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Effect of castration at different ages on growth and carcass characteristics of Kilis goats: Physicochemical changes and fatty acid profile of meat

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Abstract

Aim of study: In this study, the effects of castration at different months of age on carcass and meat characteristics in goats reared under semi-extensive prolonged fattening conditions were investigated.

Area of study: The experiment was conducted in the Yayladağı district of Hatay province, Türkiye.

Material and methods: The experiment was conducted with 48 male goats from the Kilis goat breed randomly allocated to 4 groups of 12 individuals each. Intact goats (uncastrated goats) functioned as the control group. Each of the other 3 groups was castrated using burdizzo forceps at the 4th, 6th, and 8th months after birth. During the experiment, all goats were exposed to the same management and feeding conditions. The effects of castration age on growth, carcass and slaughter parameters, as well as the muscle characteristics of the *Longissimus thoracis*, *Semitendinosus*, *Psoas major*, *Triceps brachii*, and *Vastus lateralis* were investigated.

Main results: At the end of the fattening period, castration at 4-months age increased the weight of muscle tissue ($P < 0.05$) and fat deposition ($P < 0.001$). Additionally, an increase in intramuscular fat and tenderness of the meat, and a decrease in redness and cooking loss were observed with castration at 6-months age ($P < 0.05$). Despite the increase in adiposity with early castration, the oleic acid and the ratio of unsaturated fatty acids to saturated fatty acids (UFA:SFA), hypocholesterolemic/hypercholesterolemic index (h/H) and Δ^9 desaturase index of the meat tended to increase as the castration age decreased. In conclusion, the most appropriate castration age is at 6-months in terms of growth performance and at 4- and/or 6-months in terms of meat quality.

Research highlights: Castration of goats at the correct age plays a crucial role in managing herd dynamics, enhancing meat quality, improving efficiency, and meeting market demands in goat farming.

Keywords: castration; cooking loss; intramuscular fat; meat quality.

Efecto de la castración a diferentes edades sobre el crecimiento y las características de la canal en cabras Kilis: Cambios fisicoquímicos y perfil de ácidos grasos de la carne

Resumen

Objetivo del estudio: En este estudio se investigaron los efectos de la castración a diferentes edades (en meses) sobre las características de la canal y de la carne en cabras criadas bajo condiciones de engorde prolongado en un sistema semi-extensivo.

Área de estudio: El experimento se llevó a cabo en el distrito de Yayladağı, en la provincia de Hatay, Türkiye.

Materiales y métodos: El experimento se realizó con 48 cabritos machos de la raza Kilis, asignados aleatoriamente a 4 grupos de 12 individuos cada uno. Los machos íntegros (no castrados) funcionaron como grupo control. Cada uno de los otros 3 grupos fue castrado con pinzas Burdizzo al 4.º, 6.º y 8.º mes de vida. Durante el experimento, todos los animales fueron sometidos a las mismas condiciones de manejo y alimentación. Se investigaron los efectos de la edad de castración sobre el crecimiento, los parámetros de la canal y del sacrificio, así como las características musculares de los músculos *Longissimus* *thoracis*, *Semitendinosus*, *Psoas major*, *Triceps brachii* y *Vastus lateralis*.

Resultados principales: Al final del período de engorde, la castración a los 4 meses de edad aumentó el peso del tejido muscular ($P < 0,05$) y la deposición de grasa ($P < 0,001$). Además, se observó un aumento en la grasa intramuscular y la terneza de la carne, así como una disminución en el enrojecimiento y la pérdida por cocción con la castración a los 6 meses de edad ($P < 0,05$). A pesar del incremento en la adiposidad con la castración temprana, el contenido de ácido oleico, la proporción de ácidos grasos insaturados a saturados (UFA:SFA), el índice hipocolesterolémico/hipercolesterolémico (h/H) y el índice de la enzima Δ9-desaturasa de la carne tendieron a aumentar a medida que disminuía la edad de castración. En conclusión, la edad de castración más adecuada es a los 6 meses en términos de rendimiento productivo, y a los 4 y/o 6 meses en términos de calidad de la carne.

Aspectos destacados de la investigación: La castración de los cabritos a la edad adecuada desempeña un papel crucial en la gestión de la dinámica del rebaño, la mejora de la calidad de la carne, el aumento de la eficiencia y el cumplimiento de las demandas del mercado en la producción caprina.

Palabras clave: calidad de la carne; castración; grasa intramuscular; pérdida por cocción.

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Introduction

Goat meat is a lean and highly nutritious food that is consumed as a staple food in many parts of the world, especially in developing countries (Barkley, 2012). Two types of goat meat are popular in Europe: chevon and cabrito (capretto). Chevon is goat meat obtained from older weaned kids, while cabrito is typically milk-fed young goat kids (Dhanda et al., 1999). In Türkiye, which has approximately 12 million head of goats, the meat produced from male goats around 1-year-old (chevon) is in high demand and can be sold at high prices. Additionally, consumers with goat meat consumption habits prefer meat produced from castrated male goats (Hatipoğlu et al., 2016; Koşum et al., 2019).

The main income from Türkiye's goat production is obtained through the milk yield of dams and the fattening of male offspring, which is generally carried out in extensive or semi-intensive conditions with local breeds. Male goats are weaned at the age of 3 months and then remain in the pasture with their dams. In order to produce more desirable meat, the bucks are castrated after weaning and slaughtered at 1-2 years old (Koşum et al., 2019). Castration increases the fat content in the carcass and removes the undesirable odor in meat.

As some saturated fatty acids such as myristic and palmitic acids increase blood low-density lipoproteins (LDL), there has been a decreasing trend in red meat consumption (EFSA, 2010). However, stearic acid increases LDL cholesterol, and lower high-density lipoprotein (HDL). In this sense, goat meat has become an alternative food for human who want to eat lean red meat, thanks to its low fat and cholesterol content (Park et al., 1991) compared to beef, pork and lamb (Swize et al., 1992; Madruga et al., 2001). It has also been reported that goat meat fat has a higher level of polyunsaturated fatty acids (PUFA) than beef and sheep meat (Park and Washingyon, 1993; Enser et al., 1998). On the other hand, there are some prejudices about goat meat consumption: goat meat causes diarrhoea because the meat is stored incorrectly, has an unpleasant odor, low-fat content, and is tough (Koşum et al., 2019). Bishei and Emami (1988) noted that castrated Nadooshani goats were found to excel in meat aroma, flavor, and tenderness, according to evaluations from a non-professional tasting panel. Therefore, consumers may prefer castrated male goats as the meat is less odorous and has more fat, making it more desirable. Parameters such as gender and slaughtering age also play an important role in the consumer's preference for goat meat (Mahgoub et al., 2004; Zamiri et al., 2012).

Castration, which diminishes the anabolic effects of testosterone by lowering its secretion from the testicles, leads to a reduction in body weight gain and growth rate in male goats (Stafford & Mellor, 2005). However, it has several advantages; (i) eliminating the strong male odor, (ii) preventing mating after the age of puberty, (iii) reducing aggression, and (iv) avoiding unwanted pregnancies by stopping the activities of the testicular and androgens (Teixeira et al., 2020). Castration also positively affects meat quality and carcass composition, particularly with marbling (Kebede et al., 2008). Thus, it is widely used in goat breeding in different countries (Teixeira et al., 2020). However, there is uncertainty about the age of castration under farm conditions, and it differs from breeder to breeder. Therefore, it is necessary to determine the optimum castration age in terms of growth performance, carcass characteristics and meat quality.

In this study, we aimed to investigate the effects of castration timing on growth performance, carcass characteristics, and the meat fatty acid profile in Kilis goats at different castration ages.

Material and methods

Animal management

The study procedures were approved by the Local Animal Care and Ethics Committee of Hatay Mustafa Kemal University (Regd. No: 2018/3-1). The experiment was conducted with 48 male Kilis goat kids in the Yayladağı district of Hatay province. The farm is located at an altitude of 400 m above sea level and longitude of 35.93°E and a latitude of 36.09°N in the Eastern Mediterranean region, where climatic conditions are hot and dry in summer, and warm and rainy in winter. Kids born between 20 January and 5 February 2020 were weaned at approximately 90 days of age. They were grazed during the daytime with the does, starting about two weeks after birth, until weaning. After weaning, the kids were assigned to four groups (each group consisted of 12 bucks). The kids in three different groups were castrated at 4-, 6- and 8-months ages, using burdizzo forceps. One group of intact kids (bucks) was the control group. Xylazine (Alfazyne 2%) was administered at a dose of 0.05 mg/kg intramuscularly for sedation to the animals before castration. Then, Lidocaine (Jetokain 2%), as a local anaesthetic, was injected subcutaneously at a dose of 2 cc to the area where the Burdizo forceps would be applied. Castration ages were selected as early (4 months), middle (6 months) and late (8 months) periods based on the pubertal periods of the kids. Puberty in male kids typically marks the time when they begin developing secondary sexual characteristics and reproductive capacity. The timing of castration relative to these developmental stages was carefully selected to explore its effects on growth, carcass and meat quality.

The kids in each group were raised in a closed pen on a private farm and were subjected to the same care and feeding conditions.

After grazing during the daytime, the kids returned to the pen in the evening and were provided with a concentrate feed which contained 18% crude protein and 2400 kcal metabolizable energy in 1 kg dry matter, at 500 g per animal (NRC, 1985). They were able to access water *ad libitum*. Experimental animals were weighed after fasting for 12 hours once a month from 4 weeks of age to 12 months of age.

Slaughter conditions and carcass dissection

Weighing at the 12th month was accepted as the slaughter weight. To evaluate some carcass characteristics, these goats were slaughtered without stunning in the official municipal slaughterhouse of Hatay, according to Islamic tradition, and subsequently skinned individually (Kumar et al., 2023). After exsanguination, the weights of the hot carcass, skin, four legs, head and lung-liver-heart were determined separately. The cold carcass weight, including the retained kidneys and perinephric-pelvic fat, was determined after the carcasses were hung by both tarsal-metatarsal joints and kept in the fridge at 4 ºC for 24 h. Subsequently, the kidneys and the perinephric-pelvic fat were removed from the carcasses. The yields were calculated as the weight of the hot or cold carcass relative to the weight of the slaughter. The differences between the hot and cold carcass weights were determined as cooling loss.

After chilling, the carcasses were split into two halves, and the left half of the carcass was divided into five primal cuts: neck, ribs, shoulder, flank, and long leg as described by Colomer-Rocher et al. (1987). The *Longissimus thoracis* (LT) muscle area was determined using a planimeter between the 12th and 13th ribs (Zamiri et al., 2012). The LT area was drawn on tracing paper and scanned into a computer. The area of the LT was measured using the AutoCAD programme. Additionally, each primal cut of the carcass was dissected into muscle, bone, subcutaneous fat, intermuscular fat, and waste (such as nerves, tendons, connective tissue, etc.). The thickness of back fat was measured between the 12th and 13th ribs with a digital calliper (Zamiri et al., 2012).

Physicochemical and fatty acid analysis of muscles

Longissimus thoracis (LT), *Semitendinosus* (ST), *Psoas major* (PM), *Triceps brachii* (TB) and *Vastus lateralis* (VL) muscles obtained from the left half of the carcass during the carcass dissection were used to determine the meat quality characteristics, including dry matter, protein, intramuscular fat, ash, ultimate pH, titratable acidity, colour ($L*$ (lightness), $a*$ (redness) and $b*$ (yellowness),, hue angle, chroma), Warner Bratzler Shear Force (WBSF, N), cooking loss (%), and fatty acids. The analysis except for fatty acids was carried out in fresh muscle after 24 h post-mortem. The muscles were stored at -18ºC until analysis of fatty acids. The muscles were analysed for chemical composition according to the Association of Analytical Chemists methods (AOAC, 2000). Dry matter was obtained by oven drying at 105 ºC until constant weight (method 950.46, AOAC, 2000). Nitrogen content was determined by the Micro-Kjeldahl method (AOAC method 992.15) and protein was calculated by multiplying the total nitrogen content by a coefficient factor of 6.25. The intramuscular fat of muscles was extracted using chloroform:methanol (2:1 v/v) as reported by Folch et al. (1957). The ash content was obtained by dry ashing in a muffle furnace at 550ºC until constant weight (AOAC method 923.03). The ultimate pH (pH_{24}, measured at 24 h after slaughter) measurements were carried out on samples homogenized in distilled water (10:1 v/w water: sample) using an Ultra Turrax homogenizer (IKA T18 basic, Deutschland, Germany), and the pH values were measured using a digital pH meter (Orion, Thermo, Massachusetts, USA) calibrated with 4.01 and pH 7.00 standards. The pH meter was (re)calibrated at each measurement interval. Ten mL taken from homogenate prepared for pH measure was titrated with 0.1 N NaOH in the presence of phenolphthalein indicator. Titratable acidity was calculated as lactic acid.

Meat colour was measured in triplicate at 24 h postmortem on the surface of the LT (about 80 g), ST (85 g), PM (50 g), TB (110 g) and VL (240 g) muscles. The samples were allowed to bloom for 30 min, and the colour was evaluated using the CIELAB colour space. L^*, a^* and b^* values were measured using a Minolta CR 300 colorimeter (Minolta Camera Co., Osaka, Japan) with an aperture of 8 mm, illuminant D65, and 10° standard observer. The L^*, a^*, and b^* values were also used to calculate the hue angle and chroma values which represent the colour definition and intensity, respectively. These values were calculated according to:

$$\text{Hue angle} = \tan^{-1}\left(\frac{b^*}{a^*}\right)$$

$$\text{Chroma} = \sqrt{a^{*2}+b^{*2}}$$

Shear force was determined according to the method proposed by Cai et al. (2011) with minor modifications. Muscle samples were obtained from three animals in each castration group. Each sample was prepared with dimensions of 5 cm (length) × 2.5 cm (width) × 1.5 cm (height), ensuring that the length axis was aligned parallel to the orientation of the muscle fibres. Cooking loss was measured after cooking the meat samples in a water bath at 80 °C for 45 min as described by Honikel (1998). A total of 60 cuboids (5x4x3: muscle x castration age groups x animals) in each muscle were subjected to one cooking batch. The average measurement results for each castration group were used for cooking loss. The weight of the samples before and after cooking was measured, and the cooking loss was calculated as the weight of the cooked meat relative to the weight of the raw meat. Then, the cooked samples were cooled for 4 h at room temperature was cut with a cross-section against the fibre direction, which was measured using a Texture Analyser (TA-XT Plus, Stable Micro System) equipped with WBSF apparatus, setting the cross-head speed to 1 mm/s.

Fatty acid composition of muscles was carried out by referring to the method of Rule (1997), and Park &Washington (1993). The saponification and methylation of extracted fat from muscles were performed as reported by Güler & Dursun (2023). Fatty acid methyl esters (FAMEs) were analysed by a gas chromatography (Agilent 6890)-mass spectrometry (Agilent 5973N, Palo Alto, USA) coupled with a capillary column (Supelco SP-2380, 60 m length x 0.25 mm ID x 0.20 µm film thickness). Gas chromatography operating conditions for fatty acid analysis were applied as reported by Peng et al. (2010) with minor modifications. Peak identification was performed by comparing retention times and ion spectra from authentic standards (Sigma Aldrich Chemical Co., Steinheim, Germany) and spectra from the Mass Spectral Database (Wiley7n.1/Nist.02. L.). As noted by Seiquer et al. (2019), the proportion of each fatty acid was calculated as a percentage of the total fatty acids present in the sample. The analysis and peaks' areas were also checked using an internal standard (tridecanoic acid, 100 mg/L).

The fatty acid profile was used to determine several nutritional parameters of intramuscular fat in goat muscles. They were calculated according to the following equations:

$$\text{NVI}=\frac{18{:}0+18{:}1}{16{:}0}$$

$$\text{AI} =\frac{12{:}0+(4\text{x}14{:}0)+16{:}0}{\sum \text{UFA}}$$

$$\text{h/H} =\frac{\sum \text{n6}(18{:}2,\ 18{:}3,\ 20{:}3,\ 20{:}4,\ 22{:}4)+\sum \text{n3}(18{:}3,\ 20{:}5,\ 22{:}5,\ 22{:}6)+18{:}1\text{n9}+18{:}1\text{n7}}{14{:}0+16{:}0}$$

$$\text{DI} =\frac{\text{c9-18:1}}{18{:}0}$$

$$\text{EI}=\frac{18{:}0+\text{c9-18:1}}{16{:}0+\text{c9-16:1}+18{:}0+\text{c9-18:1}}$$

Where:

NVI: Nutritive value index
AI: Atherogenic index
h/H: hypocholesterolemic/Hypercholesterolemic index
DI: Δ^9 desaturase index
EI: Elongase index

Statistical analysis

Statistical analysis of the data was performed by One-way ANOVA and Duncan multiple range test procedures in the SPSS package program according to the following model:

$$Y_{ij}=\mu+\alpha_i+e_{ij}$$

Where,
Y_{ij}, recorded the value of the jth animal in the ith treatment group
μ, mean of the population
α_i, the effect of ith castration age group (intact, 4-, 6-, and 8-months of age)
e_{ij}, error term

The live weight of goats was analysed by repeated measure according to the following model:

$$Y_{ijk}=\mu+\alpha_i+\beta_j+(\alpha\beta)_{ij}+e_{ijk}$$

Where,
Y_{ijk}, recorded the value of live weight
μ, mean of the population
α_i, the effect of ith castration age group (intact, 4-, 6-, and 8-months of age)
β_j, the effect of jth time (4th, 5th, 6th …12th month)
$\alpha\beta_{ij}$, the effect of interaction between castration age and time
e_{ijk}, error term

The meat characteristics were analysed for 5 different muscles from each castration age. Statistical analysis of the meat characteristics was performed by Two-way ANOVA according to the following general linear model:

$$Y_{ijk}=\mu+\alpha_i+\beta_j+(\alpha\beta)_{ij}+e_{ijk}$$

Where,
Y_{ijk}, recorded the value of meat characteristics
μ, mean of the population
α_i, the effect of ith castration age group (intact, 4-, 6-, and 8-months of age)
β_j, the effect of jth muscle (LT, ST, PM, TB, VL)
$\alpha\beta_{ij}$, the effect of interaction between castration age and muscle
e_{ijk}, error term

Results

Growth and carcass characteristics

No behavioural disorders or health problems were observed in goats during the experiment. The monthly live weights of the goats in different treatment groups are presented in Fig. 1.

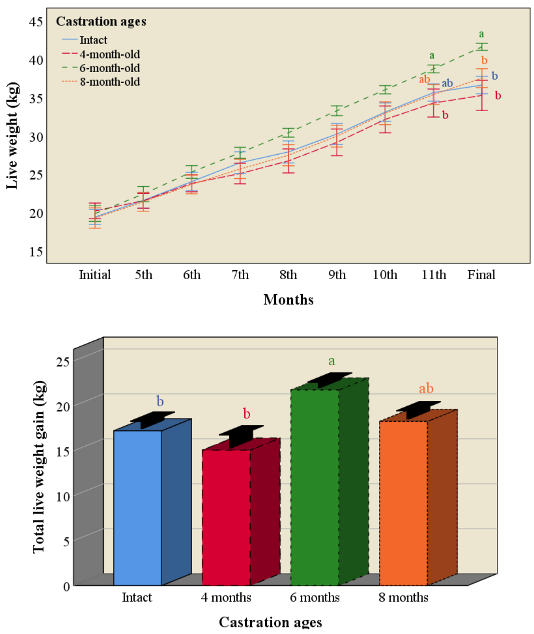


Figure 1. The average and total live weight gain of goats in different groups during the experiment. a-b The difference between castration ages is statistically significant (P <0.05).

There were no significant differences (P >0.05) in the live weight values of goats in different groups at the beginning of the experiment (Fig. 1). At the age of 12 months, the heaviest live weight was 41.6±0.46 kg in the group castrated at the age of 6 months (P <0.01).

The carcass characteristics obtained are shown in Table 1. The 6-month castrated group had the heaviest slaughter, hot and cold carcass weights (Table 1), consistent with their heavier live weights (Table 1). No significant differences (P >0.05) between the remaining groups were determined. Dressing percentages were calculated as 43.8±0.45%, 45.9±0.27%, 45.3±1.35%, 43.5±0.19% in the intact, 4-, 6- and 8-month-old castrated groups, respectively (P <0.05). There were also significant differences between the groups in terms of head, four legs, heart, and liver weights (Table 1; P <0.05). Additionally, a significant effect of castration at different ages was observed in the thickness of the back fat of the carcasses (P <0.001). The thickest mean back fat was measured in goats castrated at the 4- and 6-month-old castration groups and the thinnest in the intact and 8-month-old castrated groups.

Table 1. The average descriptive characteristics of the carcass in goats castrated at different ages.

Characteristics	Intact	4-month	6-month	8-month	P
Slaughter weight (kg)	35.9^{b}±1.10	35.2^{b}±0.43	41.6^{a}±1.23	37.2^{b}±0.33	0.003
Hot carcass weight (kg)	15.7^{b}±0.48	16.3^{b}±0.24	19.1^{a}±0.13	16.3^{b}±0.07	<0.001
Cold carcass weight (kg)	15.5^{b}±0.48	16.2^{b}±0.27	18.8^{a}±0.23	16.2^{b}±0.09	<0.001
Hot carcass ratio (%)	43.8^{b}±0.45	46.4^{a}±0.19	46.1^{ab}±1.35	43.9^{ab}±0.22	0.039
Cold carcass ratio (%)	43.2^{b}±0.45	45.9^{a}±0.27	45.3^{ab}±1.35	43.5^{ab}±0.19	0.041
Cooling loss (%)	1.02±0.20	1.58±0.52	1.02±0.22	1.27±0.03	0.270
Head (g)	2465^{a}±4.86	2073.3^{b}±6.32	2523.3^{a}±7.86	2295.0^{ab}±9.92	0.044
Four legs (g)	1120^{b}±4.72	1103.3^{b}±3.46	1285.0^{a}±8.03	1093.3^{b}±6.03	0.008
Skin (g)	2610±4.33	2580±5.85	2985±3.30	2715±4.14	0.506
Lung (g)	558.3±7.35	596.7±3.81	603.3±8.78	573.3±9.69	0.944
Liver (g)	691.7^{b}±6.55	685^{b}±3.29	855^{a}±2.91	698.3^{b}±6.48	0.034
Heart (g)	203.3^{b}±4.41	208.3^{b}±3.64	246.7^{a}±6.41	216.7^{ab}±1.67	0.036
Spleen (g)	110.0±7.64	116.7±6.01	106.7±9.93	98.3±6.01	0.470
Back-fat thickness (mm)	0.3^{b}±0.03	0.5^{a}±0.02	0.4^{a}±0.03	0.3^{b}±0.03	<0.001
Longissimus thoracis area (cm^2)	12.3^{ab}±1.45	11.1^{b}±0.53	14.8^{ab}±1.47	15.8^{a}±1.20	0.049
Kidney weight (g)	61.7±8.82	63.3±3.33	61.7±4.47	55.0±0.01	0.420
Kidney-pelvic fat weight (g)	85.0^{b}±9.24	205.0^{a}±8.03	173.3^{a}±9.19	118.3^{a}±9.63	0.031
Testicle weight (g)	148.3^{a}±2.28	16.7^{b}±9.28	33.3^{b}±6.01	61.7^{b}±4.55	0.002

The data were expressed as mean±standard error. a-b Means in the same row with different lowercase superscripts are significantly different among treatment groups (P <0.05).

As depicted in Table 2, castration at different ages affected muscle, bone, and fat tissue contents (%) in the different carcass joints (P <0.05).

The lowest relative percentage of muscle tissue (P < 0.05), and the highest subcutaneous and intramuscular fat weights (P <0.01) were obtained in the 4-month-old castrated group (Table 2). Castration age did not affect the proportional distribution of tissues (Table 2); however, the weights of the shoulder, ribs and long-leg were significantly (P <0.01) heavier in the 4-month groups (Table 3).

No significant differences (P >0.05) in bone percentages of the shoulder cuts of castrated groups were observed. Compared with the other groups, the shoulder weight from 8-month-old castrated goats had the lightest (P <0.05) muscle tissue and the subcutaneous and intermuscular fat tissue weights whilst the 4-month-old castrated goats had the heaviest weights (Table 3; P <0.001). Similarly, the heaviest muscle and fat tissue weights in the rib (P <0.05) and the long-leg carcass (P <0.01) cuts were obtained from the 4-month-old castrated goats.

The bone percentages of the castrated goats (4- or 6-months old when castrated) were lower (P <0.05) in the flank cut than in the other two groups (8-months old castrated and intact control). The highest muscle tissue and the lowest intermuscular fat percentages in the flank cut were found in the intact group (P <0.05).

Table 2. Proportional (%) distributions of different tissues in different carcass cuts of goats castrated at different ages.

Groups	Total	Bone	Muscle	SF	IMF	Waste^{ʒ}	Evap
	Neck						
Intact	10.3±0.64	29.9^{a}±0.45	60.6^{a}±1.00	1.1^{c}±0.87	2.2^{c}±0.05	4.5±1.25	1.6±0.33
4-month	9.1±0.67	21.1^{bc}±0.72	53.8^{b}±2.19	7.0^{a}±0.93	12.7^{a}±1.10	3.6±1.24	1.8±0.41
6-month	10.0±0.08	21.0^{c}±0.51	60.8^{a}±0.65	4.0^{b}±0.20	9.2^{b}±0.28	3.8±0.70	1.3±0.37
8-month	10.7±0.37	23.5^{b}±1.09	58.8^{a}±1.64	3.1^{bc}±0.20	9.3^{b}±0.20	3.5±0.65	1.8±0.35
P	0.194	<0.001	0.032	0.001	<0.001	0.875	0.628
	Shoulder						
Intact	21.3±0.46	23.9±1.26	65.6^{a}±0.12	3.9^{b}±0.19	3.2^{c}±0.51	2.4±0.33	1.0±0.21
4-month	21.1±0.13	22.5±0.10	55.0^{b}±0.40	10.2^{a}±0.70	9.1^{a}±0.48	2.0±0.13	1.3±0.16
6-month	21.6±0.14	23.4±0.35	63.6^{a}±0.29	4.6^{b}±0.61	5.3^{b}±0.25	1.9±0.09	1.1±0.47
8-month	20.4±0.34	23.9±1.83	63.8^{a}±1.58	5.2^{b}±0.62	3.9^{c}±0.31	2.3±0.06	0.8±0.19
P	0.097	0.819	<0.001	<0.001	<0.001	0.139	0.682
	Rib						
Intact	18.7±0.90	32.9^{a}±1.25	57.3±0.48	2.1^{b}±0.96	3.0^{b}±0.42	4.0±0.43	0.7±0.20
4-month	20.4±0.88	21.5^{c}±1.41	51.5±1.98	15.5^{a}±1.82	8.8^{a}±1.63	1.8±0.63	1.1±0.18
6-month	19.2±0.10	27.3^{b}±0.49	56.5±1.02	6.1^{b}±0.98	6.3^{ab}±1.08	2.8±0.13	1.0±0.34
8-month	18.8±0.18	33.7^{a}±1.00	54.8±2.87	4.4^{b}±1.94	4.3^{b}±0.57	2.0±0.25	0.7±0.23
P	0.296	<0.001	0.192	0.001	0.021	0.115	0.624
	Flank						
Intact	9.7±0.87	26.9^{a}±0.45	49.6^{a}±2.76	11.4±1.82	3.4^{b}±1.20	6.5±0.21	2.3±0.99
4-month	9.4±0.73	20.8^{b}±1.22	44.0^{b}±1.12	16.5±2.12	12.4^{a}±1.48	4.1±1.14	2.1±0.64
6-month	10.4±0.03	19.8^{b}±0.35	47.0^{b}±3.20	16.6±1.87	10.9^{a}±3.24	4.0±0.14	1.6±0.69
8-month	10.7±0.24	24.3^{a}±0.12	45.5^{ab}±2.30	15.0±1.06	9.7^{a}±1.69	4.1±0.65	1.4±0.51
P	0.415	<0.001	0.047	0.205	0.049	0.183	0.799
	Long-leg						
Intact	39.9±0.60	24.8^{a}±2.01	64.7^{a}±1.09	5.6^{b}±1.05	3.3^{b}±0.87	1.2±0.20	0.4±0.11
4-month	40.0±0.56	20.0^{b}±0.05	59.6^{b}±0.12	11.2^{a}±0.51	7.4^{a}±0.51	1.1±0.16	0.8±0.04
6-month	38.8±0.20	23.6^{a}±0.14	60.0^{b}±0.47	8.0^{ab}±1.71	6.5^{a}±1.11	1.4±0.03	0.6±0.06
8-month	39.4±0.56	27.6^{a}±0.20	62.4^{ab}±1.29	4.8^{b}±1.16	3.7^{b}±0.04	1.3±0.06	0.3±0.01
P	0.342	0.005	0.011	0.020	0.011	0.447	0.119

The data were expressed as mean±standard error. Total, Proportional content of each piece in the total carcass; SF: Subcutaneous fat; IMF: intermuscular fat; Evap: Evaporation; ʒIncludes weight loss during dissection and minor tissues considered as waste, such as nerves, tendons, lymph nodes, etc. a-c Means in the same column with different lowercase superscripts are significantly different among treatment groups ($P < 0.05$).

Table 3. Distribution of different tissues by weight (g) in different carcass cuts of goats castrated at different ages.

Groups	Total	Bone	Muscle	SF	IMF	Waste^{ʒ}	Evap
	Neck						
Intact	805.0±5.68	223.3^{a}±9.22	493.3±7.84	20.0^{b}±6.82	40.0^{c}±2.89	28.3±6.67	13.3±3.33
4-month	830.0±7.63	193.3^{ab}±9.28	455.0±8.22	60.0^{a}±1.55	93.3^{a}±4.41	28.3±1.14	11.7±1.67
6-month	783.3±9.28	175.0^{b}±2.89	445.0±6.01	55.0^{a}±2.89	80.0^{bc}±2.89	28.3±3.33	11.7±1.67
8-month	806.7±5.85	191.7^{ab}±3.33	483.3±9.83	26.7^{b}±1.67	76.7^{b}±6.01	28.3±6.01	13.3±1.67
P	0.941	0.045	0.724	0.004	<0.001	0.997	0.901
	Shoulder						
Intact	1671.7^{b}±5.02	405.0±7.54	1108.3^{a}±4.44	65.0^{b}±2.89	53.3^{c}±7.26	40.0±5.00	16.7±3.33
4-month	1928.3^{a}±2.05	438.3±3.33	1073.3^{a}±8.56	200.0^{a}±2.58	176.7^{a}±8.82	40.0±2.89	23.3±1.67
6-month	1713.3^{b}±4.53	405.0±2.89	1100^{a}±4.55	83.3^{b}±1.14	91.7^{b}±3.33	33.3±1.66	15.0±8.33
8-month	1541.7^{c}±4.45	373.3±2.02	991.7^{b}±3.64	80.0^{b}±7.64	61.7^{c}±6.67	35.0±0.01	13.3±3.33
P	<0.001	0.345	0.021	<0.001	<0.001	0.337	0.278
	Ribs						
Intact	1465.0^{b}±6.45	488.3^{a}±3.14	853.3^{ab}±3.19	41.7^{b}±3.19	45.0^{c}±7.64	36.7±1.67	18.3±1.67
4-month	1866.7^{a}±6.54	403.3^{c}±6.41	966.7^{a}±9.28	295.0^{a}±6.19	165.0^{a}±6.06	36.7±1.67	16.7±4.41
6-month	1521.7^{b}±3.33	420.0^{bc}±7.64	868.3^{ab}±2.05	93.3^{b}±5.90	96.7^{b}±5.90	43.3±1.67	15.0±5.00
8-month	1421.7^{b}±5.74	478.3^{ab}±7.26	783.3^{b}±5.66	63.3^{b}±8.92	61.7^{c}±6.01	35.0±2.89	10.0±0.01
P	0.002	0.027	0.036	0.001	0.013	0.180	0.404

				Flank			
Intact	753.3±6.53	206.7^{a}±5.90	376.7±6.91	90.0^{b}±2.21	30.0^{b}±1.41	50.0±5.00	16.7±4.41
4-month	856.7±7.18	180.0^{ab}±7.64	385.0±4.52	145.0^{a}±4.66	111.7^{a}±4.24	35.0±7.64	15.0±2.89
6-month	816.7±9.93	165.0^{b}±5.77	391.7±8.48	138.3^{a}±5.90	88.3^{a}±5.22	33.3±1.67	15.0±5.00
8-month	805.0±4.93	196.7^{ab}±8.33	373.3±3.45	123.3^{a}±4.24	78.3^{ab}±2.02	33.3±3.33	13.3±3.33
P	0.609	0.040	0.976	0.025	0.043	0.117	0.948
				Long-leg			
Intact	3151.7^{b}±7.90	786.7±2.12	2046.7^{b}±4.53	175.0^{b}±3.14	105.0^{b}±2.84	38.3±6.01	13.3±3.33
4-month	3673.3^{a}±6.01	740.0±2.89	2201.7^{a}±6.01	413.3^{a}±1.22	275.0^{a}±5.28	40.0±5.77	21.7±1.67
6-month	3078.3^{b}±6.00	730.0±1.41	1856.7^{c}±4.55	248.3^{b}±5.74	200.0^{a}±3.14	43.3±1.67	18.3±1.67
8-month	2983.3^{b}±4.78	786.7±1.67	1870.0^{c}±6.34	178.3^{b}±1.53	110.0^{b}±2.89	38.3±1.67	13.0±3.33
P	<0.001	0.681	0.001	0.003	0.002	0.827	0.143

The data were expressed as mean±standard error. Total: Quantity by weight of each piece; SF: Subcutaneous fat; IMF: intermuscular fat; Evap: Evaporation; ƷIncludes weight loss during dissection and minor tissues considered as waste, such as nerves, tendons, lymph nodes, etc. a-c Means in the same column with different lowercase superscripts are significantly different among treatment groups (P <0.05).

The proportional (%) and absolute value (g) changes of the different tissues in the cold carcass are presented in Table 4. The lowest amount of bone tissue in the carcass was found in the 4-month-old castrated group, while the highest amounts were detected in 8-month-old castrated group and the non-castrated/control group (P <0.01). Although early castration (4-months) increased the weight of muscle tissue in the carcass, it negatively affected its percentage (P <0.01). The highest muscle tissue percentage (61.6±0.63%) was observed in the intact group (P <0.01). Contrary to muscle tissue, the highest intermuscular and subcutaneous fat tissue percentages (12.1±0.26% and 8.9±0.53%, respectively) were detected in the group castrated at an age of 4 months (P <0.001).

Table 4. Total carcass tissue parameters in goats castrated at different ages.

Groups (%)	Bone	Muscle	SF	IMF	WasteƷ	Evap
Intact	26.6^{a}±1.15	61.6^{a}±0.63	5.0^{c}±0.59	3.5^{c}±0.46	2.4±0.10	1.0±0.07
4-month	21.2^{c}±0.25	55.0^{c}±0.46	12.1^{a}±0.26	8.9^{a}±0.53	1.9±0.16	1.0±0.04
6-month	23.7^{b}±0.18	58.4^{b}±0.57	7.7^{b}±1.11	7.0^{b}±0.90	2.3±0.05	0.9±0.10
8-month	26.6^{a}±0.26	59.0^{b}±1.03	6.2^{bc}±0.45	5.1^{c}±0.19	2.2±0.16	0.8±0.07
P	0.001	0.001	<0.001	0.001	0.123	0.459
Groups (g)						
Intact	2110.0±2.69	4878.3^{bc}±4.87	391.7^{c}±2.56	273.3^{c}±4.80	193.3±8.82	78.3±4.41
4-month	1955.0±1.56	5081.7^{a}±1.32	1116.7^{a}±1.14	821.7^{a}±6.31	180.0±7.56	88.3±4.41
6-month	1895.0±2.91	4661.7^{bc}±1.12	618.3^{b}±4.53	556.7^{b}±6.60	181.7±4.41	75.0±7.64
8-month	2026.7±3.72	4501.7^{c}±2.10	471.7^{bc}±3.87	338.3^{c}±1.93	170.0±7.64	63.3±6.01
P	0.162	0.042	<0.001	<0.001	0.533	0.084

The data were expressed as mean±standard error. SF: Subcutaneous fat; IMF: intermuscular fat; Evap: Evaporation; ƷIncludes weight loss during dissection and minor tissues considered as waste, such as nerves, tendons, lymph nodes, etc. a-c Means in the same column with different lowercase superscripts are significantly different among treatment groups (P <0.05).

Physicochemical characteristics of meat

The chemical composition of goat muscles in the different groups is presented in Fig. 2. The content of dry matter, ash, protein, and fat (intramuscular) of muscles varied between 21.9-25.5%, 0.86-1.12%, 17.4-19.3% and 3.48-6.52%, respectively. Six months-old, castrated goat meat had the highest content of dry matter (P <0.01). The interaction between castration and muscle significantly impacted the fat content of the muscles alone. The most marked change in castrated goat meat was observed in the content of intramuscular fat. The highest fat content was determined in the meat of goats castrated at 6 months of age, followed by 4 months of age (P <0.01). No significant difference between goats castrated at 8-month-old and non-castrated/control goats was observed in the fat content of muscles. The ash contents of the goat meat castrated at the age of 4- and 6-months were lower than the controls (P <0.01).

During the conversion of muscle to meat, lactic acid forms as a result of glycolysis metabolism causing a decrease in meat pH. The pH and titratable acidity (% lactic acid) values of the muscles obtained from the experimental groups are presented in Fig. 3.

The highest and lowest pH values were determined in the TB and the PM muscles, respectively (P <0.05). A significant (P <0.05) decrease in the post-mortem meat pH was observed in goats castrated at 4-months of age compared to late castration (8-month) and the intact groups (Fig. 3).

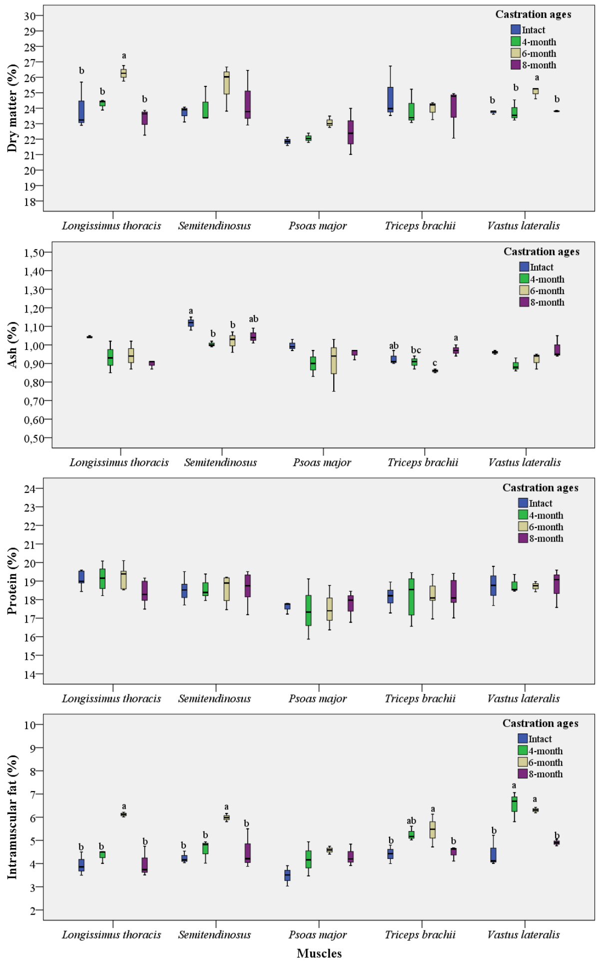
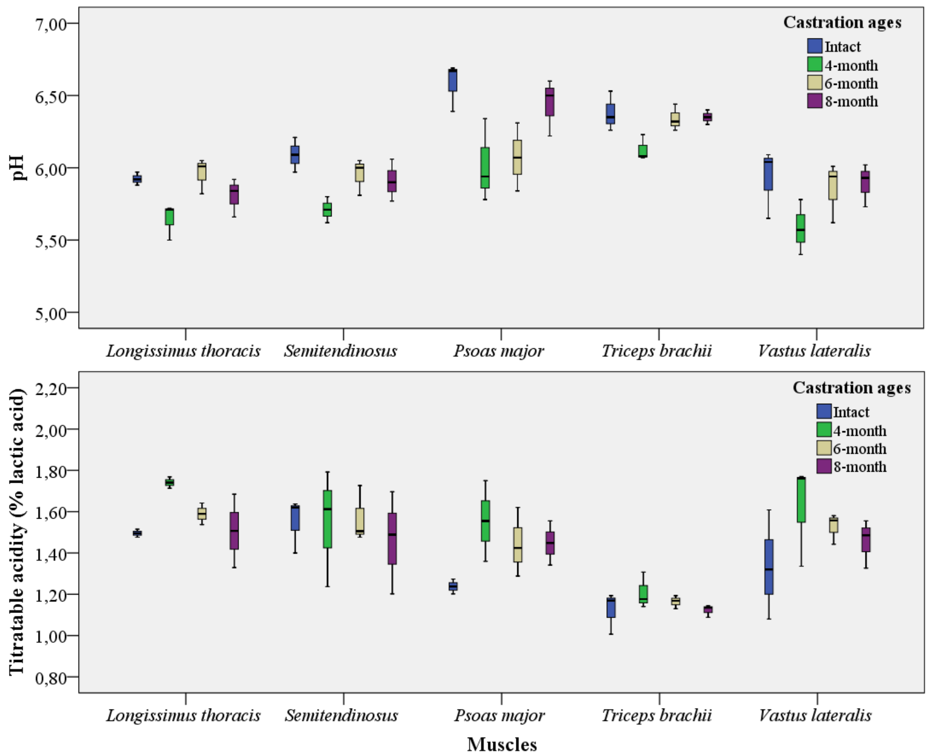


Figure 2. Chemical composition of muscles of intact and castrated Kilis goats. a-c Different lowercase letters indicate significant differences among treatment groups for the same muscle (P <0.05).



The colour values of *L**, *a**, *b**, hue angle and chroma were significantly (P <0.05) affected by the interaction between

Figure 3. Ultimate pH and titratable acidity of muscles of intact and castrated Kilis goats.

castration and muscle. $L*$, $a*$ and $b*$ values of the meat varied between 38.8 to 46.5, 15.3 to 20.6 and 3.7 to 6.2, respectively (Fig. 4). Castration at different ages caused significant differences in meat colour, especially $L*$ and $a*$ values (P <0.05). Regardless of muscle type, the mean $L*$, $a*$ and $b*$ values of the meat from the 6-month group were found to be lower than the other groups. Regarding colour intensity (hue angle) and colour saturation (chroma) values of the meat varied from 13.4 to 17.8° and 15.7 to 21.4, respectively.

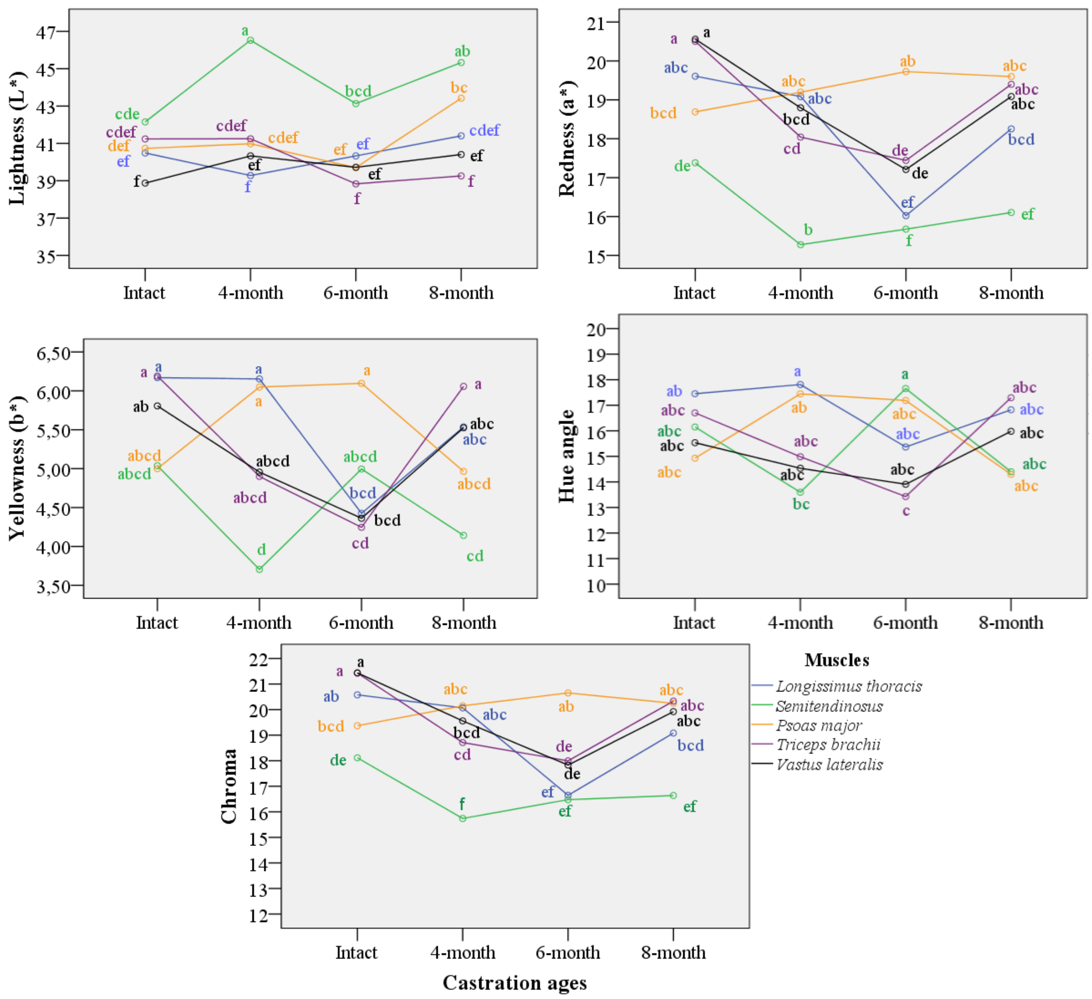


Figure 4. The effect of the interaction between castration age and muscle type on the colour values of Kilis goat meat. a-f Different lowercase letters indicate significant differences among treatment groups (P <0.05).

Since meat is consumed after cooking, the texture of cooked meat, defined as "meat tenderness", is of great importance in terms of consumer acceptability. In this case, cooked meat texture is evaluated as tough and tender. Tough meats cannot crumble easily in the mouth, while tender meats are soft and easily crumble. Therefore, as the cutting force value decreases, the tenderness of the meat increases. WBSF values of the meat varied between 20.2 N to 37.4 N (Fig. 5). Regardless of muscle types, mean WBSF values were significantly (P <0.05) affected by castration at different ages. Among the muscles, the only PM muscle was significantly affected by the castration ages (P <0.05) in terms of WBSF value, which had the lowest value in meat from goats castrated at 6-months-old.

Cooking loss values in the muscles ranged from 35.6% to 41.7% (Fig. 5). The interaction between castration ages and muscle types significantly affected the cooking loss (P <0.05). Regardless of muscle type, the cooking loss was found to be lowest in the meat produced from the goats castrated at 6-months-old age (P <0.05). The castration ages had a significant effect on cooking loss in muscle types except for LT muscle (Fig. 5). The highest cooking loss was observed in ST and VL muscles at 8 months of age, and the lowest in ST, PM and VL muscles at 6 months of age (Fig. 5; P <0.05).

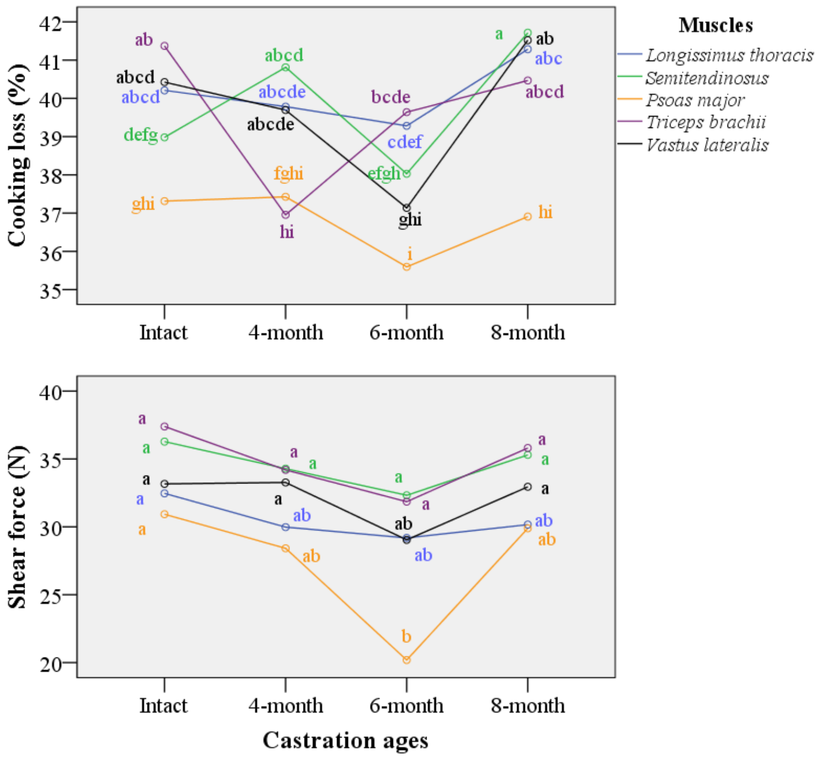


Figure 5. The effect of the interaction between castration age and muscle type on the Warner Bratzler shear force and cooking loss of the colour values of Kilis goat meat. a-i Different lowercase letters indicate significant differences among treatment groups (P <0.05).

Fatty acid profile of muscles

A total of 16 fatty acids (FAs) were found, including eight saturated fatty acids (SFA), three monounsaturated fatty acids (MUFA) and five polyunsaturated fatty acids (PUFA, Table 5). Regardless of muscle, castration at 4- and 6-months-age caused a decrease in total SFA and PUFA and an increase in MUFA compared to 8-month-old castrated and intact goats (Table 5). Stearic acid (18:0) was the principal SFA, followed by 16:0, 14:0, 17:0 and 15:0. The effect of castration at different ages on 15:0 and 18:0 fatty acids was significant (P <0.01). Intact goat meat had the highest 15:0 fatty acid level (P <0.001). The 4- and 6-months-old castrated goats also had the lowest 18:0 level (P <0.05). Castration at an earlier age resulted in a decrease in the 18:0 of goat muscles. Among the SFA, 10:0 was determined only in TB and VL muscles, and 12:0 was also present in the ST along with both TB and VL muscles (Table 5). Eicosenoic acid (20:0) was found in the LT muscle of 4-month-old castrated goats and the TB muscle of 4- and 6-month-old castrated goats (Table 5).

Table 5. Fatty acid profile of the muscles of goats castrated at different ages.

Fatty acids (%)	Castration ages (A)	Muscles (B) LT	PM	ST	TB	VL	Mean	SEM	*A x B*
ΣSFA	Intact	49.9±1.46	65.3±1.29	50.7±2.47	57.8^{a}±2.18	54.2±1.88	55.6^{a}	1.66	0.065
	4-month	41.3±2.53	55.3±2.88	47.4±0.06	48.6^{b}±0.51	50.6±0.09	48.7^{b}	1.38	
	6-month	47.5±0.61	56.6±3.20	47.1±1.45	47.7^{b}±0.31	50.8±0.23	50.0^{b}	1.14	
	8-month	49.6±0.77	63.6±0.94	46.7±0.88	52.7^{ab}±1.47	52.7±1.18	53.1^{ab}	1.58	
	P	0.097	0.094	0.357	0.029	0.160	0.006		
10:0	Intact	-	-	-	0.13^{a}±0.01	-	0.13	<0.01	-
	4-month	-	-	-	0.08^{b}±0.01	0.17^{a}±0.01	0.12	0.01	
	6-month	-	-	-	0.15^{a}±0.01	0.09^{b}±0.02	0.12	0.01	
	8-month	-	-	-	0.14^{a}±0.00	-	0.14	<0.01	
	P				0.008	0.050	1.000		
12:0	Intact	-	-	-	-	-	-		-
	4-month	-	-	-	-	0.10±0.01	0.10	<0.01	
	6-month	-	-	0.08±0.01	0.11±0.02	0.09±0.02	0.09	0.01	
	8-month	-	-	-	-	-	-		
	P					0.291	1.000		
14:0	Intact	0.84±0.05	0.18^{c}±0.08	2.14±0.25	1.55±0.24	1.37±0.23	1.47	0.15	0.109
	4-month	1.22±0.26	0.40^{b}±0.17	1.50±0.19	1.54±0.11	1.06±0.35	1.14	0.14	
	6-month	1.23±0.10	1.43^{a}±0.13	2.04±0.17	1.92±0.31	1.53±0.05	1.63	0.10	
	8-month	0.81±0.01	0.39^{b}±0.10	1.84±0.42	1.94±0.50	1.14±0.12	1.23	0.19	
	P	0.110	<0.001	0.475	0.759	0.464	0.149		

15:0	Intact	1.72^{a}±0.10	0.63^{a}±0.10	1.51^{a}±0.13	0.54^{bc}±0.07	1.13^{a}±0.09	1.23^{a}	0.13	<0.001
	4-month	0.68^{c}±0.04	0.52^{a}±0.11	0.51^{b}±0.07	0.76^{a}±0.05	0.60^{b}±0.04	0.60^{b}	0.04	
	6-month	0.55^{c}±0.01	0.38^{b}±0.10	0.28^{c}±0.00	0.61^{ab}±0.08	0.64^{b}±0.01	0.49^{b}	0.04	
	8-month	1.40^{b}±0.06	0.37^{b}±0.07	0.67^{b}±0.01	0.35^{c}±0.04	1.01^{a}±0.13	0.76^{ab}	0.11	
	P	<0.001	0.008	<0.001	0.010	0.003	0.013		
16:0	Intact	21.1±0.81	26.6±1.09	22.0±1.19	21.2±2.17	23.2±1.06	22.8	0.75	0.775
	4-month	21.7±2.72	27.7±2.62	23.4±0.90	21.5±0.73	22.9±0.66	23.4	0.90	
	6-month	22.8±0.49	25.4±1.11	25.5±0.80	23.5±0.98	22.9±0.44	24.0	0.45	
	8-month	21.5±0.67	26.6±1.60	25.6±0.63	21.4±0.54	24.0±1.38	23.8	0.69	
	P	0.909	0.844	0.120	0.395	0.828	0.641		
17:0	Intact	0.63^{b}±0.02	2.38^{a}±0.00	0.83±0.22	1.30^{a}±0.13	0.84^{b}±0.08	1.20	0.17	<0.001
	4-month	0.43^{c}±0.03	1.54^{bc}±0.29	0.71±0.02	0.83^{bc}±0.05	0.73^{b}±0.05	0.85	0.11	
	6-month	0.73^{a}±0.01	0.84^{c}±0.07	0.83±0.02	0.94^{b}±0.06	1.04^{a}±0.05	0.88	0.03	
	8-month	0.58^{b}±0.01	2.16^{ab}±0.32	0.59±0.02	0.64^{c}±0.06	0.69^{b}±0.02	0.93	0.17	
	P	<0.001	0.004	0.390	0.008	0.010	0.261		
18:0	Intact	25.6^{a}±0.70	36.3^{a}±2.29	24.3^{a}±1.33	33.2^{a}±2.33	27.6±1.02	29.4^{a}	1.38	0.002
	4-month	17.2^{c}±1.09	25.2^{b}±1.50	21.3^{a}±0.99	23.8^{bc}±1.03	25.1±0.42	22.5^{b}	0.90	
	6-month	22.2^{b}±0.43	28.6^{ab}±2.56	18.1^{b}±1.38	20.3^{c}±0.88	24.5±0.44	22.7^{b}	1.10	
	8-month	25.4^{a}±0.07	34.1^{a}±2.00	18.0^{b}±0.66	28.2^{ab}±2.39	25.9±1.88	26.3^{ab}	1.52	
	P	<0.001	0.047	0.005	0.018	0.293	0.001		
20:0	Intact	-	-	-	-	-	-		-
	4-month	-	-	-	0.09±0.01	-	0.09	<0.01	
	6-month	0.06±0.03	-	-	0.11±0.01	-	0.08	0.01	
	8-month	-	-	-	-	-	-		
	P				1.000		1.000		
ΣMUFA	Intact	36.3^{b}±1.56	24.0±0.89	33.7±2.45	32.6^{b}±1.12	33.5±1.99	32.0^{b}	1.29	0.051
	4-month	48.4^{a}±2.20	34.3±2.64	44.4±0.51	42.2^{a}±0.85	41.1±0.47	42.1^{a}	1.38	
	6-month	45.3^{a}±0.71	32.8±4.01	46.4±1.32	43.1^{a}±0.31	40.2±0.57	41.6^{a}	1.49	
	8-month	36.8^{b}±1.25	25.0±0.81	44.7±0.32	39.7^{a}±0.82	36.9±1.53	36.6^{b}	1.77	
	P	0.004	0.116	0.079	0.005	0.053	<0.001		
c9-16:1	Intact	3.80^{a}±0.79	2.82^{a}±0.10	1.89±0.21	1.27±0.20	0.98±0.10	2.15^{a}	0.31	<0.001
	4-month	2.07^{b}±0.19	1.50^{b}±0.37	1.44±0.25	1.41±0.21	1.02±0.35	1.49^{b}	0.14	
	6-month	1.26^{b}±0.05	1.00^{bc}±0.08	2.08±0.32	1.57±0.12	1.44±0.07	1.47^{b}	0.11	
	8-month	0.71^{b}±0.06	0.78^{c}±0.09	1.78±0.27	1.63±0.33	1.11±0.17	1.20^{b}	0.14	
	P	0.006	<0.001	0.461	0.760	0.424	0.008		
c9-18:1	Intact	32.5^{b}±0.78	21.2±0.99	31.8±2.52	31.2^{b}±0.95	32.3±1.93	29.8^{c}	1.30	0.101
	4-month	46.3^{a}±2.09	32.8±2.98	42.9±0.27	40.5^{a}±0.74	39.8±0.71	40.5^{a}	1.35	
	6-month	43.8^{a}±0.74	31.8±3.99	43.9±1.59	41.2^{a}±0.43	38.3±0.49	39.8^{ab}	1.41	
	8-month	36.1^{b}±1.19	24.2±0.85	42.9±0.20	37.8^{a}±0.51	35.8±1.40	35.4^{b}	1.68	
	P	0.001	0.092	0.079	0.003	0.065	<0.001		
t11-18:1	Intact	-	-	-	0.14^{c}±0.02	0.21^{b}±0.06	0.18^{b}	0.02	-
	4-month	-	-	-	0.25^{ab}±0.03	0.22^{b}±0.01	0.23^{b}	0.01	
	6-month	0.25±0.02	-	0.41±0.05	0.29^{a}±0.01	0.47^{a}±0.02	0.35^{a}	0.03	
	8-month	-	-	-	0.21^{b}±0.00	0.20^{b}±0.04	0.21^{b}	<0.01	
	P				0.006	<0.001	<0.001		
ΣPUFA	Intact	13.8^{a}±0.10	10.7±0.43	15.6^{a}±0.78	9.59±1.11	12.4^{a}±0.64	12.4^{a}	0.63	<0.001
	4-month	10.3^{b}±0.57	10.4±0.82	8.22^{b}±0.52	9.22±0.35	8.30^{b}±0.49	9.29^{bc}	0.33	
	6-month	7.20^{c}±0.28	10.6±0.81	6.49^{b}±0.14	9.18±0.19	9.02^{b}±0.79	8.49^{c}	0.44	
	8-month	13.5^{a}±0.48	11.4±0.54	8.59^{b}±1.01	7.67±0.71	10.4^{ab}±0.76	10.3^{b}	0.62	
	P	<0.001	0.720	<0.001	0.463	0.013	<0.001		
Σn-3	Intact	1.61^{a}±0.05	0.82±0.03	1.97^{a}±0.13	0.77±0.11	1.01±0.02	1.23	0.13	<0.001
	4-month	1.08^{bc}±0.16	0.81±0.10	1.14^{b}±0.02	0.77±0.04	1.17±0.18	0.99	0.06	
	6-month	0.94^{c}±0.06	0.70±0.04	0.92^{b}±0.03	1.00±0.04	1.07±0.08	0.93	0.04	
	8-month	1.32^{ab}±0.10	0.66±0.05	1.14^{b}±0.04	0.69±0.10	1.04±0.13	0.97	0.08	
	P	0.004	0.262	0.003	0.212	0.770	0.053		
18:3n-3	Intact	0.55±0.07	0.82±0.0	1.13^{a}±0.10	0.77^{a}±0.11	0.62±0.04	0.78^{a}	0.06	0.001
	4-month	0.70±0.14	0.81±0.10	0.45^{b}±0.00	0.62^{ab}±0.04	0.73±0.08	0.66^{a}	0.05	
	6-month	0.62±0.03	0.70±0.04	0.68^{b}±0.02	0.85^{a}±0.05	0.81±0.06	0.73^{a}	0.03	
	8-month	0.52±0.06	0.66±0.05	0.40^{b}±0.05	0.43^{b}±0.04	0.58±0.05	0.52^{b}	0.03	
	P	0.420	0.262	0.002	0.001	0.433	0.001		
20:5n-3	Intact	1.06^{a}±0.09	-	0.82^{a}±0.04	0.10±0.01	0.38±0.02	0.75	0.08	<0.001
	4-month	0.38^{c}±0.02	-	0.69^{a}±0.02	0.14±0.00	0.44±0.08	0.41	0.06	
	6-month	0.32^{c}±0.04	-	0.24^{b}±0.02	0.15±0.01	0.26±0.02	0.24	0.02	
	8-month	0.80^{b}±0.05	-	0.73^{a}±0.01	0.24±0.09	0.45±0.09	0.56	0.06	
	P	<0.001		<0.001	0.051	0.198	0.085		
Σn-6	Intact	12.2^{a}±0.14	9.88±0.46	13.6^{a}±0.88	8.64±1.01	11.1^{a}±0.60	11.1^{a}	0.53	<0.001
	4-month	9.09^{b}±0.40	9.58±0.86	7.08^{b}±0.51	8.30±0.29	6.94^{c}±0.40	8.20^{bc}	0.34	
	6-month	6.06^{c}±0.27	9.86±0.77	5.28^{b}±0.11	7.92±0.24	7.70^{bc}±0.70	7.36^{c}	0.47	

	8-month	12.2^{a}±0.38	10.7±0.59	7.45^{b}±0.97	6.74±0.69	9.34^{ab}±0.70	9.29^{ab}	0.60	
	P	<0.001	0.667	<0.001	0.409	0.006	<0.001		
18:2n-6	Intact	8.76^{b}±0.26	8.21^{b}±0.58	10.2^{a}±0.82	7.79^{a}±0.96	8.79^{a}±0.40	8.73^{a}	0.33	<0.001
	4-month	7.16^{c}±0.22	8.54^{ab}±0.90	5.84^{b}±0.31	7.42^{a}±0.30	5.71^{c}±0.34	6.93^{b}	0.34	
	6-month	4.83^{d}±0.15	8.84^{a}±0.68	4.58^{b}±0.14	7.16^{a}±0.20	6.35^{bc}±0.59	6.35^{b}	0.45	
	8-month	9.14^{a}±0.35	9.14^{a}±0.67	5.38^{b}±0.54	5.86^{b}±0.75	7.58^{ab}±0.46	7.42^{b}	0.48	
	P	<0.001	0.047	<0.001	0.042	0.006	0.001		
20:4n-6	Intact	3.42^{a}±0.12	1.67^{a}±0.22	3.46^{a}±0.07	0.94±0.05	2.28^{a}±0.26	2.35^{a}	0.27	0<001
	4-month	1.93^{b}±0.18	1.04^{b}±0.05	1.24^{b}±0.19	0.88±0.04	1.24^{b}±0.06	1.26^{b}	0.11	
	6-month	1.23^{c}±0.22	1.02^{b}±0.12	0.71^{b}±0.03	0.76±0.05	1.36^{b}±0.13	1.02^{b}	0.08	
	8-month	3.07^{a}±0.03	1.54^{a}±0.11	2.07^{ab}±0.76	0.88±0.21	1.76^{ab}±0.33	1.87^{a}	0.24	
	P	<0.001	0.012	0.008	0.733	0.038	<0.001		
CLA	Intact	-	-	-	0.19^{ab}±0.02	0.29±0.09	0.24^{a}	0.03	-
c9.t11-18:2	4-month	0.17±0.03	-	-	0.16^{b}±0.02	0.18±0.04	0.17^{b}	0.01	
	6-month	0.21±0.02	-	-	0.25^{a}±0.03	0.24±0.01	0.25^{a}	0.01	
	8-month	-	-	-	0.25^{ab}±0.00	0.20±0.03	0.23^{a}	<0.01	
	P	0.206			0.001	0.055	0.006		

The data were expressed as mean±standard error. LT: Longissimus thoracis, ST: Semitendinosus, PM: Psoas major, TB: Triceps brachii, VL: Vastus lateralis. c: cis; t: trans; ΣSFA: sum of saturated fatty acids (10:0, 12:0, 14:0, 15:0, 16:0, 18:0, 20:0); ΣMUFA: sum of the monounsaturated fatty acids (c9-16:1, c9-18:1, t11-18:1); ΣPUFA: sum of polyunsaturated fatty acids (Σn-3 + Σn-6); Σn-3: sum of 18:3n-3 and 20:5n-3; Σn-6: sum of 18:2n-6 and 20:4n-6. CLA: conjugated linoleic acid. AxB: The interaction of castration ages (A) and muscles (B) a-c The difference between the mean values of fatty acids represented by different letters in the same column is statistically significant (P <0.05); -: not detected.

Oleic acid (c9-18:1) was the principal MUFA (and also FA). Although meat from castrated goats had the lowest level of c9-16:1, meat from goats castrated at 6-months of age had the highest 18:1 (c9 and t11) level (P <0.01).

Among PUFA, linoleic acid (18:2n-6), linolenic acid (18:3n-3), conjugated linoleic acid (CLA, c9,t11-18:2), arachidonic (20:4n-6) and eicosapentaenoic acid (20:5n-3) were found in goat meat (Table 5). Castration had a significant effect on 18:3n-3, 18:2n6, 20:4n-6 and CLA of goat muscles (P <0.05). The n-6 polyunsaturated fatty acids were determined to be higher in intact goats than at 4- and 6-month-old castrated goats (P <0.001). However, both n-3 and n-6 PUFA were significantly (P <0.01) influenced by the interaction between castration age and muscle (Table 5). The LT and PM muscles had lower n-3 (P <0.01) and n-6 PUFA levels (P <0.001) at 4- and 6-month-old castrated goats than those at intact and 8-months-old ones. A similar trend was observed in the VL muscle for n-6 PUFA. The TB and ST muscles had a slightly higher n-3 PUFA and n-6 PUFA at 6 and 8 months of age, respectively, compared to the intact and 4-months-old (Table 5). Among muscle types, PM and ST muscles had no CLA (c9,t11-18:2), but only LT muscles from 4- and 6-month-old castrated goats had.

The nutritional value indices of intramuscular fat in goats are presented in Table 6. The castration ages and muscles interacted on UFA:SFA (P<0.05), PUFA:SFA (P<0.001) and n6:n3 ratios (P <0.05). Considering the NVI and total UFA:SFA, an evaluation of the possible beneficial effects of goat meat fat on health, it was determined that the UFA:SFA ratio was the highest in the meat of 4-month-old castrated goats, irrespective of muscle type. The highest NVI ratio was also determined in the LT and PM fats of 4- and 6-month-old castrated goats, respectively (Table 6). The ST muscle of intact goats had the highest PUFA:SFA ratio. No significant difference in PUFA:SFA of LT muscle of intact and castrated at 4- and 6-month-old was observed. The effect of castration ages on n-6:n-3 differed in the muscles. The LT and VL muscles showed the highest n-6:n-3 ratio at 4- and 8-month-old, and intact goat, respectively. Regarding the AI and EI indices, there were no significant differences between the castration ages. Regardless of the type of muscle, the ratio of hypocholesterolemic to hypercholesterolemic fatty acids (h/H index) was higher in castrated goats than in intact ones (Table 6).

Table 6. Nutritional quality indices of intramuscular fat in the muscles of goats castrated at different ages.

Indices	Castration ages (A)	Muscles LT	PM	ST	TB	VL	Mean	SEM	*A x B*
UFA:SFA	Intact	1.01^{b}±0.06	0.53±0.03	0.98±0.09	0.73^{c}±0.06	0.85±0.07	0.82^{c}	0.05	0.036
	4-month	1.44^{a}±0.15	0.82±0.10	1.11±0.01	1.06^{a}±0.02	0.97±0.01	1.08^{a}	0.06	
	6-month	1.11^{b}±0.03	0.78±0.10	1.13±0.07	1.10^{a}±0.01	0.97±0.01	1.02^{ab}	0.04	
	8-month	1.02^{b}±0.03	0.57±0.02	1.14±0.04	0.90^{b}±0.05	0.90±0.04	0.91^{bc}	0.05	
	P	0.017	0.059	0.286	<0.001	0.846	0.005		
PUFA:SFA	Intact	0.28^{a}±0.01	0.17±0.01	0.31^{a}±0.02	0.17±0.02	0.23±0.02	0.23^{a}	0.02	<0.001
	4-month	0.25^{a}±0.03	0.19±0.02	0.17^{b}±0.01	0.19±0.01	0.17±0.01	0.19^{ab}	0.01	
	6-month	0.15^{b}±0.01	0.19±0.01	0.14^{b}±0.01	0.19±0.01	0.18±0.02	0.17^{b}	0.01	
	8-month	0.27^{a}±0.01	0.18±0.01	0.19^{b}±0.02	0.14±0.02	0.20±0.01	0.20^{ab}	0.01	

	P	0.002	0.586	0.001	0.143	0.058	0.010		
n-6:n-3	Intact	7.59^{ab}±0.31	12.1±0.97	7.08±0.84	11.3±0.33	11.0^{a}±0.79	9.83^{ab}	0.61	0.039
	4-month	8.66^{a}±0.84	12.4±2.42	6.20±0.35	10.9±0.27	6.16^{c}±0.85	8.86^{bc}	0.81	
	6-month	6.48^{b}±0.39	14.0±0.43	5.78±0.22	7.96±0.56	7.18^{bc}±0.24	8.28^{c}	0.80	
	8-month	9.33^{a}±0.40	16.5±2.03	6.50±0.66	10.2±1.83	9.20^{ab}±1.16	10.3^{a}	1.02	
	P	0.023	0.303	0.481	0.150	0.013	0.295		
NVI	Intact	2.77^{b}±0.11	2.18^{b}±0.14	2.56±0.18	3.12±0.42	2.59±0.16	2.65	0.12	0.140
	4-month	3.06^{a}±0.53	2.16^{b}±0.34	2.76±0.14	3.01±0.14	2.84±0.07	2.76	0.14	
	6-month	2.89^{b}±0.08	2.39^{a}±0.17	2.44±0.12	2.63±0.16	2.75±0.08	2.62	0.07	
	8-month	2.87^{b}±0.14	2.22^{ab}±0.19	2.38±0.06	3.09±0.16	2.59±0.17	2.63	0.05	
	P	0.037	0.048	0.265	0.510	0.489	0.780		
AI	Intact	0.49±0.03	0.76±0.01	0.63±0.07	0.65±0.05	0.63±0.03	0.63	0.03	0.998
	4-month	0.46±0.06	0.67±0.11	0.56±0.03	0.54±0.02	0.55±0.02	0.56	0.03	
	6-month	0.53±0.02	0.73±0.08	0.64±0.03	0.60±0.05	0.59±0.01	0.62	0.02	
	8-month	0.49±0.02	0.78±0.05	0.62±0.02	0.62±0.04	0.60±0.04	0.62	0.03	
	P	0.600	0.712	0.593	0.334	0.301	0.191		
h/H	Intact	2.12±0.11	1.20±0.01	1.98±0.21	1.83±0.23	1.82±0.14	1.79^{c}	0.10	0.950
	4-month	2.56±0.41	1.59±0.29	2.06±0.10	2.17±0.08	2.01±0.04	2.08^{a}	0.12	
	6-month	2.13±0.07	1.59±0.17	1.84±0.10	1.99±0.12	1.95±0.03	1.90^{ab}	0.06	
	8-month	2.23±0.10	1.33±0.09	1.88±0.05	1.95±0.06	1.85±0.11	1.85^{bc}	0.08	
	P	0.505	0.354	0.617	0.423	0.491	0.049		
DI	Intact	1.27^{c}±0.06	0.59^{c}±0.06	1.33^{b}±0.17	0.95^{c}±0.10	1.18±0.11	1.06^{c}	0.08	<0.001
	4-month	2.71^{a}±0.25	1.31^{a}±0.15	2.02^{a}±0.11	1.71^{a}±0.09	1.59±0.05	1.87^{a}	0.14	
	6-month	1.98^{b}±0.07	1.16^{ab}±0.26	2.46^{a}±0.25	2.03^{a}±0.08	1.56±0.02	1.84^{a}	0.13	
	8-month	1.43^{c}±0.05	0.72^{bc}±0.07	2.40^{a}±0.09	1.36^{b}±0.14	1.40±0.14	1.46^{b}	0.15	
	P	<0.001	0.034	0.005	<0.001	0.055	<0.001		
EI	Intact	0.70±0.01	0.66±0.01	0.70±0.02	0.74±0.02	0.71±0.01	0.70	0.01	0.538
	4-month	0.73±0.03	0.67±0.03	0.72±0.01	0.74±0.01	0.73±0.01	0.72	0.01	
	6-month	0.73±0.01	0.70±0.02	0.69±0.01	0.71±0.01	0.72±0.01	0.71	0.01	
	8-month	0.73±0.01	0.68±0.02	0.69±0.01	0.74±0.01	0.71±0.02	0.71	0.01	
	P	0.426	0.682	0.266	0.448	0.533	0.746		

The data were expressed as mean±standard error. LT: Longissimus thoracis, ST: Semitendinosus, PM: Psoas major, TB: Triceps brachii, VL: Vastus lateralis. NVI: Nutritive value index, AI: Atherogenic index, h/H: hypocholesterolemic/Hypercholesterolemic index, DI: Δ9 Desaturase index, EI: Elongase index. AxB: The interaction of castration ages (A) and muscles (B) a-c The difference between the mean values of fatty acids represented by different letters in the same column is statistically significant (P <0.05).

Discussion

Growth and carcass characteristics

Since the meat of goats slaughtered at a young age is tender, it is highly demanded by consumers (Madruga et al., 2001). Castration can affect the growth performance and carcass composition of animals (Koyuncu et al., 2007; Zamiri et al., 2012). As the slaughter age increases after puberty, consumers tend to prefer the meat of castrated male goats more (Koşum et al., 2019). This raises the important question of the optimal age for castration in goats. Some researchers have conducted studies indicating the importance of castration at different ages to improve carcass quality with minimal negative effects on the growth performance of goats (Madruga et al., 2001; Koyuncu et al., 2007). In the current study, no significant differences were observed between the groups for growth performance from the 4th month to the 11th month. But goats castrated at 6-month-old reached the heaviest final weight (12th months) (Fig. 1). It is known that body weight and the amount of fat deposits increase with the maturation period and age depending on the hormonal system (Nagamine & Sunagawa, 2017). The endocrine system, especially the anabolic-acting testosterone hormone, plays an important role in the differences in body weight gain between males and females. In wethers, hormonal balance changes with an increase in luteinizing hormone levels and follicle-stimulating hormone secretion, and a decrease in testosterone secretion. As a result of these changes, live weight gains decrease in castrated animals (Nagamine & Sunagawa, 2017). However, Kebede et al. (2008) have reported that castration increases daily body weight gain while increasing the fat content in the carcass. Zamiri et al. (2012) also noted that the average daily weight gain or live weight was not affected in castrated and intact goats during the fattening period. In the present study, the highest total body weight gain occurred in male goats castrated at 6-months of age (P <0.01).

The results for slaughter weight and carcass composition are important parameters to evaluate concerning the effect of castration on the performance of goats. The goats castrated at 6-months of age were heavier than the goats castrated at the other age groups or intact ones, and they also had the highest carcass weight. Although, the slaughter weight of intact goats and 4-month-old castrated goats were similar, both hot and cold carcass yields (ratio of carcass weight to slaughter weight) were higher in 4-month-old castrated goats than intact goats. These results were in line with the findings of Koyuncu et al. (2007) and Solomon et al. (1991) who reported that castration at an early age increased the carcass yield.

Head, the four-legs, the liver and heart weight were affected by the age of castration, similar to the results reported by Kebede et al. (2008). No significant ($P > 0.05$) differences in kidney weight between all the goat groups were observed, but the kidney fat of the castrated goats was heavier than that of non-castrated ones. It has been stated that castration in goats causes an increase in kidney-pelvic fat (Koyuncu et al., 2007). The LT area was found to be larger in goats castrated at 8-months of age, which is consistent with the findings of Zamiri et al. (2012) and Anneke et al. (2019) for castrated and non-castrated goats.

The testicular weight was affected by castration, likely due to compromised blood supply resulting from vascular damage at the castration site. Similarly, Kebede et al. (2008) stated that castrated goats had significantly lower testis weights than intact males.

It is well known that goat carcass composition and quality are influenced by diet, production system, genotype, sex, slaughter weight and age (Todaro et al., 2004). As shown in Tables 3 and 4, castration had a significant effect on muscle, bone, subcutaneous and intermuscular fat contents of the various carcass cuts. Although the percentages of the five primal cuts relative to the carcass weights were not significant, the weights of shoulder, rib and long-leg were found to be highest in the 4-month-old castrated group. Bone tissue percentage in each carcass cut, except the shoulder, was affected by castration age and the intact and 8-month-old groups had the highest bone tissue content ($P < 0.01$; 0.05, respectively). Castration performed in the early period reduced bone tissue development, as reported by Marichal et al. (2003) and Santos et al. (2007). The lowest percentage of muscle tissue was calculated for the 4-month-old castrated group (Tables 3, 4 and 5), probably due to less muscle formation in goats with castration at an early age. The most pronounced effect of castration was observed in the subcutaneous and intramuscular fat tissue. The rates similar to the SF and IF rates determined in the present study were compatible with the rates previously reported (Johnson et al., 1995; Çiftçi & Kor, 2010). Castration at an early age promotes fat deposition in the body while slowing bone and muscle growth. As mentioned above, higher live weight gains in castrated goats are probably due to increased adipose tissue since castration increases the activity of lipogenic enzymes (Haddad et al., 2006). As reported by Mourad et al. (2001) and Kebede et al. (2008), castration, especially at an early age (4-months of age), increased the adipose tissue percentage in the carcass and decreased the muscle tissue percentage, and therefore negatively affected the carcass quality.

Physicochemical characteristics of meat

The present findings for dry matter, ash and protein were similar to those reported in Mestiço and Saanen goat muscles (Madruga et al., 1999; De Palo et al., 2015). The content of fat detected in goat muscles was consistent with the findings of Madruga et al. (1999) but was higher than that reported by De Palo et al. (2015). The meat of goats castrated at 4- and 6-months age had more intramuscular fat than the other groups (Fig. 2). It has also been highlighted that castration causes fattening in ruminants (Koyuncu et al., 2007; Gkarane et al., 2018). Johnson et al. (1995) determined the fat content of the carcasses of male, female and castrated male goats reared in the USA to be 7.4%, 13.0% and 11.0%, respectively, but the fat, dry matter and protein of goat meats did not differ significantly by sex and castration.

As shown in Fig. 3, the lowest pH values for all muscles were obtained with castration at an early age (4-months). This may be due to the change in the energy metabolism of the castrated goats compared to the intact ones. Castration is thought to affect the goats' susceptibility to pre-slaughter stress. Less stress and glycogen consumption before slaughter may result in a lower pH value in meat. Similarly, Li et al. (2020) reported that castrated sheep had a higher glucose content in PM muscle than intact ones. To understand the effect of castration on energy metabolism in meats, a more detailed study on organic acids in energy metabolism and their reaction products is necessary.

The differences in the pH values between muscle types are thought to be due to the difference in the red and white fibre contents of the muscles and, therefore, the difference in energy metabolism in both ante- and post-mortem periods. Muscles are generally divided into three types according to the variety of muscle fibres and energy metabolism; (1) slow-oxidative fibre, (2) fast-oxidative fibre and (3) fast-glycolytic fibre (Lawrie & Ledward, 2006). The TB muscle is a slow oxidative muscle and has less glycogen stored and therefore a higher pH than the other muscles (Shen et al., 2015), consistent with the findings of the present study. The pH value of goat meat may be high compared to the red meat of the other livestock species since they are more susceptible to pre-slaughter stress (Kumar et al., 2023). Similar to our findings, Kannan et al. (2001) found a higher pH value (6.33) in the TB muscle than in the LT muscle (5.96) in Spanish adult female goats. Regardless of carcass cuts and castration age, goat meat had a mean pH value of 5.8, which is consistent with the value reported by Ekiz et al. (2010) for Saanen, Gökçeada and Maltese goat meats.

Compared with the control group, castration caused a decrease in the redness (a^*) of the meat. Since chroma is derived from the a* and b* values, any changes observed in the a* value will inherently influence the chroma value. Zamiri et al. (2012) reported that castrated goats produced redder meat than non-castrated bucks. This may be associated with higher intramuscular fattening (Jankowiak et al., 2019) and also due to the difference in energy metabolism as stated by van Wyk et al. (2022). It has been reported that isocitrate dehydrogenase enzyme activity, having an important role in energy metabolism, has been strongly associated with meat redness value (Calnan et al., 2014). As expected, differences in colour values among muscles were observed. Shen et al. (2015) reported that fast-glycolytic muscles (LT and ST) having a high mitochondria content have a lighter red colour due to their higher content of whiter fibres. The interaction between castration age and muscle L^*, a^*, b^*, hue angle and chroma values were found to be significant (P <0.05). This indicates that the effect of castration age on meat colour varies from muscle to muscle. In goats castrated at 6-months of age, the highest hue value was observed in the ST muscle, while the lowest hue value was observed in the TB muscle. Additionally, castration at 6-months of age decreased chroma values in the LT muscle but increased them in the PM muscle (Fig. 4). There are conflicting reports on the effect of castration on meat colour since meat colour varies depending on the muscle type and sex etc. Seideman et al. (1982) reported darker meat from intact male animals compared to females and castrated males. On the contrary, Wyk et al. (2022) noted that the wethers had darker meat compared to the bucks.

Regarding meat tenderness, castration, especially at 6-months of age, compared to the intact bucks produced more tender meat (lower WBSF values). This finding was consistent with the ultimate pH values of the meat since proteolytic enzymes are more active at a low pH. Additionally, the increase in the content of intramuscular fat (Fig. 2) relating to castration may increase tenderness. Consistent with our findings, Ueda et al. (2007) have reported a negative correlation (r = -0.83, P <0.05) between the amount of intramuscular fat and the shear force of meat. Some researchers reported that the sensory score for tenderness was higher in castrated sheep meat than in intact sheep (Sales, 2014). To the best of our knowledge, there is no comparative study in the literature in terms of WBSF values according to muscle types in castrated or intact goat meat. In all the experimental groups, TB and PM muscles had the lowest and the highest WBSF values, respectively (Fig. 5). The differences in WBSF between the TB and PM muscles may be attributed to variations in ultimate pH and collagen content, as increased toughness in muscles with higher collagen levels and pH values is likely due to greater moisture loss and fibre shrinkage during cooking (Torrescano et al., 2003; Hoffman et al., 2008). It is considered that castration may be an important application for obtaining more tender goat meats (Fig. 4), in terms of consumer acceptability.

During the heat treatment applied to meat for cooking, not only protein denaturation occurs, but also structural changes such as disruption of the cell membrane, shrinkage of muscle fibres, aggregation of sarcoplasmic proteins and narrowing of connective tissue. Among them, in particular, the change in the connective tissue causes cooking losses in meat (Hoffman et al., 2022). In all the experimental groups, the cooking loss values of the meat ranged from 35.6% to 41.7%, values similar to those reported for Saanen, Gökçeada and Maltese goat meats (34.0% to 36.8%), but were higher than those reported for Hair and Saanen x Hair goat crossbreds (Ekiz et al., 2010). This could be attributed to the differences in goat breeds, as stated by Dhanda et al. (1999). On the other hand, differences between muscles in terms of myofibrils and connective tissue proteins may also affect the cooking loss of meat. The cooking loss in castrated goat meat was lower than that of the intact bucks, probably due to more intramuscular fattening (Fig. 2). Similarly, a negative correlation between the cooking loss and the amount of muscle fat was observed by Ueda et al. (2007). Low-fat muscles tend to lose more water with cooking, which makes the meat drier and tougher. Also, both intramuscular fat and cooking loss were significantly influenced by the interaction between castration age and muscle type (P <0.01). The tendency to increase in fat resulteing from the castration age varied from muscle to muscle. The TB muscle had the highest fat and the lowest cooking loss at 4 months of age, but the ST muscle had at 6 months of age.

Fatty acid profile of muscles

Consistent with the findings of the present study, Madruga et al. (2001) reported SFA as 46.6% and 48.8% for castrated and intact goat muscles, respectively. Also, it was determined that the SFA percentage of the LT muscle of castrated Boer and Feral goats was lower than that of intact goats (Werdi Pratiwi et al., 2004). Capric acid was found only in TB and VL muscles, and 12:0 was in ST, along with TB and VL (Table 5). This may be due to different fatty acid accumulation patterns of ST (shoulder), TB and VL (long-leg) in relation to muscle activity.

Among the fatty acids, c9-18:1 (37%) was found to be the highest in all of the goat muscles, followed by 18:0 (26%), 16:0 (23%) and 18:2n-6 (7%). The fatty acid profile of the muscles was consistent with those obtained from previous studies (Park and Washington, 1993; Banskalieva et al., 2000; Madruga et al., 2001). A high level of c9-18:1 and t11-18:1 in the intramuscular fat of muscle from early castrated goats was consistent with its low 18:0. This could be attributed to the inverse correlation between ruminal oleic acid and its bio-hydrogenation intermediates (Shingfield & Wallace, 2014). Therefore, an early castration led to greater desaturase activity (Table 6), which resulted in the replacement of stearic acid with oleic acid (Güler & Dursun, 2023).

CLA (c9,t11-18:2), also known as rumenic acid, is a product of rumen metabolism and formed from hydrogenation of linoleic acid, and a precursor of vaccenic acid. Ruminant meats are among the main sources of CLA. Therefore, vaccenic acid, which is the only trans-form fatty acid detected in the muscles, is not considered among the unhealthy trans-fatty acids since it is obtained from the hydrogenation of CLA double bonds during rumen metabolism (Urrutia et al., 2020). Regardless of muscle type, the highest vaccenic acid level was determined in the muscles of goats castrated at 6-months of age. CLA has only detected in the LT muscle in goats castrated at 4- and 6-months of age. Therefore, it is postulated that castration at an early age may affect CLA formation in intramuscular fat.

While the total MUFA increased with early castration, the PUFA, especially the n-6 fatty acids, decreased. However, the interaction between castration age and muscle (P <0.01) in PUFA showed that the change in PUFA differed from muscle to muscle. This could likely be attributed to the differences in oxidative and glycolytic energy metabolism of the muscles. Also, linoleic, and arachidonic acids are omega-6; linolenic and eicosapentaenoic acids are omega-3 fatty acids. Among the analysed muscles, the PM muscle had no 20:5n-3 fatty acid, probably due to its dominant slow-twitch fibres (Lawrie & Ledward, 2006). Fast-twitch muscles that have specific fatty acids like 20:5n-3 may accumulate higher fatty acids. 18:2n-6, 18:3n-3 and 20:4n-6 fatty acids are also essential fatty acids and cannot be synthesized in the human body. Although long-chain polyunsaturated fatty acids such as eicosapentaenoic acid can be synthesised from ALA during metabolism, it is very important to include the mentioned fatty acid in the human diet, since the efficiency of this reaction is low.

The possible health effects of goat meat could be described in terms of the nutritional quality indices as shown in Table 6. In the present study, the NVI values agreed with those (2.3–2.8) previously reported in the LT muscle of goats by Banskalieva et al. (2000), who also reported that the NVI of goat meat may be higher than beef (1.9-2.2) and sheep (2.1-2.5) meat. In the present study, the PUFA:SFA ratio ranged from 0.14 to 0.28. Hoffman et al. (2003) stated that the PUFA:SFA ratio should be at least '0.12'. The castration ages and muscle types interacted with UFA:SFA ($P<0.05$) and also PUFA:SFA ($P<0.001$). The ST muscles from intact goats and castrated at 6-month-old had the highest and the lowest PUFA:SFA ratios, respectively (Table 6). In general, castration at 6-month-old resulted in a reduction in the PUFA:SFA ratio, as reported by Lima et al. (2019). The h/H index indicates the effects of specific fatty acids on cholesterol. A high h/H value has nutritionally beneficial effects on human health.

The activity indices were also calculated for elongase and Δ^9-desaturase enzymes in relation to 16 and 18 carbons fatty acids. Δ^9-desaturase enzyme converts the saturated fatty acids to their corresponding mono-unsaturated forms (Malau-Aduli et al., 1997). The elongation of fatty acids involves the addition of two carbon units to their carboxyl end. The Δ^9-desaturase index (DI) ranged from 0.59 in the PM muscle of intact goats to 2.71 in the LT muscle of castrated at 4-month-old. Castration, especially at early age, resulted in a high DI in intramuscular fat. No significant difference was observed in elongase activity between castrated and non-castrated goats. Although castration at an early age increases the fat content of both carcasses (Table 4) and meat (Fig. 2), this fattening could be healthier for the human diet due to the high UFA:SFA, h/H and DI indices (Table 6).

Conclusions

In this study, castration of goats at different ages had significant effects on the fattening performance, as well as some carcass and meat characteristics. Accordingly, the following results were revealed:

-The most suitable castration ages for the development of goats were found to be at 6-months. Goats castrated at 6-months had the highest live weight.

- Castration of goats at an early age (4-months) increased the ratios of subcutaneous and intermuscular fat in different tissues of carcass cuts and decreased the ratio of muscle compared to late castration (8-months old) and intact goats. However, an early castration increased the oleic acid of muscles and provided a high UFA:SFA, h/H and DI indices. This could be considered an advantage for consumers.

-Among the carcass cuts, long-leg muscle, subcutaneous fat, and intermuscular fat from 4-month-old castrated goats had the highest weights.

-The goats castrated at 4-month produced meat with lower pH and was more tender, and 6-month-old castration resulted in lower cooking loss than those of intact goats, but with lower redness attributes of the meat.

In conclusion, it is recommended that a goat producer who engages in long-term fattening on pasture with additional feed should consider castrating their goats at the age of 6 months, in terms of investigated parameters. With respect to meat quality, castration at 4 months may be recommended to consumers. Further research is needed to determine the effects of castration on blood parameters and hormones in relation to fatty acid profiles.

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