DOI: 10.5433/1679-0359.2025v46n3p689

Organic selenium dietary supplementation improves pork meat stability during vacuum-packaged storage

Suplementação dietética com selênio orgânico melhora a estabilidade da carne suína embalada a vácuo durante o armazenamento

Marcela Maíra Miqueletto[1]; Sthefany Kamile dos Santos[2]; Leandro Batista Costa[3]; Marcos Aronovich[4]; Renata Ernlund Freitas de Macedo[5]*

Highlights

Organic selenium supplementation improves the quality and stability of pork meat.
Meat from supplemented animals can be labeled as rich in selenium.
Supplementation increased tenderness and color stability during storage.

Abstract

This study assessed the effects of organic selenium supplementation in pig diets on meat quality and stability during refrigerated vacuum storage. The animals were categorized into two treatment groups: CONT (control group; basal diet) and SEL (experimental group; basal diet + 0.3 ppm organic selenium, supplemented during the finishing phase). After slaughter, samples of loin were vacuum packaged, and physicochemical analyses were performed during 28 days of storage at 4 °C. Dietary selenium supplementation resulted in a 3-fold increase in meat selenium content. The color coordinate (a*, b*, C*, and h) results demonstrated the protective effect of organic selenium and increased stability during storage. No inhibitory effect was observed on protein or lipid oxidation in meat, probably because of the low fat content of the samples. Meat from the SEL group showed higher tenderness than meat from the CONT group. Supplementation with organic selenium in the diet of animals promotes significant nutritional enrichment of meat and beneficial technological effects, providing increased tenderness and maintaining color stability during storage.

Key words: Organic mineral. Shelf life. Color. Nutritional enrichment. Health.

[1] M.e in Animal Science, Graduate Program in Animal Science, Pontificia Universidade Católica do Paraná, PUCPR, Laboratory of Agri-food Research and Innovation, Curitiba, PR, Brazil. E-mail: marcela.miqueletto@hotmail.com
[2] PhD in Animal Science, Graduate Program in Animal Science, PUCPR, Laboratory of Agri-food Research and Innovation, Curitiba, PR, Brazil. E-mail: sthefanykamile@hotmail.com
[3] Prof. Dr., Graduate Program in Animal Science, PUCPR, Laboratory of Agri-food Research and Innovation, Curitiba, PR, Brazil. E-mail: batista.leandro@pucpr.br
[4] PhD in Food Technology, Phileo by Lesaffre, Campinas, SP, Brazil. E-mail: marcosaronovich@gmail.com
[5] Profª Drª, Graduate Program in Animal Science, PUCPR, Laboratory of Agri-food Research and Innovation, Curitiba, PR, Brazil. E-mail: renata.macedo@pucpr.br
* Author for correspondence

Received: May 07, 2024 Approved: Feb. 11, 2025

Resumo

Este estudo avaliou os efeitos da suplementação de selênio orgânico em dietas para suínos na qualidade e estabilidade da carne durante o armazenamento refrigerado a vácuo. Os animais foram categorizados em dois grupos de tratamento: CONT (grupo controle; dieta basal) e SEL (grupo experimental; dieta basal + 0,3 ppm de selênio orgânico, suplementado na fase de terminação). Após o abate, amostras de lombo foram embaladas a vácuo e estocadas durante 28 dias de armazenamento a 4 °C. A suplementação dietética de selênio resultou em um teor três vezes maior de selênio na carne. Os resultados das coordenadas de cor (a*, b*, C* e h) mostraram efeito protetor do selênio orgânico e maior estabilidade durante o armazenamento. Nenhum efeito inibitório sobre a oxidação proteica ou lipídica da carne foi observado, provavelmente devido ao baixo teor de gordura das amostras. A carne do grupo SEL apresentou maior maciez que a do grupo CONT. A suplementação com selênio orgânico na dieta dos animais promoveu significativo enriquecimento nutricional da carne e efeitos tecnológicos benéficos, proporcionando maior maciez e manutenção da estabilidade da cor durante o armazenamento.
Palavras-chave: Mineral orgânico. Prazo de validade. Cor. Enriquecimento nutricional. Saúde.

Introduction

Pork production is one of the most important activities in Brazilian agribusiness and occupies the 4th place in the ranking of pork producing and exporting countries. In 2022, Brazil produced 4,983 million tons of pork and exported more than 1,120 thousand tons of pork meat. In addition, the world consumption of pork has increased each year; in 2022 the per capita consumption of pork was 18.0 kg/inhabitant, whereas in 2017, it increased to 14.7 kg/inhabitant (Associação Brasileira de Proteína Animal [ABPA], 2023).

High animal productivity can be achieved using better management techniques, genetics, nutrition, health, and ambience. Nutrition strongly affects animal productivity, and appropriately formulated and balanced diets result in increased productivity and meat quality (MAPA, Ministério da Agricultura, Pecuária e Abastecimento [MAPA], 2016; Peres et al., 2014).

Selenium is an essential micromineral that must be supplemented in the diet. It is part of the enzyme glutathione peroxidase, which is utilized in important body functions and processes, such as antioxidant defense, immune competence, and regulation of thyroid function (Brown & Arthur, 2001). It protects cell membranes from free radicals and other oxidative damage by inhibiting the formation of peroxides during the oxidation of cell membrane lipids.

The use of organic selenium in the diet of pigs has beneficial effects on their growth performance and physiological parameters (Downs et al., 2000; Lisiak et al., 2014; Mahan et al., 1999; Štefanka et al., 2013). Consumption of meat enriched with selenium can improve selenium levels in the human body, particularly in populations with selenium deficiency (Kim & Mahan, 2001; Mahan & Parrett, 1996). Moreover, selenium can have beneficial effects in cancer treatment, including its ability to selectively attack cancer cells while preserving healthy cells and decreasing angiogenesis (Collery, 2018).

Numerous studies have highlighted the benefits of supplementing diets of pigs with organic selenium (Bobček et al., 2004; Calvo et al., 2017; J. Chen et al., 2019; Silva et al., 2019; X. Zhan et al., 2007). However, few studies have examined its effect on meat quality during storage. Calvo et al. (2017) and S. Zhang et al. (2020) explored some quality parameters of fresh pork meat, considering various organic selenium sources in the diets of animals within 7 days of atmospheric storage. However, information on how organic selenium affects the shelf life, color, and oxidative stability of pork meat under typical commercial storage conditions (refrigerated vacuum storage) is lacking. This study aimed to evaluate the effects of organic selenium supplementation in the diets of pigs on pork meat quality over a 28-day storage period.

Materials and Methods

This study was approved by the Ethics Committee on the Use of Animals of Pontifícia Universidade Católica do Paraná – PUCPR (protocol no. 02227).

Animals, treatments, and handling

Sixty pigs (Landrace and Large White crossbreeds) 30 barrows and 30 females from a commercial breeding, rearing, and finishing farm were used. The pigs were weaned at 3 weeks of age and relocated to collective pens during the nursery phase (approximately 42 d), followed by the growing and finishing phases (approximately 98 d). During the final 50 d of the finishing phase (at approximately 110 days of age), the animals were allocated into two groups of 30 animals each (15 barrows and 15 females) and subjected to two feeding regimes based on the source of selenium, as described below.

CONT = control group that received the basal diet, and

SEL = experimental group that received the basal diet + 0.3 ppm organic selenium (SELSAF® 3000 - Phileo by Lesaffre).

The organic selenium used comprised 2/3 selenomethionine and 1/3 selenocysteine produced by the yeast strain (CNCM I-3399).

The pigs were fed a commercial finishing diet as listed in Table 1.

Table 1
Composition and calculated values of the basal diet provided to pigs during the finishing phase

Items	%
Ground corn 7,5 %	41.218
Rye grains	10
Triticale	25
Soybean meal	20
Soy oil	1
PX Rono Blend ms [1]	0.1
Lysine SGS	0.477
Mig ceva 2% [2]	2
L – Threonine	0.082
DL – Tryptophan	0.011
DL – Methionine	0.037
Ractopamine [3]	0.075
Total	100
Calculated Values	
Protein (%)	16.52
Ether extract (%)	3.28
Raw fiber (%)	2.51
Ash (%)	4.17
Calcium (%)	0.84
Avaliable match (%)	0.31
Total lysine (%)	1.02
Metabolizable energy kcal/kg	3,319.95

1 – Enzyme premix for pigs – enzyme additive, *Bacillus licheniformis, Bacillus subtilis.* Protease 1, 125, 10, and 07 PRT, endo-1,4-β-xylanase 200,000 FXU, alpha-amylase 42,000 KNU.
2 - Mig Ceva 2% – folic acid (min) 22 mg/kg; pantothenic acid (min) 985 mg/kg; biotin (min) 1.3 mg/kg; calcium (min–max) 150–260 g/kg; cobalt (min) 24 mg/kg; choline (min) 12 g/kg; iron (min) 3,800 mg/kg; phytase 25,000 FTU/kg; flavomycin, 200 mg/kg; phosphorus (min) 30 g/kg; iodine (min) 65 mg/kg; manganese (min) 3,400 mg/kg; niacin (min) 1200 mg/kg; selenium (min) 20 mg/kg; sodium (min) 70 g/kg; Vitamin A (min) 298,000 IU/kg; Vitamin B1 (min) 45 mg/kg; Vitamin B12 (min) 975 mcg/kg; Vitamin B2 (min) 240 mg/kg; Vitamin B6 (min) 95 mg/kg; Vitamin D3 (min) 49,000 IU/kg; Vitamin E (min) 1960 IU/kg; Vitamin K3 (min) 70 mg/kg; zinc (min) 7,400 mg/kg.
3 - Ractomax – ractopamine hydrochloride 2 g.

This formulation was based on the nutritional requirements of the pig farm lineage. The basal diet was prepared in a feed factory attached to the farm. For the SEL group, the organic selenium source was added at the end of the feed mixture during homogenization of the ingredients.

Water and feed were provided *ad libitum.* The troughs were filled daily in the morning and late afternoon, and the feed volume was guaranteed such that feed was always available.

Slaughter of animals

At the end of the finishing phase (at approximately 160 days of age), the animals were fasted for 12 h and slaughtered in a certified commercial slaughterhouse following humanitarian slaughter standards (Portaria nº 365/2021).

Physicochemical evaluation of meat

After slaughter, eight carcasses from each group (four females and four barrows) were randomly selected for meat quality analysis. The carcasses were cooled for 24 h at 4 °C. Samples of the right and left loins (*Longissimus thoracis et lumborum*) of the half carcasses were removed by sectioning the loin between the penultimate and last ribs to extract a sample approximately 43 cm in length. The loin was sectioned transversely to obtain 35 subsamples (chops) from each animal, measuring approximately 2.5 cm in thickness.

Loin samples were packaged under vacuum for 28 d at 4 °C. On days 1, 7, 14, 21, and 28 (T1, T7, T14, T21, and T28, respectively), the samples were assessed for pH, instrumental color, drip loss (DL), cooking loss (CL), shear force (SF), and lipid and protein oxidation using the methodologies described below. The lipid and selenium levels of the samples were determined only at T1.

Tissue selenium content

Hydride generation atomic absorption spectrometry using a hydride generator (Analytik Jena model HS60) and atomic absorption spectrometry (Analytik Jena model NovA 300) were used to determine tissue selenium concentrations. The procedure was performed according to Abdolmohammad-Zadeh et al. (2013) and the results are expressed in mg/kg.

Determination of instrumental color

Color measurements of the samples were performed after 30 min of exposure to atmospheric air. Three consecutive measurements were recorded at different points on each sample covering the entire surface.

The CIELab color coordinates (L*, lightness; a*, red; and b*, yellow) were measured using a Minolta portable colorimeter (CR410, Japan) equipped with a D65 illuminant with an observation angle of 2° and aperture diameter of 50–53 mm. The chroma (saturation) and hue angle (discoloration) were calculated as C* = √a2 × b2 and h* = arctangent (b*/a*), respectively (American Meat Science Association [AMSA], 2012).

The color differences (ΔE) of the meat of the CONT and SEL groups between days 1 and 28 of storage were calculated as $\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$ (AMSA, 2012).

Determination of pH

A pH meter with an insertion electrode (Hanna, model HI 99163) calibrated at pH 4.0 and 7.0 was inserted consecutively at three different points in each sample to obtain the pH measurement.

Drip loss

The methodology proposed by Lundstrom and Malmfors (1985) was used for DL analysis. The results are expressed as the weight loss of the sample (g) relative to the initial weight (in percentage) at each storage time.

Cooking loss

Cooking loss was determined in samples cooked in an industrial gas oven (General Industry Company, model FG, series 050823) for 20 min at 170 °C. The samples were precooked until they reached an internal temperature of 40 °C, turned over, and were kept cooking until they reached an internal temperature of 71 °C. After cooling to room temperature (20 °C), the samples were packaged in plastic bags and chilled at 5 °C for 24 h before weighing. The differences in sample weight before and after cooking were calculated as CL and are expressed as percentages (Zhao et al., 2017).

Shear force

After the determination of CL, cylindrical samples (1.27 cm diameter) were cut from the cooked loins, parallel to the orientation of the muscle fibers. These samples were used to measure SF using a TAXT2i texturometer (Stable Micro Systems, Surrey, England) equipped with a Warner-Bratzler blade. The samples were sheared perpendicular to the muscle fiber orientation using the following conditions recommended for pork: distance from the base, 25 mm; pretest speed, 5 mm/s; test speed, 2 mm/s; and post-test speed, 5 mm/s (AMSA, 2015). The results are expressed in Newton (N).

Lipid oxidation

Lipid oxidation was determined as thiobarbituric acid reactive substance (TBARS) values according to Vyncke (1970). A spectrophotometer (Spectrum, Model SP-1105) was used to measure the absorbance of the samples at 538 nm in triplicates. The results are expressed as malondialdehyde (MDA) mg/kg and 1,1,3,3-tetramethoxypropane was used as a standard (0.06 μM–1.5 μM) (Crackel et al., 1988).

Protein oxidation

Carbonyl content was used to measure protein oxidation in the samples. First, myofibrillar proteins were extracted (Jongberg et al., 2013; Santos et al., 2020). The colorimetric method, with an absorption coefficient of 22,000 M^{-1} cm^{-1} (Colombo et al., 2016) was then used to quantify the carbonyl content, which is expressed in nmol carbonyl/mg protein.

Lipid content

Lipid content was determined according to the official methods of the Association of Official Analytical Chemists (Association of Official Analytical Chemists [AOAC], 2016). The results are expressed in g/100 g.

Statistical analysis

Data were analyzed using analysis of variance with complete models that included the fixed effects of treatment (CON, SEL), storage time (days 0, 7, 14, 21, and 28), sex (female, male), and their interactions. For selenium and lipid levels, the fixed effects included treatment, sex, and their interactions. Tukey's test was used to compare means ($P < 0.05$).

All data are presented as standard error of the mean. Statgraphics Centurion XVI software for Windows (v. 16.1.11) was used for the statistical analyses.

Results and Discussion

Selenium content

Treatments showed significant differences ($P < 0.05$) in the selenium content of the meat, indicating that supplementation with organic selenium (SEL) in the diet significantly increased its content in meat, achieving a value three times higher (0.206 mg/kg) than that in the control group (0.064 mg/kg) (Figure 1). Sex had no effect on selenium content.

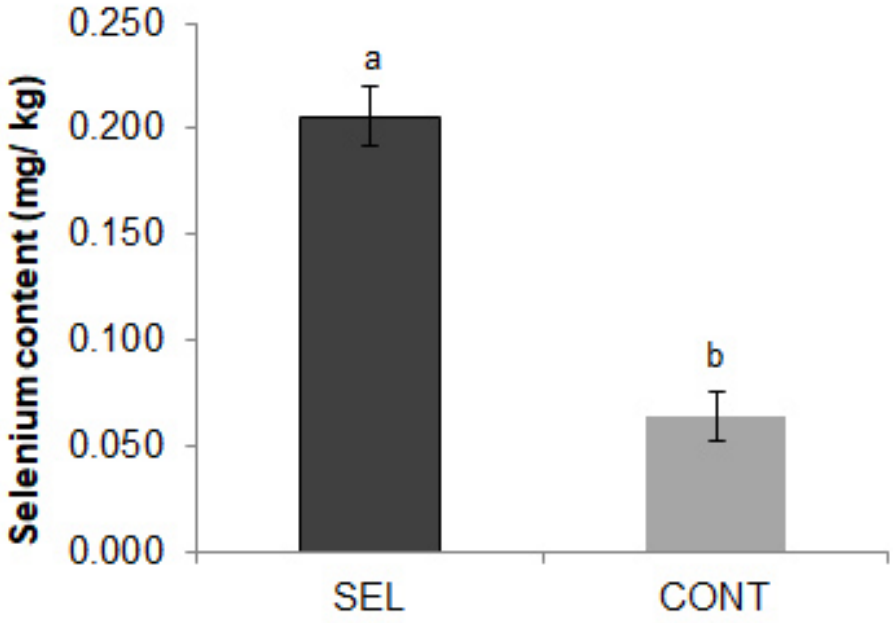

Figure 1. Selenium content in pork meat in the two experimental groups. SEL (n = 8), organic selenium-supplemented animals and CONT (n = 8), control group. "a" and "b" indicate differences in the selenium content between the treatments ($P < 0.05$).

The tissue concentrations of selenium can be influenced by both its source and dietary levels (Mahan & Parrett, 1996). Some studies have confirmed that organic selenium is retained more by tissues (muscle and liver) than is inorganic selenium (Mahan et al., 2014; Mahan & Parrett, 1996) and that its concentration can be significantly higher in pork meat when organic selenium is supplemented in the diet of the animals (Bobček et al., 2004).

According to Brazilian legislation regarding the technical requirements for the declaration of nutrition labeling of packaged foods (Instrução Normativa nº 75/2020), a solid food (100 g) must provide 30% of the recommended daily intake (RDI) to be considered high or rich in essential nutrients. The RDI of selenium for adults is 60 µg. Therefore, an intake of 100 g of pork from animals supplemented with organic selenium in this study would provide >30% of the RDI for selenium; hence, pork meat can be claimed to be rich in selenium. This contributes to human nutrition because the addition of selenium to the diet of pigs is one method to solve the problems of selenium deficiency in human food (Bobček et al., 2004).

Instrumental color

The color coordinates were influenced by the storage time ($P < 0.05$); a decrease in redness (a*) and an increase in luminosity (L*) and yellowness (b*) were observed over time. Therefore, discoloration (h) increased and color saturation (C*) decreased (Table 2). These color changes over storage time were speculated because of the oxidation of oxymyoglobin (red color) to metmyoglobin (brown color) and protein denaturation, which increases light scattering, making the meat lighter with an increased L* value (Warner, 2014; Gravador et al., 2015).

Table 2
Influence of the diet supplemented with organic selenium, storage time, and sex on color coordinates of pork meat during 28 days of storage at 4 °C

		Storage time (days)					Sex	
Parameter	Group	1	7	14	21	28	M	F
L*	SEL	55.4 ± 1.2 ^{aBC}	55.1 ± 0.3 ^{aC}	57.0 ± 0.3 ^{aA}	56.8 ± 0.3 ^{aAB}	57.4 ± 0.3 ^{bA}	56.7 ± 0.2 ^{xX}	56.1 ± 0.2 ^{yY}
	CONT	56.1 ± 0.4 ^{aAB}	55.9 ± 0.9 ^{aB}	57.0 ± 0.6 ^{aAB}	57.1 ± 0.3 ^{aAB}	58.8 ± 0.4 ^{aA}	56.5 ± 0.4 ^{xX}	57.6 ± 0.3 ^{xX}
a*	SEL	15.2 ± 0.2 ^{aA}	14.9 ± 0.2 ^{bAB}	14.9 ± 0.1 ^{aA}	14.7 ± 0.1 ^{aAB}	14.4 ± 0.1 ^{aB}	14.7 ± 0.1 ^{xX}	14.9 ± 0.1 ^{xX}
	CONT	14.7 ± 0.2 ^{aAB}	15.4 ± 0.1 ^{aA}	14.7 ± 0.1 ^{aB}	14.4 ± 0.1 ^{aB}	13.5 ± 0.2 ^{bC}	14.8 ± 0.1 ^{xX}	14.3 ± 0.1 ^{yY}
b*	SEL	4.5 ± 0.2 ^{aB}	6.1 ± 0.2 ^{aA}	5.0 ± 0.1 ^{aB}	5.6 ± 0.1 ^{aA}	5.9 ± 0.1 ^{aA}	5.5 ± 0.1 ^{xX}	5.6 ± 0.1 ^{xX}
	CONT	4.6 ± 0.1 ^{aC}	5.9 ± 0.2 ^{aA}	5.3 ± 0.1 ^{aB}	5.1 ± 0.1 ^{bBC}	6.1 ± 0.2 ^{aA}	5.6 ± 0.1 ^{xX}	5.3 ± 0.1 ^{xY}
C*	SEL	15.9 ± 0.2 ^{aAB}	16.2 ± 0.1 ^{aA}	15.8 ± 0.1 ^{aAB}	15.8 ± 0.1 ^{aAB}	15.6 ± 0.1 ^{aB}	15.8 ± 0.1 ^{xX}	15.9 ± 0.1 ^{xX}
	CONT	15.4 ± 0.2 ^{aBC}	16.5 ± 0.1 ^{aA}	15.7 ± 0.1 ^{aB}	15.3 ± 0.1 ^{bBC}	14.9 ± 0.2 ^{bC}	15.9 ± 0.1 ^{xX}	15.2 ± 0.1 ^{yY}
h	SEL	16.1 ± 0.4 ^{aB}	22.5 ± 0.9 ^{aA}	18.7 ± 0.3 ^{aB}	20.8 ± 0.4 ^{aA}	22.4 ± 0.4 ^{bA}	20.6 ± 0.4 ^{xX}	20.5 ± 0.4 ^{xX}
	CONT	17.4 ± 0.5 ^{aC}	21.2 ± 0.6 ^{aB}	19.8 ± 0.5 ^{aBC}	19.8 ± 0.5 ^{aBC}	24.4 ± 0.5 ^{aA}	21.2 ± 0.5 ^{xX}	20.6 ± 0.3 ^{xX}

SEL, organic selenium diet (n = 8); CONT, basal diet (n = 8). Lowercase letters (a, b) in the column indicate differences between treatments, and uppercase letters (A, B, C) in the row indicate differences between storage times ($P < 0.05$). Lowercase letters (x, y) in the same column indicate differences in the same sex (M or F) between the SEL and CONT groups. Uppercase letters (X, Y) in the same row indicate differences between males and females within the same group (SEL or CONT). ($P < 0.05$).

SEMINA Ciências Agrárias

The treatment also influenced the color coordinates (P < 0.05), indicating a protective effect of organic selenium on meat color. The meat of the SEL group showed higher redness and color saturation than those of the control group after 28 d of storage. Other authors have also reported higher redness in pork loins after organic selenium supplementation (Calvo et al., 2017; X. Zhan et al., 2007), corroborating the color-stabilizing effect of organic selenium (J. Chen et al., 2019). Conversely, the meat from the SEL group showed lower luminosity and discoloration (h), consistent with reports by Jiang et al. (2017) and Silva et al. (2019). Yellowness was not influenced by treatment (Table 2).

The structural integrity of muscle proteins influences the stability of the red color of meat. The use of organic sources of selenium can improve the performance of glutathione peroxidase, increase antioxidant activity in muscles, and protect cell membranes and muscle proteins from oxidation (Jiang et al., 2017). Therefore, selenium preserves the color of meat during storage by preventing the oxidation of oxymyoglobin and metmyoglobin. To assess whether color differences could be perceived by the human eye, the absolute difference in color (ΔE) was used. As a criterion adopted by the International Commission on Illumination, it presents the possibility of perceiving differences between two products. Considering the differences in L*, a*, and b* values between days 1 and 28 of storage, the ΔE was 2.57 and 3.31 for the SEL and CONT groups, respectively. Values of ΔE within the range of 0–1 indicate that the difference cannot be perceived by the observer, within 1–2 indicate that the difference can only be visually recognized by an experienced observer, within 2–3.5 indicate that an inexperienced observer can recognize the difference, values >3.5 indicate that the observer has a clear color difference, and values >5 indicate that the observer has the impression of two different colors (Mokrzycki & Tatol, 2012). The ΔE values of CONT and SEL were between 2–3.5, which indicates that an inexperienced observer could recognize the differences in meat color over 28 days of storage.

The human visual system efficiently discriminates between colors presented simultaneously but poorly memorizes them (Salueña et al., 2019). Although color changes are expected over the storage period, the results showed a visible difference between days 1 and 28 of storage. The higher the ΔE, the greater was the relative color change compared with the original color of the meat (Seydim et al., 2006). Although the two groups were in the same classification range, the SEL group showed fewer color changes during storage, indicating the protective effect of selenium on meat color.

Regarding the interaction between sex and treatment, differences in values were observed only in females. Meat from SEL females showed lower luminosity and higher a* and C* values than those from the CONT group. When comparing sexes within the same treatment group, males showed higher L* values than females in the SEL group (P < 0.05), and higher redness, yellowness, and chroma values in the CONT group (P < 0.05). The meat of barrows has a higher myoglobin content than that of sows; hence, it is redder than that of females (Cisneros et al., 1996).

pH and drip loss

In both groups, an increase in pH was observed at T7, with a slight reduction between T7 and T14 and subsequent stabilization over storage time ($P < 0.05$) (Table 3). Meat from the SEL group had a lower pH ($P < 0.05$) during storage on days 7, 21, and 28. However, the difference in numerical values was small and did not affect the DL, which was similar between the treatments.

Calvo et al. (2017), Jiang et al. (2017), and Svoboda et al. (2010) also found no effect of selenium supplementation on DL in pork. However, lower DL in pork was found when levels of supplemented dietary Se were high (>0.4 mg/kg), e.g., Lisiak et al. (2014) using 0.4–0.5 mg organic Se/kg and Li et al. (2011) using 3.0 mg of selenium-enriched yeast/kg). Organic selenium increased the water-holding capacity of meat (Calvo et al., 2016) and reduced loin DL (J. Chen et al., 2019). Although it is generally accepted that selenium in animal diets is essential for the water-retaining properties of meat (Cai et al., 2012; Vignola et al., 2009), whether the form of selenium is involved in controlling DL in meat remains unclear.

Considering the effect of time on the DL, an increase in values was observed only between T7 and T14. Afterward, the values stabilized, with no significant differences observed. The increase in DL between T7 and T14 could be attributed to the slight decrease in pH during this interval, as lower pH levels reduce the water-holding capacity, leading to greater muscle fluid loss (drip loss) (Jankowiak et al., 2021). There was no increase in CL after 14 days, and the values remained stable until the end of the storage period.

Regarding the sex and treatment effects on pH and DL, a difference was observed only in pH, for which meat from males in the SEL group showed a lower pH than that in the CONT group, although the difference in the numerical values was low (0.04). Females from the CONT and SEL groups showed no significant differences.

Within the same group, females from the CONT group exhibited lower DL (Table 3) than males, whereas females from the SEL group showed higher pH than males, indicating that sex plays a more pivotal role than does selenium supplementation in the parameters influencing meat water-holding capacity. A higher pH in meat usually corresponds to a lower DL and exudation, which is the result of the shrinkage of myofibrils in the *postmortem* period and is one of the main factors contributing to the loss of meat product quality (Jensen et al., 2007). Meat water retention can be influenced by pre-slaughter stress, and males are more aggressive and agitated than females (Thun et al., 2006), which can result in lower pH (Jeleníková et al., 2008) and greater exudation in the meat of males (Caldara et al., 2013) aligning with the findings of the present study.

Table 3
Influence of dietary selenium, storage time, and sex on selenium tissue content, pH, drip loss (DL), cooking loss (CL), shear force (SF), lipid (TBARS) and protein (carbonyls) oxidation, and lipid content of pork meat

Parameter	Group	Storage time (days)					Sex	
		1	7	14	21	28	M	F
Se content (mg/kg)	SEL	0.206 ± 0.014 ^{a}	ND	ND	ND	ND	0.217 ± 0.025 ^{xX}	0.195 ± 0.010 ^{xX}
	CONT	0.064 ± 0.012 ^{b}	ND	ND	ND	ND	0.067 ± 0.021 ^{yX}	0.062 ± 0.012 ^{yX}
pH	SEL	5.56 ± 0.01 ^{aC}	5.78 ± 0.01 ^{bA}	5.68 ± 0.01 ^{aB}	5.66 ± 0.01 ^{bB}	5.66 ± 0.01 ^{bB}	5.66 ± 0.01 ^{yY}	5.71 ± 0.01 ^{xX}
	CONT	5.54 ± 0.01 ^{aD}	5.82 ± 0.01 ^{aA}	5.67 ± 0.01 ^{aC}	5.69 ± 0.01 ^{aBC}	5.71 ± 0.01 ^{aB}	5.70 ± 0.01 ^{xX}	5.71 ± 0.01 ^{xX}
DL (%)	SEL	ND	9.76 ± 1.08 ^{aB}	13.65 ± 1.07 ^{aA}	13.98 ± 0.53 ^{aA}	14.70 ± 0.81 ^{aA}	13.74 ± 0.69 ^{xX}	12.30 ± 0.86 ^{xX}
	CONT	ND	8.40 ± 1.01 ^{aB}	11.89 ± 0.80 ^{aAB}	13.94 ± 0.73 ^{aA}	15.05 ± 1.03 ^{aA}	13.78 ± 0.93 ^{xX}	10.86 ± 0.70 ^{xY}
CL (%)	SEL	37.94 ± 1.07 ^{aA}	38.48 ± 0.55 ^{aA}	39.09 ± 0.73 ^{aA}	35.57 ± 0.99 ^{aB}	39.01 ± 0.51 ^{aA}	39.01 ± 0.51 ^{xX}	37.03 ± 0.53 ^{xY}
	CONT	37.70 ± 0.95 ^{aAB}	38.81 ± 0.63 ^{aAB}	39.72 ± 0.74 ^{aA}	35.80 ± 2.42 ^{aB}	39.85 ± 0.37 ^{aA}	38.01 ± 0.54 ^{xX}	38.74 ± 1.03 ^{xX}
SF (N)	SEL	73.60 ± 2.98 ^{aA}	51.45 ± 1.57 ^{aB}	51.26 ± 1.38 ^{bB}	43.81 ± 1.45 ^{bC}	53.15 ± 1.31 ^{aB}	56.55 ± 1.50 ^{xX}	52.16 ± 1.12 ^{yY}
	CONT	77.01 ± 2.24 ^{aA}	50.69 ± 1.46 ^{aB}	55.78 ± 1.42 ^{aB}	51.64 ± 1.38 ^{aB}	55.09 ± 1.53 ^{aB}	54.71 ± 1.17 ^{xY}	60.24 ± 1.22 ^{xX}
TBARS (mg MDA/kg)	SEL	0.118 ± 0.009 ^{aD}	0.175 ± 0.009 ^{aC}	0.302 ± 0.016 ^{aA}	0.230 ± 0.014 ^{aB}	0.253 ± 0.014 ^{aAB}	0.214 ± 0.012 ^{xX}	0.217 ± 0.011 ^{xX}
	CONT	0.112 ± 0.007 ^{aD}	0.179 ± 0.010 ^{aC}	0.289 ± 0.017 ^{aA}	0.222 ± 0.015 ^{aBC}	0.244 ± 0.020 ^{aAB}	0.209 ± 0.011 ^{xX}	0.210 ± 0.014 ^{xX}
Carbonyls (nmol/mg protein)	SEL	0.601 ± 0.039 ^{aA}	0.594 ± 0.025 ^{aA}	0.617 ± 0.027 ^{aA}	0.670 ± 0.038 ^{aA}	0.679 ± 0.020 ^{aA}	0.687 ± 0.019 ^{xX}	0.577 ± 0.018 ^{xY}
	CONT	0.690 ± 0.019 ^{aA}	0.570 ± 0.023 ^{aB}	0.571 ± 0.026 ^{aB}	0.666 ± 0.036 ^{aA}	0.666 ± 0.031 ^{aA}	0.640 ± 0.020 ^{xX}	0.626 ± 0.017 ^{xX}
Lipid content (%)	SEL	0.712 ± 0.076 ^{a}	ND	ND	ND	ND	0.641 ± 0.125 ^{xX}	0.784 ± 0.073 ^{xX}
	CONT	0.614 ± 0.098 ^{a}	ND	ND	ND	ND	0.660 ± 0.163 ^{xX}	0.568 ± 0.103 ^{xX}

SEL, organic selenium diet (n = 8); CONT, basal diet (n = 8); ND, not determined. Lowercase letters (a, b) in the column indicate differences between treatments, and uppercase letters (A, B, C, D) in the row indicate differences between storage times ($P < 0.05$). Regarding the effect of sex, lowercase letters (x, y) in the same column indicate differences in the same sex (M or F) between the SEL and CONT groups. Differences in uppercase letters (X, Y) in the same row indicate differences between males and females within the same group (SEL or CONT).

Cooking loss and SF

The treatment did not affect CL, corroborating the results of Castro-Ríos and Narvaéz-Solarte (2013), Svoboda et al. (2009), and Wolter et al. (1999), who found no significant effect of dietary selenium on meat CL. The CL values varied over time, with higher values at T14 and T28 than at T21 (Table 3). However, despite these fluctuations, there was no overall increase in CL during storage.

The SF was influenced by both treatment and storage time. The SEL group showed lower SF values at T14 and T21 than the CONT group, with overall means of 54.65 N for SEL and 58.04 N for CONT ($P < 0.05$).

In both groups, SF levels decreased with increasing storage time. Meat tenderness usually increases during storage because of the increased activity of proteolytic enzymes and a reduction in the strength of connective tissues (Hopkins, 2017). Although the SEL group presented tender meat, both groups showed moderate to hard tenderness, considering that meat with SF values between 42.87 N and 52.68 N has moderate tenderness, whereas values greater than 52.68 N are considered hard (Destefanis et al., 2008).

The tenderness of meat is influenced by its water-holding capacity (WHC); consequently, a lower WHC in meat tends to result in tougher meat after cooking (L. Chen et al., 2015). Meat with lower water retention, as evidenced by the higher DL and CL values, was also associated with low fat content and may have contributed to the moderate tenderness of the meat in both groups. Conversely, Ju et al. (2021) found no effects of pigs fed different levels of organic selenium on SF, CL, or DL in pork meat.

Regarding the effects of sex and treatment on CL and SF, females in the SEL group had lower CL and more tender meat than did males ($P < 0.05$), whereas males in the CONT group had lower SF than did females ($P < 0.05$).

As previously mentioned, WHC reflects meat tenderness. Females in the SEL group had lower CL values, which may reflect meat tenderness. A previous study also found that males had lower pH values, which influenced their WHC; hence, pork from males underwent further water loss during exudation and cooking (Richardson et al., 2018), negatively affecting meat tenderness.

The difference in CL may also be due to myofibril shrinkage during the process, which may be influenced by cooking time and temperature, because high temperatures cause protein denaturation and intermuscular, intramuscular, and subcutaneous fat loss (Jensen et al., 2007).

Lipid oxidation and protein oxidation

Lipid oxidation did not differ between treatments ($P < 0.05$). However, storage time increased lipid oxidation, with higher values observed at 21 and 28 days, and a peak at 14 days (Table 3).

Similarly, protein oxidation, as evaluated by carbonyl content, did not differ between treatments; it differed among time points only in the CONT group ($P < 0.05$), with increased oxidation at T21 and T28 (Table 3).

Despite the increase in TBARS levels throughout storage, the values remained lower than 1 mg MDA/kg, which is considered the threshold for the perception of rancidity

(Ripoll et al., 2011). The MDA content of meat is an important marker of lipid oxidation intensity because MDA is one of the most important metabolites of lipid peroxides. It is generated by lipid oxidation reactions induced by oxygen radicals in tissues (Pappas et al., 2012; X. Zhan et al., 2007). Lean meat usually has low levels of lipid oxidation, and the lipid content of the pork meat used in this study confirms this effect.

Lipid and protein oxidation processes are interrelated, with lipid oxidation products acting as precursors that accelerate protein oxidation (Geng et al., 2023). Therefore, the increase in carbonyl content in the CONT group during refrigeration may be related to lipid oxidation. Conversely, in the SEL group, the stability of the carbonyl values despite the increase in TBARS indicated a positive effect of organic selenium throughout the storage period.

The oxidation of lipids and proteins affects the redox stability of myoglobin, the protein responsible for meat color, thereby favoring discoloration during storage (Domínguez et al., 2021; Terevinto et al., 2023). Hence, it can be inferred that although organic selenium did not control the oxidation of lipids and the formation of carbonyls, it had a protective effect against myoglobin oxidation, thus maintaining meat color stability in the group supplemented with organic selenium.

Carbonyl content was lower in females than in males only in the SEL group ($P < 0.05$). In contrast, sex did not affect lipid oxidation (Table 3). Protein oxidation negatively affects meat texture, juiciness, and tenderness (Bao et al., 2021). Thus, lower protein oxidation in the meat of females may have contributed to the greater tenderness observed in meat from females in the SEL group.

Lipid content

Lipid levels in pork meat from animals subjected to different diets were not affected by treatment or sex ($P < 0.05$). In both groups, the lipid content was considered low (<1%) (Table 3).

Intramuscular fat (IMF) content plays an important role in pork quality attributes, particularly sensory properties. The IMF acts as a barrier against the loss of muscle juice during cooking, thereby increasing water retention and the sensation of juiciness and tenderness in meat (Aaslyng et al., 2003). Intramuscular fat content improves the sensory profile of pork, whereas a low amount of fat leads to less taste (Alfaia et al., 2019).

Genetic selection seeking to reduce the subcutaneous fat index in commercial crossbred pigs also markedly reduces the IMF, causing a significant negative effect on the sensory properties (flavor, juiciness, and tenderness) and, consequently, on the acceptability of pork meat by consumers. In this way, pig farming professionals have developed strategies in pork production seeking greater amounts of IMF to meet consumer demands without increasing subcutaneous fat and yet considering health concerns (Madeira et al., 2017).

DeVol et al. (1988) demonstrated that when IMF is reduced to below 2%–2.5%, the sensory characteristics of pork, such as juiciness, tenderness, and acceptability, are negatively affected. According to Bertol et al. (2017), the IMF content in pork ranges from

1% to 4%, and in current industrial production systems, more than 50% of animals have marbling content that is less than or just approaching the minimum desirable level to ensure technological and sensorial quality. Therefore, the low IMF content of the meat from the animals in the experiment might have influenced other physicochemical characteristics of the meat, such as the low water retention capacity and toughness of the meat.

Conclusions

Supplementation of the diet of finishing pigs with organic selenium for 50 days promoted significant nutritional enrichment of the meat, enabling a claim of selenium-enriched pork meat. Supplementation also promoted beneficial technological effects in pork stored under vacuum for 28 d, increasing tenderness and color stability.

Acknowledgment

The authors disclose the receipt of the following financial support for this article. This work was supported by Phileo by Lesaffre and PUCPR.

References

Aaslyng, M. D., Bejerholm, C., Ertbjerg, P., Bertram, H. C., & Andersen, H. J. (2003). Cooking loss and juiciness of pork in relation to raw meat quality and cooking procedure. *Food Quality and Preference, 14*(4), 277-288. doi: 10.1016/S0950-3293(02)00086-1

Abdolmohammad-Zadeh, H., Jouyban, A., Amini, R., & Sadeghi, G. (2013). Nickel-aluminum layered double hydroxide as a nano-sorbent for the solid phase extraction of selenium, and its determination by continuous flow HG-AAS. *Microchimica Acta, 180*(7), 619-626. doi: 10.1007/s00604-013-0967-x

Alfaia, C. M., Lopes, P. A., Madeira, M. S., Pestana, J. M., Coelho, D., Toldrá, F., & Prates, J. A. M. (2019). Current feeding strategies to improve pork intramuscular fat content and its nutritional quality. *Advances in Food and Nutrition Research, 89*(3), 53-94. doi: 10.1016/bs.afnr.2019.03.006

American Meat Science Association (2012). *Meat color measurement guidelines.* AMSA.

American Meat Science Association (2015). *Research guidelines for cookery, sensory evaluation, and instrumental tenderness measurements of meat* (2nd ed.). AMSA.

Associação Brasileira de Proteína Animal (2023). *Relatório anual.* ABPA. https://abpa-br.org/abpa-relatorio-anual

Association of Official Analytical Chemists (2016). *Official methods of analysis* (20nd ed.). AOAC.

Bao, Y., Ertbjerg, P., Estévez, M., Yuan, L., & Gao, R. (2021). Freezing of meat and aquatic food: underlying mechanisms and implications on protein oxidation. *Comprehensive Reviews in Food Science and Food Safety, 20*(6), 5548-5569. doi: 10.1111/1541-4337.12841

Bertol, T. M., Coldebella, A., Santos, J. I., Fº., & Guidoni, A. L. (2017). Swine carcasses classified by degree of exudation and marbling content. *Pesquisa Agropecuária Brasileira, 52*(2), 121-128. doi: 10.1590/S01 00-204X2017000200006

Bobček, B., Lahučký, R., Mrázová, J., Bobček, R., Novotná, K., & Vašíček, D. (2004). Effects of dietary organic selenium supplementation on selenium content, antioxidative status of muscles and meat quality of pigs. *Czech Journal of Animal Science, 49*(9), 411-417. doi: 10.17221/4326-CJAS

Brown, K. M., & Arthur, J. R. (2001). Selenium, selenoproteins and human health: a review. *Public Health Nutrition, 4*(2b), 593-599. doi: 10.1079/phn2001143

Cai, S. J., Wu, C. X., Gong, L. M., Song, T., Wu, H., & Zhang, L. Y. (2012). Effects of nano-selenium on performance, meat quality, immune function, oxidation resistance, and tissue selenium content in broilers. *Poultry Science, 91*(10), 2532-2539. doi: 10.3382/ps.2012-02160

Caldara, F. R., Moi, M., Santos, L. S., Paz, I. C. L. A., Garcia, R. G., Nääs, I. A., & Fernandes, A. R. M. (2013). Carcass characteristics and qualitative attributes of pork from immunocastrated animals. *Asian-Australasian Journal of Animal Sciences, 26*(11), 1630-1636. doi: 10.5713/ajas.2013.13160

Calvo, L., Toldrá, F., Aristoy, M. C., López-Bote, C. J., & Rey, A. I. (2016). Effect of dietary organic selenium on muscle proteolytic activity and water-holding capacity in pork. *Meat Science, 121*(11), 1-11. doi: 10.1016/j.meatsci.2016.05.006

Calvo, L., Toldrá, F., Rodríguez, A. I., López-Bote, C. J., & Rey, A. I. (2017). Effect of dietary selenium source (organic vs. mineral) and muscle pH on meat quality characteristics of pigs. *Food Science and Nutrition, 5*(1), 94-102. doi: 10.1002/fsn3.368

Castro-Ríos, K., & Narvaéz-Solarte, W. (2013). Sensory quality and cooking loss in pork meat: effect of sex and source of selenium. *Biotecnología en el Sector Agropecuario y Agroindustrial, 11*(1), 130-135. https://revistas.unicauca.edu.co/index.php/biotecnologia/article/view/289/488

Chen, J., Tian, M., Guan, W., Wen, T., Yang, F., Chen, F., Zhang, S., Song, J., Ren, C., Zhang, Y., & Song, H. (2019). Increasing selenium supplementation to a moderately reduced energy and protein diet improves antioxidant status and meat quality without affecting growth performance in finishing pigs. *Journal of Trace Elements in Medicine and Biology: Organ of the Society for Minerals and Trace Elements, 56*(6), 38-45. doi: 10.1016/j.jtemb.2019.07.004

Chen, L., Zhou, G., & Zhang, W. (2015). Effects of high oxygen packaging on tenderness and water holding capacity of pork through protein oxidation. *Food and Bioprocess Technology, 8*(11), 2287-2297. doi: 10. 1007/s11947-015-1566-0

Cisneros, F., Ellis, M., McKeith, F. K., McCaw, J., & Fernando, R. L. (1996). Influence of slaughter weight on growth and carcass characteristics, commercial cutting and curing yields, and meat quality of barrows and gilts from two genotypes.

Journal of Animal Science, 74(5), 925-933. doi: 10.2527/1996.745925x

Collery, P. (2018). Strategies for the development of selenium-based anticancer drugs. *Journal of Trace Elements in Medicine and Biology: Organ of the Society for Minerals and Trace Elements, 50*(6), 498-507. doi: 10.1016/j.jtemb.2018.02.024

Colombo, G., Clerici, M., Garavaglia, M. E., Giustarini, D., Rossi, R., Milzani, A., & Dalle-Donne, I. (2016). A step-by-step protocol for assaying protein carbonylation in biological samples. *Journal of Chromatography. B, Analytical Technologies in the Biomedical and Life Sciences, 1019*(8), 178-190. doi: 10.1016/j.jchromb.2015.11.052

Crackel, R. L., Gray, I. J., Pearson, A. M., Booren, A. M., & Buckley, D. J. (1988). Some further observations on the TBA test as an index of lipid oxidation in meats. *Food Chemistry, 28*(3), 187-196. doi: 10.1016/0308-8146(88)90050-7

Destefanis, G., Brugiapaglia, A., Barge, M. T., & Dal Molin, E. (2008). Relationship between beef consumer tenderness perception and Warner–Bratzler shear force. *Meat Science, 78*(3), 153-156. doi: 10.1016/j.meatsci.2007.05.031

Devol, D. L., Mckeith, F. K., Bechtel, P. J., Novakofski, J., Shanks, R. D., & Carr, T. R. (1988). Variation in composition and palatability traits and relationships between muscle characteristics and palatability in a random sample of pork carcasses. *Journal of Animal Science, 66*(2), 385-395. doi: 10.2527/jas1988.662385x

Domínguez, R., Pateiro, M., Munekata, P. E S., Zhang, W., Garcia-Oliveira, P., Carpena, M., Prieto, M. A., Bohrer, B., & Lorenzo, J. M. (2021). Protein oxidation in muscle foods: a comprehensive review. *Antioxidants, 11*(1), 1-24. doi: 10.3390/antiox11010060

Downs, K. M., Hess, J. B., & Bilgili, S. F. (2000). Selenium source effect on broiler carcass characteristics, meat quality and drip loss. *Journal of Applied Animal Research, 18*(1), 61-72. doi: 10.1080/09712119.2000.9706324

Geng, L., Liu, K., & Zhang, H. (2023). Lipid oxidation in foods and its implications on proteins. *Frontiers in Nutrition, 10*(6), 1192-2199. doi: 10.3389/fnut.2023.1192199

Gravador, R. S., Luciano, G., Jongberg, S., Bognanno, M., Scerra, M., Andersen, M. L., Lund, M. N., & Priolo, A. (2015). Fatty acids and oxidative stability of meat from lambs fed carob-containing diets. *Food Chemistry, 182*(17), 27-34. doi: 10.1016/j.foodchem.2015.02.094

Hopkins, D. L. (2017). The eating quality of meat: II-Tenderness. In F. Toldrá (Ed.), *Lawrie's meat science* (pp. 357-381). UK.

Instrução Normativa n° 75, de 08 de outubro de 2020. *Diário Oficial da União nº 195 - Sessão A.* Ministério da Saúde/Agência Nacional de Vigilância Sanitária/Diretoria Colegiada.

Jankowiak, H., Cebulska, A., & Bocian, M. (2021). The relationship between acidification (pH) and meat quality traits of polish white breed pigs. *European Food Research and Technology, 247*(11), 2813-2820. doi: 10.1007/s00217-021-03837-4

Jeleníková, J., Pipek, P., & Miyahara, M. (2008). The effects of breed, sex, intramuscular fat and ultimate pH on pork tenderness. *European Food Research and Technology, 227*(4), 989-994. doi: 10.1007/s00217-007-0810-x

Jensen, J. M., Prestat, C., Ryan, K. J., Robbins, K. L., Homco-Ryan, C. L., Mckeith, F., & Brewer, M. S. (2007). Enhancement solution effects on shelf-life, color and sensory characteristics of pork chops during retail display. *Journal of Food Quality, 26*(4), 271-283. doi: 10.1111/j.1745-4557.2003.tb00245.x

Jiang, J., Tang, X., Xue, Y., Lin, G., & Xiong, Y. L. (2017). Dietary linseed oil supplemented with organic selenium improved the fatty acid nutritional profile, muscular selenium deposition, water retention, and tenderness of fresh pork. *Meat Science, 131*(9), 99-106. doi: 10.1016/j.meatsci.2017.03.014

Jongberg, S., Tørngren, M. A., Gunvig, A., Skibsted, L. H., & Lund, M. N. (2013). Effect of green tea or rosemary extract on protein oxidation in Bologna type sausages prepared from oxidatively stressed pork. *Meat Science, 93*(3), 538-546. doi: 10.1016/j.meatsci.2012.11.005

Ju, Y., Liu, M., Huang, L., Luo, Y., Qi, L., Ye, J., Wu, X., Cao, N., Bo, J., Liu, X., Yan, Y., & Li, Y. (2021). Effects of selenium Auricularia cornea culture supplementation on growth performance, antioxidant status, tissue selenium concentration and meat quality in growing-finishing pigs. *Animals, 11*(9), 2701. doi: 10.3390/ani11092701

Kim, Y. Y., & Mahan, D. C. (2001). Comparative effects of high dietary levels of organic and inorganic selenium on selenium toxicity of growing-finishing pigs. *Journal of Animal Science, 79*(4), 942-948. doi: 10.2527/2001.794942x

Li, J. G., Zhou, J. C., Zhao, H., Lei, X. G., Xia, X. J., Gao, G., & Wang, K. N. (2011). Enhanced water-holding capacity of meat was associated with increased Sepw1 gene expression in pigs fed selenium-enriched yeast. *Meat Science, 87*(2), 95-100. doi: 10.1016/j.meatsci.2010.05.019

Lisiak, D., Janiszewski, P., Blicharski, T., Borzuta, K., Grześkowiak, E., Lisiak, B., Powałowski, K., Samardakiewicz, Ł., Batorska, M., Skrzymowska, K., & Hammermeister, A. (2014). Effect of selenium supplementation in pig feed on slaughter value and physicochemical and sensory characteristics of meat. *Annals of Animal Science, 14*(1), 213-222. doi: 10.2478/aoas-2013-0063

Lundstrom, K., & Malmfors, G. (1985). Variation in light scattering and water-holding capacity along the porcine Longissimus dorsi muscle. *Meat Science, 15*(4), 203-214. doi: 10.1016/0309-1740(85)90076-2

Madeira, M. S., Lopes, P. A., Costa, P., Coelho, D., Alfaia, C. M., & Prates, J. A. M. (2017). Reduced protein diets increase intramuscular fat of psoas major, a red muscle, in lean and fatty pig genotypes. *Animal, 11*(11), 2094-2102. doi: 10.1017/S1751731117000921

Mahan, D. C., & Parrett, N. A. (1996). Evaluating the efficacy of selenium-enriched yeast and sodium selenite on

tissue selenium retention and serum glutathione peroxidase activity in grower and finisher swine. *Journal of Animal Science, 74*(12), 2967-2974. doi: 10.2527/1996.74122967x

Mahan, D. C., Azain, M., Crenshaw, T. D., Cromwell, G. L., Dove, C. R., Kim, S. W., Lindemann, M. D., Miller, P. S., Pettigrew, J. E., Stein, H. H., & Van Heugten, E. (2014). Supplementation of organic and inorganic selenium to diets using grains grown in various regions of the United States with differing natural Se concentrations and fed to grower–finisher swine. *Journal of Animal Science, 92*(11), 4991-4997. doi: 10.2527/jas.2014-7735

Mahan, D. C., Cline, T. R., & Richert, B. (1999). Effects of dietary levels of selenium-enriched yeast and sodium selenite as selenium sources fed to growing-finishing pigs on performance, tissue selenium, serum glutathione peroxidase activity, carcass characteristics, and loin quality. *Journal of Animal Science, 77*(8), 2172-2179. doi: 10.2527/1999.7782172x

Ministério da Agricultura, Pecuária e Abastecimento - MAPA (2016). *Suinocultura de baixa emissão de carbono: tecnologias de produção mais limpa e aproveitamento econômico dos resíduos da produção de suínos.* MAPA. Secretaria de Mobilidade Social, do Produtor Rural e do Cooperativismo. Brasília, Brasil.

Mokrzycki, W. S., & Tatol, M. (2012). Colour difference ΔE - A survey. *Machine Graphics and Vision International Journal, 20*(4), 383-411. doi: 10.5555/3166160.3166161

Pappas, A. C., Zoidis, E., Papadomichelakis, G., & Fegeros, K. (2012). Supranutritional selenium level affects fatty acid composition and oxidative stability of chicken breast muscle tissue. *Journal of Animal Physiology and Animal Nutrition, 96*(3), 385-394. doi: 10.1111/j.1439-0396.2011.01152.x

Peres, L. M., Bridi, A. M., Silva, C. A., Andreo, N., Barata, C. C. P., & Dário, J. G. N. (2014). Effect of supplementing finishing pigs with different sources of chromium on performance and meat quality. *Revista Brasileira de Zootecnia, 43*(7), 369-375. doi: 10.1590/S1516-35982014000700005

Portaria n° 365, de 16 de julho de 2021. Diário Oficial da União nº 138-A - Sessão 1. Ministério da Agricultura, Pecuária e Abastecimento/Secretaria de Defesa Agropecuária.

Richardson, E. L., Fields, B., Dilger, A. C., & Boler, D. D. (2018). The effects of ultimate pH and color on sensory traits of pork loin chops cooked to a medium-rare degree of doneness. *Journal of Animal Science, 96*(9), 3768-3776. doi: 10.1093/jas/sky258

Ripoll, G., Joy, M., & Muñoz, F. (2011). Use of dietary vitamin E and selenium (Se) to increase the shelf life of modified atmosphere packaged light lamb meat. *Meat Science, 87*(1), 88-93. doi: 10.1016/j.meatsci.2010.09.008

Salueña, B. H., Gamasa, C. S., Rubial, J. M. D., & Odriozola, C. A. (2019). CIELAB color paths during meat shelf life. *Meat Science, 157*(11), 107889. doi: 10.1016/j.meatsci.2019.107889

Santos, S. K., Rosset, M., Miqueletto, M. M., Jesus, R. M. M., Sotomaior, C. S., & Macedo, R. E. F. (2020). Effects of dietary supplementation with quebracho tannins on oxidation parameters and shelf life of lamb meat. *Food Science and Technology, 42*(1), e55920. doi: 10.1590/fst.55920

Seydim, A. C., Acton, J. C., Hall, M. A., & Dawson, P. L. (2006). Effects of packaging atmospheres on shelf-life quality of ground ostrich meat. *Meat Science, 73*(3), 503-510. doi: 10.1016/j.meatsci.2006.01.010

Silva, V. A., Bertechini, A. G., Clemente, A. H. S., Freitas, L. F. V. B. de, Nogueira, B. R. F., Oliveira, B. L. de, & Ramos, A. L. S. (2019). Different levels of selenomethionine on the meat quality and selenium deposition in tissue of finishing pigs. *Journal of Animal Physiology and Animal Nutrition, 103*(6), 1866-1874. doi: 10.1111/jpn.13179

Štefanka, P., Bučko, O., Gálik, B., Čanigová, M., & Debrecéni, O. (2013). The analysis of the carcass characteristics and physical-technological quality of pork after the using diet with the addition of organic chromium and selenium. *Journal of Central European Agriculture, 14*(3), 1039-1049. doi: 10.5513/JCEA01/14.3.1302

Svoboda, M., Fajt, Z., Baňoch, T., Drábek, J., & Saláková, A. (2010). The use of selenium enriched Enterococcus faecium as an alternative selenium source for growing-finishing pigs. *Acta Veterinaria Brno, 79*(4), 511-517. doi: 10.2754/avb201079040511

Svoboda, M., Saláková, A., Fajt, Z., Kotrbácek, V., Ficek, R., & Drábek, J. (2009). Efficacy of Se-enriched alga Chlorella spp. and Se- enriched yeast on tissue selenium retention and carcass characteristics in finisher pigs. *Acta Veterinaria Brno, 78*(4), 579-587. doi: 10.2754/avb200978040579

Terevinto, A., Cabrera, M. C., Zacarri, F., & Saadoun, A. (2023). The oxidative and color stability of beef from steers fed pasture of concentrate during retail display. *Animals, 13*(18), 2972. doi: 10.3390/ani1318 2972

Thun, R., Gajewski, Z., & Janett, F. (2006). Castration in male pigs: techniques and animal welfare issues. *Journal of Physiology and Pharmacology, 57*(8), 189-194. https://www.jpp.krakow.pl/journal/archive/11_06_s8/articles/14_article.html

Vignola, G., Lambertini, L., Mazzone, G., Giammarco, M., Tassinari, M., Martelli, G., & Bertin, G. (2009). Effects of selenium source and level of supplementation on the performance and meat quality of lambs. *Meat Science, 81*(4), 678-685. doi: 10.1016/j.meatsci.2008.11.009

Vyncke, W. (1970). Direct determination of the thiobarbituric acid value in trichloroacetic acid extracts of fish as e measure of oxidative rancidity. *Fette, Seifen, Anstrichmittel, 72*(12), 1084-1087. doi: 10.1002/lipi. 19700721218

Warner, R. (2014). Measurement of meat quality: measurements of water-holding capacity and color - objective and subjective. In C. Devine, & M. Dikeman (Eds.), *Encyclopedia of meat sciences* (2nd ed., v. 2, pp. 164-171). Oxford.

Wolter, B., Ellis, M., Mckeith, F. K., Miller, K. D., & Mahan, D. C. (1999). Influence of dietary selenium source on growth performance, and carcass and meat quality characteristics in pigs. *Canadian Journal of Animal Science, 79*(1), 119-121. doi: 10.4141/A98-028

Zhan, X., Wang, M., Zhao, R., Li, W., & Xu, Z. (2007). Effects of different selenium source on selenium distribution, loin quality and antioxidant status in finishing pigs. *Animal Feed Science and Technology, 132*(3-4), 202-211. doi: 10.1016/j.anifeedsci.2006.03.020

Zhang, S., Xie, Y., Li, M., Yang, H., Li, S., Li, J., Xu, Q., Yang, W., & Jiang, S. (2020). Effects of different selenium sources on meat quality and shelf life of fattening pigs. *Animals, 10*(4), 615. doi: 10.3390/ani 10040615

Zhao, J., Li, K., Su, R., Liu, W., Ren, Y., Zhang, C., Du, M., & Zhang, J. (2017). Effect of dietary Tartary buckwheat extract supplementation on growth performance, meat quality and antioxidant activity in ewe lambs. *Meat Science, 134*(12), 79-85. doi: 10.1016/j.meatsci.2017.07.016