT than the IN group, respectively. The cholesterol content of the loin showed a significant interaction effect ($p = 0.043$) between farming system and sex, with the highest value being for the "barrows indoors reared" group (with a mean value of 0.811 mg/g). Considering the effect of sex, the meat of the barrows compared to the gilts had a lower water content (70.6 ± 0.4 versus 71.8 ± 0.4%; $p = 0.039$), but a higher lipid content (5.20 ± 0.48 versus 3.54 ± 0.41%; $p = 0.016$).

Considering the lipid oxidation in the meat, there was no significant difference between the IN and OUT groups for MDA values at 1 d after slaughter ($p = 0.089$); however, the values were significantly higher 5 d after slaughter (0.432 ± 0.019 versus 0.377 ± 0.019 mg/kg flesh; $p = 0.050$; Table 2). In contrast, there was no effect of sex ($p > 0.05$; Table 2).

The chemical composition of the lard is shown in Table 3. The farming system did not influence the chemical composition of lard ($p > 0.05$); however, the inner layer had a higher DM (93.0 ± 0.3 versus 92.3±0.3%; $p = 0.003$) and lower lipid (72.8 ± 0.6 versus 77.3 ± 1.3%; $p = 0.003$) contents than the outer layer. The triple interaction, FS × sex × layer, was significant for cholesterol (Fig. 1). Barrows had a DM content of lard that was significantly higher than that of gilts (93.25 ± 0.35 versus 92.05 ± 0.29; $p = 0.016$).

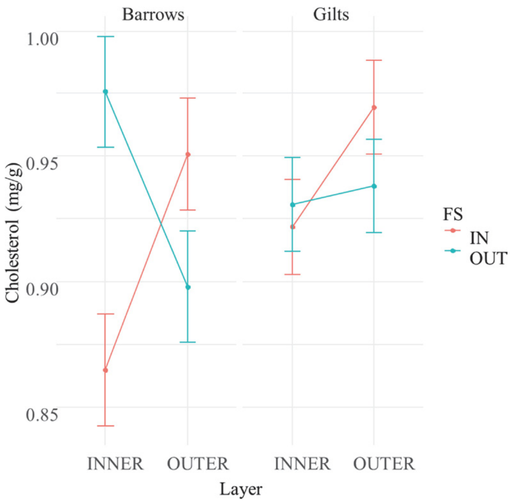

Fig. 1 Three-way interaction plot, layer × sex × farming system (FS) of cholesterol in lard of pigs for IN, pigs reared indoors and OUT pigs reared outdoors, where INNER = inner lard layer and OUTER = outer lard layer and error bars = SE.

Table 2 Effect of farming system and sex on lipid oxidation in loin of pigs reared in indoor (IN) and outdoor (OUT) systems, presented as estimated marginal means of malonaldehyde content (mg/kg flesh).

	Farming system (FS)		Sex		SE	p value		
	OUT	IN	Gilts	Barrows		FS	Sex	FS×Sex
Days after slaughter								
1	0.321	0.360	0.354	0.327	0.0109	0.089	0.237	0.145
5	0.377	0.432	0.420	0.389	0.0132	0.050	0.255	0.275

$p < 0.05$ and $0.05 < p \leq 0.10$ considered significant and tendency toward significance, respectively.

Table 3 Estimated marginal means of chemical composition of lard of gilts and barrows pigs reared under outdoor (OUT) or indoor (IN) systems.

		Layer	Farming system (FS)		Sex		SE	p value						
			OUT	IN	Gilts	Barrows		FS	Sex	FS× Sex	Layer	FS× Layer	Sex× Layer	FS×Sex ×Layer
DM (%)	Inner layer	93.0	93.0	92.3	92.05	93.25	0.227	0.186	0.016	0.346	0.003	0.655	0.266	0.934
	Outer layer	92.3												
Ash (%)	Inner layer	0.062	0.066	0.061	0.073	0.055	0.0072	0.705	0.229	0.954	0.768	0.988	0.669	0.035
	Outer layer	0.065												
Lipids (%)	Inner layer	72.8	76.2	73.9	74.7	75.4	0.720	0.121	0.670	0.328	0.003	0.275	0.892	0.380
	Outer layer	77.3												
Cholesterol (mg/g)	Inner layer	0.923	0.936	0.927	0.940	0.922	0.0087	0.613	0.317	0.262	0.161	0.000	0.291	0.010
	Outer layer	0.939												

DM = dry matter.

$p < 0.05$ and $0.05 < p \leq 0.10$ considered significant and a tendency toward significance, respectively.

The FA composition of lard is reported in Table 4. The OUT pigs tended to have a lower C18:0 content than the IN pigs (16.21 ± 0.34 versus 17.21 ± 0.34%; $p = 0.051$). Notably, at least numerically, in the C18:1n-9/ C18:0 ratio tended to be higher in the subcutaneous back fat of OUT pigs than for the IN pigs (2.04 versus 1.85; $p > 0.10$). Consequently, the OUT group had a lower SFA content than the IN pigs (41.13 ± 0.41 versus 42.43 ± 0.41%; $p = 0.037$). In contrast, the C18:2n-6 and C18:3n-3 contents were similar between the OUT and IN pigs ($p > 0.05$).

Table 4 Estimated marginal means of fatty acid (FA) composition (g/100 g of total FA) of lard of gilts and barrows pigs reared under outdoor (OUT) or indoor (IN) systems, with FAs detected at < 0.1 g/100 g of total FA not reported.

	Layer		Farming system (FS)		Sex		SEM	*p* value						
			OUT	IN	Gilts	Barrows		FS	Sex	FS×Sex	Layer	FS× Layer	Sex× Layer	FS×Sex × Layer
C10:0	Inner	0.08	0.07	0.08	0.08	0.087	0.0018	0.001	0.951	0.335	0.307	0.476	0.186	0.272
	Outer	0.08												
C12:0	Inner	0.09	0.09	0.09	0.09	0.09	0.0024	0.442	0.258	0.305	0.171	0.180	0.345	0.262
	Outer	0.08												
C14:0	Inner	1.67	1.63	1.70	1.66	1.67	0.018	0.099	0.899	0.099	0.350	0.884	0.851	0.441
	Outer	1.66												
C15:1	Inner	0.05	0.05	0.05	0.06	0.05	0.0014	0.823	0.024	0.571	0.000	0.197	0.668	0.578
	Outer	0.06												
C16:0	Inner	23.25	22.51	22.71	22.50	22.72	0.099	0.341	0.263	0.744	0.000	0.198	0.396	0.366
	Outer	21.97												
C16:1n-7	Inner	0.44	0.49	0.45	0.50	0.44	0.010	0.076	0.004	0.499	0.000	0.379	0.651	0.540
	Outer	0.50												
C16:1n-9	Inner	1.74	1.74	1.76	1.76	1.74	0.043	0.812	0.793	0.647	0.574	0.007	0.560	0.419
	Outer	1.76												
C17:0	Inner	0.30	0.33	0.33	0.34	0.31	0.008	0.991	0.071	0.414	0.000	0.157	0.855	0.252
	Outer	0.35												
C17:1	Inner	0.23	0.26	0.25	0.27	0.25	0.005	0.353	0.122	0.207	0.000	0.069	0.386	0.967
	Outer	0.28												
C18:0	Inner	17.75	16.21	17.22	16.25	17.18	0.242	0.051	0.070	0.980	0.000	0.103	0.886	0.975
	Outer	15.68												
C18:1n-9	Inner	32.11	33.15	31.81	32.36	32.60	0.213	0.005	0.586	0.942	0.001	0.031	0.451	0.700
	Outer	32.86												
C18:1n-7	Inner	2.08	2.17	2.13	2.13	2.16	0.046	0.661	0.725	0.595	0.078	0.582	0.618	0.876
	Outer	2.22												
C18:2n-6	Inner	15.57	16.54	16.50	17.08	15.97	0.201	0.932	0.012	0.765	0.000	0.150	0.789	0.770
	Outer	17.48												
C20:0	Inner	0.32	0.29	0.31	0.29	0.31	0.010	0.213	0.340	0.441	0.001	0.923	0.794	0.493
	Outer	0.28												
C18:3n-6	Inner	0.00	0.03	0.01	0.02	0.02	0.0021	0.013	0.461	0.544	0.000	0.013	0.461	0.544
	Outer	0.04												
C18:3n-3	Inner	1.10	1.20	1.21	1.24	1.17	0.024	0.853	0.132	0.681	0.000	0.419	0.794	0.632
	Outer	1.30												
C20:1n-9	Inner	1.28	1.24	1.26	1.21	1.30	0.039	0.734	0.266	0.731	0.027	0.131	0.551	0.933
	Outer	1.22												
C20:2	Inner	1.05	1.11	1.11	1.12	1.10	0.025	0.962	0.717	0.826	0.000	0.534	0.228	0.843
	Outer	1.17												
C20:3n-6	Inner	0.13	0.12	0.16	0.16	0.12	0.008	0.021	0.032	0.478	0.216	0.126	0.291	0.303
	Outer	0.15												
C20:3n-3	Inner	0.21	0.21	0.23	0.23	0.21	0.008	0.229	0.294	0.204	0.279	0.226	0.169	0.335
	Outer	0.23												
C20:4n-6	Inner	0.29	0.37	0.32	0.39	0.30	0.036	0.532	0.242	0.406	0.121	0.316	0.501	0.312
	Outer	0.40												
C22:4n-6	Inner	0.19	0.12	0.21	0.18	0.15	0.015	0.007	0.260	0.369	0.108	0.031	0.460	0.495
	Outer	0.14												

Table 4 Continued

	Layer		Farming system (FS)		Sex		SEM	p value						
			OUT	IN	Gilts	Barrows		FS	Sex	FS×Sex	Layer	FS× Layer	Sex× Layer	FS×Sex × Layer
C22:5n-3	Inner	0.07	0.08	0.09	0.09	0.08	0.0061	0.284	0.351	0.888	0.002	0.608	0.454	0.835
	Outer	0.10												
Σ SFA	Inner	43.47	41.13	42.43	41.21	42.36	0.291	0.037	0.062	0.808	0.000	0.089	0.764	0.626
	Outer	40.10												
Σ MUFA	Inner	37.93	39.10	37.72	38.29	38.54	0.246	0.011	0.618	0.981	0.000	0.029	0.630	0.772
	Outer	38.89												
Σ PUFA n-6	Inner	17.22	18.28	18.32	18.95	17.65	0.223	0.934	0.009	0.765	0.000	0.587	0.836	0.852
	Outer	19.38												
Σ PUFA n-3	Inner	1.38	1.48	1.53	1.56	1.45	0.030	0.479	0.096	0.952	0.000	0.897	0.829	0.879
	Outer	1.63												
Σ PUFA	Inner	18.60	19.77	19.85	20.51	19.11	0.250	0.873	0.011	0.796	0.000	0.642	0.877	0.853
	Outer	21.01												

SFA = saturated FA; MUFA = monounsaturated FA; PUFA = polyunsaturated FA.
$p < 0.05$ and $0.05 < p \leq 0.10$ considered significant and tendency toward significance, respectively.

Considering sex, there were significant differences for the polyunsaturated FA (PUFA), with the total PUFA (20.51 ± 0.32 versus 19.11 ± 0.38%; $p = 0.011$) and the PUFA n-6 present to a greater extent (18.95 ± 0.29 versus 17.65 ± 0.34%; $p = 0.009$) in gilts than in the barrows. Conversely, the level of SFA tended to be higher in the barrows than in the gilts (42.36 ± 0.44 versus 41.21 ± 0.38%; $p = 0.062$).

The differences in FA between the two layers were all highly significant ($p < 0.01$). In particular, the inner layer had a greater presence of SFA (43.47 ± 0.32 versus 40.10 ± 0.31%; $p < 0.001$), while PUFA (for both the n-3 and n-6 series) were present to a lesser extent in the inner layer than in the outer layer (18.60 ± 0.31 versus 21.01 ± 0.25%; $p < 0.001$). Considering individual FAs, among the SFAs, C16:0 (23.25 ± 0.12 versus 21.97 ± 0.10%; $p < 0.001$) C18:0 (17.75 ± 0.26 versus 15.68 ± 0.25%; $p < 0.001$) and C20:0 (0.32 ± 0.01 versus 0.28 ± 0.01%; $p = 0.001$) followed the overall trend of the SFAs and therefore were mainly present in the inner layer of the lard. Among the MUFAs, C18:1n-9 was more present in the outer than the inner layer of lard ($p < 0.01$); however, there was also a significant interaction farming system × layer ($p < 0.05$). Among the PUFAs, the highest were in the outer layer: C18:2n-6 (17.48 ± 0.19 versus 15.57 ± 0.25%; $p < 0.001$) and the n-3 series acids, C18:3n-3 (1.30 ± 0.02 versus 1.10 ± 0.03%; $p < 0.001$) and C22:5n-3 (0.10 ± 0.01 versus 0.07 ± 0.01%; $p = 0.002$), as well as C20:2 (1.17 ± 0.03 versus 1.05 ± 0.03%; $p < 0.001$).

Discussion

Carcass and meat characteristics

The current aimed to evaluate the effect of the raising system on the qualitative characteristics of the carcass, meat and subcutaneous fat of commercial heavy pigs, where animals were slaughtered at similar target weights. This criterion was supported by the established literature indicating that physiological maturity, in terms of carcass composition and fat deposition, was more closely correlated with live weight and carcass weight than with chronological age (Malgwi et al., 2021). The OUT pigs reached the target slaughter weight later than the IN pigs. This difference could be explained by the longer time required in outdoor conditions, where there is a greater energy expenditure by the animals, to reach suitable slaughter weight. Therefore, the adopted approach confounded the effect of age with the farming system. However, it provided a more physiological and valid comparison of the final commercial product. Therefore, the resulting age difference between systems was considered an integral component of the overall system's effect on the production cycle duration and growth rate (Malgwi et al., 2021). Trombetta et al. (2009) reported a lower growth rate and higher energy expenditure in Large White × Duroc crosses reared outdoors compared to indoor animals. Regarding the age effect, Latorre et al. (2003b) found that as the age increased, the intramuscular fat content, a* value and color intensity of the muscle also increased. Furthermore, Guo et al. (2022)

found that with increased slaughter age, there were significant increases in the dressing percentage, eye muscle area, backfat deposit, muscle yellowness (b* value), drip loss and cooking loss. Conversely, Virgili et al. (2003) reported that pigs slaughtered at age 10 mth had lower drip and cooking losses than those slaughtered at age 8 mth. Additionally, Franco et al. (2016) and Guo et al. (2022) reported decreases in the muscle pH measured 45 min *postmortem*, as well as reductions in loin L* and dorsal fat L* values in older pigs. Furthermore, increasing the slaughter age enhanced the proportions of PUFA n-3 and crude protein, while decreasing the PUFA n-6/n-3 ratio and the overall antioxidant capacity (Guo et al., 2022).

Considering carcass characteristics, the estimated lean meat percentage was higher in the IN than the OUT group, which was in agreement with Lebret (2008) but contrasted other reports (Stern et al., 2003; Trombetta et al., 2009; Maiorano et al., 2013b). Furthermore, in the current study, there was a trend toward significance for the difference in subcutaneous fat thickness between the outdoor and indoor farming systems. This difference may have been due to both an adaptation to lower winter temperatures and to a higher degree of maturity of the animals that may have resulted in a carcass richer in fat and poorer in muscle. The current results were in agreement with those reported by Lebret (2008) in his review, but contrasted with Maiorano et al. (2013b) in Polish Landrace pigs and Serrano et al. (2008b) in Iberian pigs. Thus, it would appear that the thickness of subcutaneous fat, similar to that of lean meat, varies considerably depending on the genetics considered, the diet and the breeding environment.

Based on the current results, the pH at 45 min after slaughter was higher in *gluteus medius* m. than in *semimembranousus* m., probably due to the difference in fiber composition. However, the ultimate pH was within the normal range reported by Stanišić et al. (2016). Meat color is an important quality attribute for the consumer (Listrat et al., 2016). In the current study, the OUT pigs had higher redness (a*) values than the IN pigs, which could be explained by the greater physical activity of the OUT pigs which might have had a greater amount of type I fibers and therefore a greater deposition of myoglobin in the muscle (Shorthose and Harris, 1991; Olsson and Pickova, 2005). Another important quality attribute for the consumer is tenderness (Mao et al., 2025). In the current study, WBSF tended to be higher in the OUT pigs than the IN pigs. Differences in toughness may have been caused by various factors, such as differences in fiber type proportions, sarcomere length, pH, temperature, fat, connective tissue characteristics and tenderization rate (Vaskoska et al., 2020). A slower daily growth rate may cause slower protein turnover in the muscles of more extensively raised animals. Indeed, it has been debated whether such slow protein turnover, rather than a similar lipid content between experimental groups, can explain tougher meat (Wood and Warriss, 1992). Considering the meat composition, based on the current results, the crude protein content was higher in the IN pigs than the OUT pigs. Although the mean value was in line with that reported in other studies, conflicting results were found regarding the effect of the farming system (Trombetta et al., 2009; Maiorano et al., 2013b). The higher total collagen and lower soluble collagen observed in the OUT animals may help to explain the differences in WBSF. Given that collagen provides structural and supportive functions within muscle architecture, the greater total collagen content could be associated with the increased physical activity of the OUT animals (Petersen et al., 1997; Abdullah et al., 2023). In contrast, the cholesterol levels in the inner lard layer from the OUT-reared pigs were higher than those in the IN-reared pigs (Fig.1). In animals with the same genetic background, the observed variations in cholesterol levels are complex and difficult to interpret, as they may result from a combination of environmental factors, rearing conditions, metabolic differences and individual physiological responses (Maiorano et al., 2013a; Faria et al., 2015). For example, cholesterol may originate from dietary intake or be synthesized endogenously by the animal (Argemí-Armengol et al., 2020). Thus, the differences observed in the current study were likely related to variations in metabolism influenced by both sex and physical activity. The mean cholesterol content among the pigs was 0.786 mg/g of meat, in line with the values found by Faria et al. (2015), but higher than reported by Jacyno et al. (2006) and Maiorano et al. (2013a). Considering the sex effect, based on the current results, the water and lipid contents of the meat were higher and lower, respectively, in gilts than in the barrows. These results were related to the different hormonal conditions between the two experimental groups, with higher level of estrogen in the female that could have favored greater water retention in the tissues. These results were consistent with several authors (Latorre et al., 2003a, 2003b; Peinado et al., 2008; Serrano et al., 2008a; 2008b). On the other hand, the hormonal state of castrated animals leads to an accumulation of fat in muscle (Zomeño et al., 2023).

It is well known how lipid oxidation can lead to major quality degradation in pork (Domínguez et al., 2019). However, the effects of farming system on meat lipid oxidation are contradictory (Martino et al., 2014; Abdullah et al., 2023).

For example, Abdullah et al. (2023) explained how the mechanism of lipid oxidation was complex and related to the balance of action between pro-oxidant and anti-oxidant factors, with many factors possibly playing a role, including diet, sex and genetic type. Indeed, as reported by Ali et al. (2021) an important role may be played by antioxidant-acting compounds present in pasture such as α-tocopherols and vitamins. In the current study, all animals consumed the same diet. The tendentially or significantly higher levels of MDA found in the IN group compared to the OUT group were in agreement with the findings of Andrés et al. (2001) and those of Nevrkla et al. (2021) who explained how increased physical activity was favorable in controlling oxidative mechanisms in muscle and the production of reactive species. Improved oxidative stability enhances meat resistance to rancidity and spoilage (Reitznerová et al., 2023), thereby prolonging shelf life and reinforcing potential health benefits for consumers.

Chemical and fatty acid composition of lard and lumbar subcutaneous fat

As explained above, in the current study, the farming system did not influence the chemical composition of the lard; however, the inner layer had higher DM and lower lipid contents than the outer layer. The outer layer develops early, while the inner layer develops later (Fortin, 1986); therefore, this difference in lipid content could depend on the age/growth stage of the animals; however, this did not seem to be sufficient to create a difference between the IN and OUT animals. A higher water content in gilts tissues previously discussed could explain the higher DM content of lard observed in barrows.

The pig, being a monogastric species, is susceptible to changes in the FA composition of adipose tissue based on the diet (Wood, 1984; Kloareg et al., 2007). Since C18:2n-6 and C18:3n-3 are of dietary origin only, the similar diets used may explain the lack of differences observed in the two farming systems for these FAs. However, body fat accumulation can be considered the net result of the balance between dietary absorbed fat, endogenous fat synthesis (lipogenesis) and fat catabolism through beta-oxidation (lipolysis), with C18:0 being synthesized *de-novo* by the elongation of short FAs (De Smet al., 2004). Conversely, C18:1n-9 can result from the action of delta-9 desaturase on stearic acid (C18:0) Yu et al., 2023). In line with the current results, Rey et al. (2006) reported an increased presence of C18:1n-9 in free-range Iberian pigs. Therefore, in the current study, the observed difference in C18:0 could be explained by the higher physical exercise of the OUT pigs which increased delta-9 desaturase activity (Kouba et al., 1997) and may have decreased lipogenic enzyme activity (Fiebig et al., 1998). Environmental temperature is another factor influencing FA composition (Lebret, 2008), where (in agreement with the current results) lower temperatures increasing unsaturated FA, mainly MUFA (Tomažin et al., 2019).

Considering sex, there were significant differences for PUFA, with total PUFA and PUFA n-6 present to a greater extent in the gilts than the barrows. The literature is conflicting regarding the influence of a pig's sex on the FA composition of lard. For example, Serrano et al. (2009) did not observe any gender influence on the FA composition of subcutaneous backfat from Duroc × Iberian heavy pigs. On the other hand, in agreement with the results of the current study, Cordero et al. (2010) reported that the fat of gilts was less saturated than that of males. Conversely, the level of SFA tended to be higher in the barrows pigs than in the gilts. Considering that the barrowas had a numerically higher subcutaneous fat thickness, this result was in agreement with the findings of other authors (Barton-Gade, 1987; Franci et al., 2005) who highlighted that increases in backfat were positively correlated with SFA content.

The differences in FA between the two layers were all highly significant. In particular, the inner layer had a higher level of SFA and lower levels of PUFA than the outer layer. In agreement with the current results, several authors have reported that in pig fat deposits, there was a degree of unsaturation that decreased from the outside towards the inside (Lopez-Bote et al., 2002; Daza et al., 2007; Apple et al., 2009). The fact that the outer layer had a higher percentage of unsaturated FA means that, at colder environmental temperatures, it could maintain greater fluidity than the inner layers, which are richer in saturated fats (Monziols et al., 2007). Considering individual FAs, C16:0, C18:0 and C20:0, the current results were largely consistent with those of other authors, such as Rey et al. (2006). Notably, there were differences in C18:2n-6 and in C18:3n-3 and its n-3 series derivative, C22:5n-3, as well as in C20:2. In general, the outer layer plays an important role in thermal insulation, while the two layers might have different energy metabolism in terms of FA deposition and mobilization (Mersmann and Leymaster, 1984; Abadía et al., 2008; Minelli et al., 2016).

Consumer relevance of findings

The findings of the current study confirmed that outdoor rearing influenced both the nutritional and sensory attributes of pork, with several potential advantages for consumers. The higher PUFA content observed in the outdoor pigs is particularly relevant, as it has been associated with lower atherogenic, thrombogenic and peroxidability indices (Szyndler-Nędza et al., 2021), suggesting that pork from outdoor systems may provide health benefits compared to meat from intensively reared pigs. In addition, as suggested by Szyndler-Nędza et al. (2021), the higher fat content could improve sensory attributes by acting as a carrier for flavor and enhancing juiciness, thus contributing to a distinctive eating quality that may appeal to niche markets. Outdoor rearing was linked to lower levels of MDA, an indicator of lipid oxidation, suggesting greater oxidative stability. This improved stability enhances meat resistance to rancidity and spoilage (Reitznerová et al., 2023), a benefit often correlated with higher antioxidant intake and physical activity. Consequently, meat shelf life is extended and potential health advantages for consumers are reinforced.

From a sensory standpoint, outdoor pigs had a higher redness (a*) in meat, an attribute strongly associated with freshness and quality at the point of purchase. This effect was due largely to increased physical activity, which stimulated myoglobin deposition in the muscle (Corlett et al., 2021).

Furthermore, exposure to natural environmental conditions, such as lower temperatures, higher levels of physical activity and the possibility to express natural behaviors, positively influenced both the fat composition and muscle quality. These factors align with consumer expectations of outdoor systems as more "natural" and "traditional", thereby adding to the product's secondary quality attributes (Edwards, 2005).

Overall, the findings from the current study indicated that outdoor rearing enhanced both the nutritional quality and the sensory appeal of pork, although they also highlighted trade-offs in carcass yield and tenderness that need to be addressed. Notably, the positive nutritional attributes and consumer perceptions associated with outdoor production may compensate for these limitations, particularly in markets where ethical and health-related concerns strongly influence purchasing choices.

Conclusions

The outdoor farming system resulted in pigs with carcasses with a lower percentage of lean meat, probably due to the higher energy expenditure of the animals. On the other hand, the subcutaneous fat layer tended to be greater, probably due to exposure to external temperatures. Considering the physical characteristics, the outdoor farming system resulted in a redder meat color and tended to produce meat with greater resistance to cutting (hardness)—characteristics that are a consequence of increased physical exercise. The meat of the outdoor pigs had lower protein and soluble collagen contents, while the total collagen content was higher. Furthermore, the meat of the outdoor pigs had higher oxidative stability, although this result was statistically significant only after 5 d of aging. Regarding the FA composition of lard, animals farmed outdoors had a lower SFA content than those reared indoors. It seems that outdoor farming led to better nutritional characteristics of the lard but with a worsening of the sensory characteristics of the meat (redder and harder) as well as a lower carcass meat yield. The effect of sex was limited and mainly related to the lipid content of the meat (being higher in the castrated pigs) and to the level of PUFA in the lard (higher in the gilts).

Future research should aim to clarify how the conditions of outdoor rearing can be optimized to balance the nutritional benefits of meat and fat composition with improvements in sensory quality and carcass yield. Furthermore, consumer-oriented studies are needed to evaluate how the trade-off between nutritional advantages and sensory characteristics affects consumer acceptance and willingness to pay for pork from outdoor systems. Such insights would provide valuable guidance for aligning production practices with market expectations and for promoting outdoor pork as a differentiated, high-value product.

Further research, including a larger number of animals and different genetic types, will need to be conducted to further confirm the effect of outdoor versus indoor systems.

Conflict of interest

The authors declare that there are no conflicts of interest.

Acknowledgements

Mr. Stefano Calligaris provided access to *In Cortile-Salumeria Agricola Friulana* (In the Courtyard—Friulian Farmhouse Delicatessen), where the pigs were raised and slaughtered. This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

References

Abadía, S., Mendizabal, J., Alfonso, L. 2008. Relationship between depth of individual backfat layers and size of their constituent adipocytes in sows. *Acta Agric. Scand. A Anim. Sci*. 58: 161–163. doi.org/10.1080/09064700802415702.

Abdullah, F.A.A., Trnková, M., Dordevic, D. 2023. Physiochemical properties and oxidation status of pork from three rearing systems (organic, conventional and traditional). Appl. Sci. 13: 9131. doi.org/10.3390/app13179731.

Ali, O., Petrási, Z., Donkó, T., Fébel, H., Mézes, M., Szabó, A. 2021. Muscle fibre membrane lipid composition in musculus biceps femoris of pigs reared in indoor or outdoor systems. J. Anim. Feed Sci. 30: 328–347. doi.org/10.22358/jafs/139275/2021.

Associazione nazionale allevatori suini. 2023. [National Association of Pig Breeders]. www.anas.it, 24 October 2024.

Andrés, A.I., Cava, R., Mayoral, A.I., Tejeda, JF., Morcuende, D., Ruiz, J. 2001. Oxidative stability and fatty acid composition of pig muscles as affected by rearing system, crossbreeding and metabolic type of muscle fibre. Meat Sci. 59: 39–47. doi.org/10.1016/s0309-1740(01)00050-x.

Association of Official Analytical Chemists. 2016. Association of Official Analytical Chemists. Official Methods of Analysis of AOAC International, 20th ed. AOAC International. Rockville. MD, USA.

Apple, J.K., Maxwell, C.V., Galloway, D.L., Hamilton, C.R., Yancey, J.W.S. 2009. Interactive effects of dietary fat source and slaughter weight in growing-finishing swine: II. Fatty acid composition of subcutaneous fat. J. Anim. Sci. 87: 1423–1440. doi.org/10.2527/jas.2008-1455.

Argemí-Armengol, I., Villalba, D., Tor, M., Betolín, J.R., Latorre, M.A., Álvarez-Rodríguez, J. 2020. Effect of dietary roughage on organic pig performance, behaviour and antioxidant accretion in perirenal adipose tissue. Livest. Sci. 241: 104255. doi.org/10.1016/j.livsci.2020.104255.

Barton-Gade, P.A. 1987. Meat and fat quality in boars, castrates and gilts. Livest. Prod. Sci. 16: 187–196. doi.org/10.1016/0301-6226(87)90019-4.

Commission International De l'Eclairage. 2018. Commission International De l'Eclairage. Colorimetry, 4th ed. Vienna, Austria.

Cordero, G., Isabel, B., Menoyo, D., Daza, A., Morales, J., Piñeiro, C., Lopez-Bote, C.J. 2010. Dietary CLA supplementation and gender modify fatty acid composition of subcutaneous and intramuscular fat in Iberian × Duroc finishing heavy pigs. Span. J. Agric. Res. 8: 962–970.

Corlett, M.T., Pethick, D.W., Kelman, K.R., Jacob, R.H., Gardner, G.E. 2021. Consumer perceptions of meat redness were strongly influenced by storage and display times. Foods. 10: 540. doi.org/10.3390/foods10030540.

Daza, A., Ruiz-Carrascal, J., Olivares, A., Menoyo, D., López-Bote, C.J. 2007. Fatty acids profile of the subcutaneous backfat layers from Iberian pigs raised under free-range conditions. Food Sci. Technol. Int. 13: 135–140. doi.org/0.1177/1082013207077925.

De Smet, S., Raes, K., Demeyer, D. 2004. Meat fatty acid composition as affected by fatness and genetic factors: a review. Animal Res. 53: 81–98. https://doi.org/10.1051/animres:2004003.

Domínguez, R., Pateiro, M., Gagaoua, M., Barba, F. J., Zhang, W., Lorenzo, J. M. 2019. A Comprehensive Review on Lipid Oxidation in Meat and Meat Products. Antioxidants (Basel, Switzerland), 8: 429. https://doi.org/10.3390/antiox8100429.

Edwards, S. 2005. Product quality attributes associated with outdoor pig production. Livest. Prod. Sci. 94: 5–14. doi.org/10.1016/j.livprodsci.2004.11.028.

EFSA. 2021. Scientific Opinion on the research priorities to fill knowledge gaps in wild boar management measures that could improve the control of African swine fever in wild boar populations. EFSA Journal. 19: 6716. doi.org/10.2903/j.efsa.2021.6716.

EFSA. 2022. Scientific Opinion on the welfare of pigs on farm. EFSA Journal. 20: 7421. doi.org/10.2903/j.efsa.2022.7421.

Faria, P.B., Cantarelli, V.S., Fialho, E.T., Pinto, A.M.B.G., Faria, J.H., Rocha, M.F.M., Guerreiro, M.C., Bressan, M.C. 2015. Lipid profile and cholesterol of pork with the use of glycerin in feeding. Arq. Bras. Med. Vet. Zootec. 67: 535–546. doi.org/10.1590/1678-7112.

Fiebig, R., Griffiths, M.A., Gore, M.T., Baker, D.H., Oscai, L., Ney, D.M., Ji, L.L. 1998. Exercise training downregulates hepatic lipogenic enzymes in meal-fed rats: Fructose versus complex-carbohydrate diets. J. Nutr. 128: 810–817. doi.org/10.1093/jn/128.5.810.

Franci, O., Bozzi, R., Pugliese, C., Acciaioli, A., Campodoni, G., Gandini, G. 2005. Performance of Cinta Senese pigs and their crosses with Large White: I. Muscle and subcutaneous fat characteristics. Meat Sci. 69: 545–550. doi.org/10.1016/j.meatsci.2004.10.005.

Franco, D., Carballo, J., Bermñudez, R., Lorenzo, J.M. 2016. Effect of genotype and slaughter age on carcass traits and meat quality of the Celta pig breed in extensive system. Ann. Anim. Sci. 16: 259–273. doi.org/10.1515/aoas-2015-0056.

Fortin A. 1986. Development of backfat and individual fat layers in the pig and its relationship with carcass lean. Meat Sci. 18: 255–270. https://doi.org/10.1016/0309-1740(86)90016-1.

Giannetto, C., Biondi, V., Previti, A., et al. 2023. Willingness to pay a higher price for pork obtained using Animal-Friendly raising techniques: a consumers' opinion survey. Foods. 12: 4201. doi.org/10.3390/foods12234201.

Goll, D.E., Bray, R.W., Hoekstra, W.G. 1963. Age-associated changes in muscle composition: The isolation and properties of a collagenous residue from bovine muscle. J. Food Sci. 28: 503–509. doi.org 10.1111/j.1365-2621.1963.tb00234.x.

Guo, Z., Chen, X., Chen, D., Li, M., Yin, J., Yu, B., He, J., Huang, Z. 2022. Effects of slaughter age on carcass traits and meat quality of crossbred (Duroc × Landrace × Yorkshire) finishing pigs. Anim. Biotechnol. 33: 339–345. doi.org/10.1080/10495398.2021.1916512.

Heyer, A., Andersson, H.K., Lundström, K. 2006. Performance, carcass and technological meat quality of pigs in indoor and outdoor production systems. Acta. Agr. Scand. A-Anim. Sci. 56: 55–64. doi.org/10.1080/09064700600670904.

ISTAT. 2024. Slaughtering, red meat, annual data. www.dati.istat.it, 24 October 2024.

Jacyno, E., Pietruszka, A., Kołodziej, A. 2006. Influence of pig meatiness on pork meat quality. Pol. J. Food Nutr. Sci. 2: 137–140.

Kloareg, M., Noblet, J., Van Milgen, J. 2007. Deposition of dietary fatty acids, de novo synthesis and anatomical partitioning of fatty acids in finishing pigs. Br. J. Nutr. 97: 35–44. doi.org/10.1017/S0007114507205793.

Kouba, M., Mourot, J., Peiniau, P. 1997. Stearoyl-CoA desaturase activity in adipose tissues and liver of growing Large White and Meishan pigs. Comp. Biochem. Physiol. B Biochem. Mol. Biol. 118: 509–514. doi.org/10.1016/S0305-0491(97)00173-9.

Latorre, M.A., Lázaro, R., Gracia, M.I., Nieto, M., Mateos, G.G. 2003a. Effect of sex and terminal sire genotype on performance, carcass characteristics and meat quality of pigs slaughtered at 117 kg body weight. Meat Sci. 65: 1369–1377. doi.org/10.1016/S0309-1740(03)00059-7.

Latorre, M.A., Medel, P., Fuentetaja, A., Lázaro, R., Mateos, G.G. 2003b. Effect of gender, terminal sire line and age at slaughter on performance, carcass characteristics and meat quality of heavy pigs. Anim. Sci. 77: 33–45. doi.org/10.1017/S1357729800053625.

Lebret, B. 2008. Effects of feeding and rearing systems on growth, carcass composition and meat quality in pigs. Animal. 2: 1548–1558. doi.org/10.1017/S1751731108002796.

Lebret, B., Massabie, P., Granier, R., Juin, H., Mourot, J., Chevillon, P. 2002. Influence of outdoor rearing and indoor temperature on growth performance, carcass, adipose tissue and muscle traits in pigs and on the technological and eating quality of dry-cured hams. Meat Sci. 62: 447–455. doi.org/10.1016/s0309-1740(02)00036-0.

Lebret, B., Prunier, A., Bonhomme, N., Foury, A., Mormède, P., Dourmad, J. Y. 2011. Physiological traits and meat quality of pigs as affected by genotype and housing system. Meat Sci. 88: 14–22. doi.org/10.1016/j.meatsci.2010.11.025.

Listrat, A., Lebret, B., Louveau, I., Astruc, T., Bonnet, M., Lefaucheur, L., Picard, B., Bugeon, J. 2016. How Muscle Structure and Composition Influence Meat and Flesh Quality. Sci. World J.: 3182746. https://doi.org/10.1155/2016/3182746.

Lopez-Bote, C.J., Isabel, B., Daza, A. 2002. Partial replacement of poly- with monounsaturated fatty acids and vitamin E supplementation in pig diets: effect on fatty acid composition of subcutaneous and intramuscular fat and on fat and lean firmness. Anim. Sci. 75: 349–358. doi.org/10.1017/S1357729800053121.

Ludwiczak, A., Kasprowicz-Potocka, M., Zaworska-Zakrzewska, A., et al. 2023. Husbandry practices associated with extensification in European pig production and their effects on pork quality. Meat Sci. 206: 109339. doi.org/10.1016/j.meatsci.2023.109339.

Maiorano, G., Gambacorta, M., Tavaniello, S., D'Andrea, M.S., Stefanon, B., Pilla, F. 2013a. Growth, carcass and meat quality of Casertana, Italian Large White and Duroc × (Landrace × Italian Large White) pigs reared outdoors. Ital. J. Anim. Sci. 12: e69. doi.org/10.4081/ijas.2013.e69.

Maiorano, G., Kapelański, W., Bocian, M., Pizzuto, R., Kapelańska, J. 2013b. Influence of rearing system, diet and gender on performance, carcass traits and meat quality of Polish Landrace pigs. Animal. 7: 341–347. doi.org/10.1017/S1751731112001516.

Malgwi, I.H, Gallo, L., Halas, V., Bonfatti, V., Carcò, G., Sasso, P., Carnier, P., Schiavon, S. 2021. The implications of changing age and weight at slaughter of heavy pigs on carcass and green ham quality traits. Animals. 11: 2634. doi.org/10.3390/ani11082447.

Mao, X., Zhu, J., Li, S., Diao, X., Qiu, X., Hou, Y., Shan, K., Li, C. 2025. Phenotypic differences between Chinese indigenous pig breeds and duroc × (landrace × Yorkshire): A perspective from meat science, biology, and biochemistry. Food Chem. 495: 146604. https://doi.org/10.1016/j.foodchem.2025.146604.

Martino, G., Mugnai, C., Compagnone, D., Grotta, L., Del Carlo, M., Sarti, F. 2014. Comparison of performance, meat lipids and oxidative status of pigs from commercial breed and organic crossbreed. Animals. 4: 348–360. doi.org/10.3390/ani4020348.

Mersmann, H.J., Leymaster, K.A. 1984. Differential deposition and utilization of backfat layers in swine. Growth. 48: 321–330.

Minelli, G., Macchioni, P., Ielo, M.C., Santoro, P., Lo Fiego, D.P. 2016. Effects of dietary level of pantothenic acid and sex on carcass, meat quality traits and fatty acid composition of thigh subcutaneous adipose tissue in Italian heavy pigs. Ital. J. Anim. Sci. 12: e52. doi.org/10.4081/ijas.2013.e52.

Monziols, M., Bonneau, M., Davenel, A., Kouba, M. 2007. Comparison of the lipid content and fatty acid composition of intermuscular and subcutaneous adipose tissues in pig carcasses. Meat Sci. 76: 54–60. doi.org/10.1016/j.meatsci.2006.10.013.

Ncogo Nchama, C.N., Fabro, C., Baldini, M., Saccà, E., Foletto, V., Piasentier, E., Sepulcri, A., Corazzin, M. 2022. Hempseed by-product in diets of Italian Simmental cull dairy cows and its effects on animal performance and meat quality. Animals. 12: 1014. doi.org/10.3390/ani12081014.

Ncogo Nchama, C.N., Saccà, E., Sepulcri, A., Foletto, V., Brunner, I., Corazzin, M., Piasentier, E. 2023. Characteristics of carcass, meat and subcutaneous fat of Mangalica pigs reared outdoors. Agric. Nat. Resour. 57: 625–634. doi.org/10.34044/j.anres.2023.57.4.07.

Nevrkla, P., Václavková, E., Rozkot, M. 2021. The indigenous Prestice Black-Pied breed differs from a commercial hybrid in growth intensity, carcass value and meat quality. Agriculture. 11: 331. doi.org/10.3390/agriculture11040331.

Olsson, V., Pickova, J. 2005. The influence of production systems on meat quality, with emphasis on pork. AMBIO. 34: 338–343.

Olsson, V., Andersson, K., Hansson, I., Lundström, K. 2003. Differences in meat quality between organically and conventionally produced pigs. Meat Sci. 64: 287–297. doi.org/10.1016/s0309-1740(02)00200-0.

Pagliarini, E., Laureati, M., Dinnella, C., Monteleone, E., Proserpio, C., Piasentier, E. 2015. Influence of pig genetic type on sensory properties and consumer acceptance of Parma, San Daniele and Toscano dry-cured hams. J. Sci. Food Agric. 96: 798–806. doi.org/10.1002/jsfa.7151.

Palka, K. 1999. Change in intramuscular connective tissue and collagen solubility of bovine m. semitendinosus during retorting. Meat Sci. 53: 189–194. doi.org/10.1016/S0309-1740(99)00047-9.

Peinado, J., Medel, P., Fuentetaja, A., Mateos, G.G. 2008. Influence of sex and castration of females on growth performance and carcass and meat quality of heavy pigs destined for the dry-cured industry. J. Anim. Sci. 86: 1410–1417. doi.org/10.2527/jas.2006-807.

Petersen, J.S., Henckel, P., Maribo, H., Oksbjerg, N., Sorensen, M.T. 1997. Muscle metabolic traits, post-mortem pH-decline and meat quality in pigs subjected to regular physical training and spontaneous activity. Meat Sci. 46: 259–275. doi.org/10.1016/S0309-1740(97)00021-1.

Pianezze, S., Corazzin, M., Perini, M., et al. 2021. Fatty acids stable carbon isotope fractionation in the bovine organism: a compound-specific isotope analysis through gas chromatography combustion isotope ratio mass spectrometry. J. Chromatogr. A. 1641: 461966. doi.org/10.1016/j.chroma.2021.461966.

Reitznerová, A., Semjon, B., Bartkovský, M., Šuleková, M., Nagy, J., Klempová, T., Marcinčák, S. 2023. Comparison of lipid profile and oxidative stability of Vacuum-Packed and Longtime-Frozen fallow deer, wild boar and pig meat. Appl. Sci. 13: 4059. doi.org/10.3390/app13064059.

Rey, A.I., Daza, A., López Carrasco, C., López-Bote, C.J. 2006. Feeding Iberian pigs with acorn and grass in either free-range or confinement affects the carcass characteristics and fatty acids and tocopherols accumulation in Longissimus dorsi muscle and backfat. Meat Sci. 73: 66–74. doi.org/10.1016/j.meatsci.2005.10.018.

Russo, C., Pistoia, A., Preziuso, G., D'Agata, M., Ferruzzi, G. 2007. Performance of Large White × Duroc pigs reared indoors and outdoors: Meat and fat quality. Ital. J. Anim. Sci. 6: 711. doi.org/10.4081/ijas.2007.1s.711.

Salogni, C., Capucchio, M.T., Colombino, E., Pozzi, P., Pasquali, P., Alborali, G.L. 2022. Bacterial polyarthritis in post-weaning pigs in a high-density swine breeding area in Italy. J. Vet. Diagn. Invest. 34: 709–711. doi.org/10.1177/10406387221090903.

Schwalm, A., Bauer, A., Dederer, I., Well, C., Bussemas, R., Weißmann, F. 2013. Effects of three genotypes and two roughages in organic heavy pig production for dry fermented sausage manufacture. Meat quality, fatty acid pattern and product quality. Agric. Food Sci. 63: 273–284. doi.org/10.3220/LBF_2013_273-284.

Serrano, M.P., Valencia, D.G., Fuentetaja, A., Lázaro, R., Mateos, G.G. 2008a. Effect of gender and castration of females and slaughter weight on performance and carcass and meat quality of Iberian pigs reared under intensive management systems. Meat Sci. 80: 1122–1128. doi.org/10.1016/j.meatsci.2008.05.005.

Serrano, M.P., Valencia, D.G., Nieto, M., Lázaro, R., Mateos, G.G. 2008b. Influence of sex and terminal sire line on performance and carcass and meat quality of Iberian pigs reared under intensive production systems. Meat Sci. 78: 420–428. doi.org/10.1016/j.meatsci.2007.07.006.

Serrano, M.P., Valencia, D.G., Fuentetaja, A., Lázaro, R., Mateos G.G. 2009. Influence of feed restriction and sex on growth performance and carcass and meat quality of Iberian pigs reared indoors. J. Anim. Sci. 87: 1676–1685. doi.org 10.2527/jas.2008-0989.

Shorthose, W.R., Harris, P.V. 1991. Effect of growth and composition on meat quality. In: Pearson, A.M., Dutson, T.R. (Eds.). Growth regulation in farm animals. Elsevier Applied Science. London, UK. pp. 515–555.

Siu, G.M., Draper, H.H. 1978. A survey of the malonaldehyde content of retail meats and fish. J. Food Sci. 43: 1147–1149. doi.org/10.1111/j.1365-2621.1978.tb15256.x.

Stanišić, N., Parunović, N., Stajić, S., Petrović, M., Radović, C., Živković, D., Petričević, M. 2016. Differences in meat colour between free-range Swallow Belly Mangalitsa and commercially reared Swedish Landrace pigs during 6 days of vacuum storage. Arch. Anim. Breed. 59: 159–166. doi.org/10.5194/aab-59-159-2016.

Stern, S., Heyer, A., Andersson, H.K., Rydhmer, L., Lundström, K. 2003. Production results and technological meat quality for pigs in indoor and outdoor rearing systems. Acta. Agric. Scand. A Anim. Sci. 53: 166–174. doi.org/10.1080/09064700310014979.

Szyndler-Nędza, M., Świątkiewicz, M., Migdal, L., Migdal, W. 2021. The quality and health-promoting value of meat from pigs of the native breed as the effect of extensive feeding with acorns. Animals. 11: 789. doi.org/10.3390/ani11030789.

Tomažin, U., Batorek-Lukač, N., Škrlep, M., Prevolnik-Povše, M., Čandek-Potokar, M. 2019. Meat and fat quality of Krškopolje pigs reared in conventional and organic production systems. Anim. 13: 1103–1110. doi.org/10.1017/S1751731118002409.

Trombetta, M.F., Mattii, S., Pasquini, M., Marina, A. 2009. Influence of diet and rearing system on heavy pig performance, carcass and meat quality. Ital. J. Anim. Sci. 8: 23–35. doi.org/10.4081/ijas.2009.23.

Vaskoska, R., Ha, M., Naqvi, Z.B., White, J.D., Warner, R.D. 2020. Muscle, ageing and temperature influence the changes in texture, cooking loss and shrinkage of cooked beef. Foods. 9: 1289. doi.org/10.3390/foods9091289.

Vegni, J., Zappaterra, M., Davoli, R., Virgili, R., Simoncini, N., Schivazappa, C., Cilloni, A., Zambonelli, P. 2023. Application of non-invasive tools and identification of genetic markers in swine to enhance ham quality: A preliminary study. *Animal*. 17: 100864. doi.org/10.1016/j.animal.2023.100864.

Virgili, R., Degni, M., Schivazappa, C., Faeti, V., Poletti, E., Marchetto, G., Pacchioli, M.T., Mordenti, A. 2003. Effect of age at slaughter on carcass traits and meat quality of Italian heavy pigs. J. Anim. Sci. 81: 2448–2456. doi.org/10.2527/2003.81102448x.

Wood, J.D. 1984. Fat deposition and the quality of fat tissue in meat animals. In: Wiseman, J. (Eds.). Fats in Animal Nutrition. Butterworths. London, UK. pp. 407–435.

Wood, J.D., Warriss, P.D. 1992. Effects of production factors on meat quality in pigs. In: Johnston, D.E., Knight, M.K. (Eds.). The Chemistry of Muscle-based Foods. Royal Society of Chemistry. Cambridge, UK. pp. 3–14.

Yi, W., Huang, Q., Wang, Y., Shan, T. 2023. Lipo-nutritional quality of pork: The lipid composition, regulation, and molecular mechanisms of fatty acid deposition. Animal nutrition [Zhongguo xu mu shou yi xue hui] 13: 373–385. https://doi.org/10.1016/j.aninu.2023.03.001.

Zomeño, C., Gispert, M., Čandek-Potokar, M., Mörlein, D., Font-i-Furnols, M. 2023. A matter of body weight and sex type: Pig carcass chemical composition and pork quality. Meat Sci. 197: 109077. doi.org/10.1016/j.meatsci.2022.109077.