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Analyses of the physicochemical and sensory characteristics of black goat *triceps brachii* muscle based on slaughter age

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A R T I C L E I N F O

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A B S T R A C T

In this study, we aimed to analyze the effects of slaughter age on black goat meat's physicochemical and nutritional characteristics. Goats (age: 3, 6, 9, 12, 24, and 36 months) reared under identical conditions were used in this study. The key parameters were analyzed, including color, cooking yield, shear force, free amino acid (FAA) levels, free fatty acid levels, and sensory attributes. Hue values decreased, whereas redness increased with age. Umami and sweet FAA levels increased with age, and bitter FAA levels increased from 9 months. The flavor scores increased with age up to 9 months. Off-flavors were significantly higher in goats aged 24 and 36 months than in those aged 3 and 6 months. Goats aged 9 and 12 months had significantly higher texture scores than those aged 3, 6, and 36 months. Overall, our findings suggest that goats aged 9 and 12 months exhibit the best sensory qualities.

1. Introduction

The ruminant industry is a sustainable agricultural resource that can be used to combat climate change and protect the environment. This industry is efficient in producing high-quality products while utilizing limited resources (Sejian et al., 2021). Notably, ruminants possess the unique ability to convert dietary fibers, such as cellulose that is indigestible by humans, into energy via microbial digestion (Mottet et al., 2018). This capability, in addition to their ability to yield useful products, such as milk and wool, make goats and sheep important tools to combat future environmental issues and food security challenges via meat production (Rout et al., 2021). Globally, the goat population increased from approximately 750 million in the early 2000s to 1025 million in 2018 to meet the increasing goat meat consumption (Mazinani & Rude, 2020). Therefore, small ruminants should be explored as potential meat sources.

Consumers prefer meat with high cooking yield due to its excellent water-holding capacity and favorable sensory qualities, such as marbling and color (Pophiwa et al., 2020). Many studies are focusing on modifying meat composition by varying the feeding methods according to consumer preferences across different livestock species (An et al., 2022; Cho et al., 2017). Goat meat is popular among health-conscious consumers owing to its nutrient composition and is more beneficial to health than meat from other livestock species (Mazhangara et al., 2019). Several factors, including age at slaughter, breed, pre-slaughter condition, and conditions during transport and lairage, affect the flavor and quality of goat meat (Pogorzelski et al., 2022). Therefore, understanding the mechanisms by which these factors affect and enhance the quality of goat meat is necessary to promote its consumption.

Livestock exhibit differences in intramuscular fat content, myoglobin levels, and connective tissues based on breed, sex, and age, resulting in varying meat quality and sensory attributes, such as flavor and taste (Hoffman & Fisher, 2001). Pogorzelska-Przybyłek et al. (2018) reported that slaughter age does not significantly affect the fatty acid composition of steer meat. However, steers slaughtered at 18 months exhibit higher sensory evaluation scores than those slaughtered at 15 months. Polidori et al. (2017) revealed that slaughter age affects the color and collagen content, thereby influencing the tenderness of lamb meat. Additionally, Ke et al. (2019) noted that the gut microbiome composition changes with age, leading to differences in digestion and absorption capabilities and varying body composition. These reports suggest that slaughter age significantly affects the meat quality of most livestock species.

Abbreviations: FAA, free amino acid; FFA, free fatty acid; MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid; SFA, saturated fatty acid; UFA, unsaturated fatty acid.

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Therefore, the mechanisms by which meat quality changes with slaughter age should be investigated to better understand and optimize meat production practices.

In this study, we aimed to analyze the physicochemical and nutritional characteristics of black goat meat at various slaughter ages (3, 6, 9, 12, 24, and 36 months). Additionally, we examined the factors affecting the sensory attributes of black goat meat to determine the optimal slaughter age for the production of meat with superior sensory qualities.

2. Materials and methods

2.1. Animals and sampling

Hybrid female black goats (Korean native Black goat × Boer × Saanen × Nubian; age: 3, 6, 9, 12, 24, and 36 months) were randomly selected from a specialized goat farm in Gangjin, South Korea. The goats were raised under identical conditions with the same diets based on the guidelines of the National Research Council (NRC) (2007). Fifteen black goats were purchased from three farms, with five goats per farm. Each goat was divided into left and right halves, resulting in 30 samples for analysis (3 farms × 5 animals × 2 batches). Goats were slaughtered in a commercial slaughterhouse (Agricultural Corporation Gaon, Gangjin, Korea) with appropriate slaughtering permits. The meat was delivered in a refrigerated state 24 h after slaughter.

The *triceps brachii* muscles were used in this study. After removing the excess subcutaneous fat and connective tissues, the samples were immediately used for color, cooking yield, shear force, and sensory evaluation. To analyze the free amino acid (FAA) and free fatty acid (FFA) levels, the samples were vacuum-packed and stored at −20 °C until the experiments.

2.2. Color

Lightness, redness, and yellowness values were measured using a colorimeter (CR-10; Konica Minolta, Tokyo, Japan) with a standard illuminant D_{65} and viewing angle of 8°. A white standard plate (lightness: +97.83, redness: −0.43, and yellowness: +1.98) was used for calibration. Chroma (C*) values were calculated as $C^* = [(a^*)^2 + (b^*)^2]^{1/2}$, where higher values indicated more vivid meat color. Hue angle (H°) was calculated as $H° = \arctan(b^*/a^*) \times (180/\pi)$, representing colors on a scale of 0 (=360) for redness, 90 for yellowness, 180 for –redness, and 270 for –yellowness. Measurements were repeated to avoid areas with excessive connective tissue and intramuscular fat on the cut surfaces of the uncooked samples. The samples were further exposed to air at room temperature for 30 min to allow blooming.

2.3. Cooking yield

Next, the Chamber (model 10.10ESI/SK; Alto Shaam, Menomonee Falls, WI, USA) was preheated at 80 °C for 30 min. Meat samples thawed for 24 h at 4 °C in a refrigerator were cut to a thickness of 5 cm and roasted at 80 °C in the Chamber (model 10.10ESI/SK; Alto Shaam) until reaching a core temperature of 70 °C, at which point the roasting was stopped. The cooked samples were cooled at 10 °C for 1 h, and their weights before and after heating were measured and calculated as percentages as follows:

Cooking yield (%) = after heating weight (g)/before heating weight (g) × 100.

2.4. Shear force

The cooked samples were cut into 3 × 1 × 1 cm (length × width × height) pieces and analyzed using a texture analyzer (TA 1; Lloyd, Largo, FL, USA) with a V-blade in the vertical direction of fibers under the following conditions: head speed of 2.0 mm/s, distance of 2.0 mm, and force of 5 g. The results are expressed in Newtons (N).

2.5. FAA levels

FAA levels were analyzed as described by Lee et al. (2016). Briefly, the samples were mixed with 5 % trichloroacetic acid at a ratio of 1:10 (*w/v*) and homogenized using Ultra-Turrax (T25 basic; IKA-Werke GmbH & Co. KG, Baden-Württemberg, Germany). The homogenate was stored in a refrigerator at 4 °C for 1 h to precipitate the proteins. Subsequently, centrifugation (HM-150IV; Hanil Science Inc., Gimpo, Korea) was carried out at 4 °C for 15 min at 10,000 ×*g* to separate the supernatant. The supernatant was filtered through Syringe Filters (0.2 μm hydrophilic PTFE 13 mm; Advantec, Irvine, CA, USA). Amino acid extraction and derivatization were performed using the AccQ-TAG Reagent Kit (Waters, Milford, MA, USA). AccQ-Fluor Reagent Diluent (1 mL) was added to a vial containing AccQ-Fluor Reagent powder, sealed, vortexed for 10 s, and dissolved in a water bath at 55 °C to prepare the reconstituted AccQ-Fluor reagent. The filtered sample (10 mL) was mixed with 70 mL AccQ-Fluor borate buffer and vortexed for 10 s. Reconstituted AccQ-Fluor reagent (20 mL) was added to the mixture, vortexed for another 10 s, and heated in a water bath at 55 °C for 10 min to prepare the amino acid derivatives. The amino acid derivatives were analyzed and quantified using ultra-high performance liquid chromatography (Ultimate WPS-3000RS; Thermo Fisher Scientific Inc., Waltham, MA, USA) with the AccQ-Tag Ultra C18 column (2.1 × 100 mm; 1.7 μm particles; Waters). The mobile phase consisted of gradient mode 10 % AccQ-Tag Eluent A concentrate (A) and 100 % AccQ-Tag Eluent B concentrate (B). The injection volume of the mobile phase was 10 μL, and the flow rate was set at 0.7 mL/min (0–0.54 min: 99.9 % A and 0.1 % B; 0.54–5.74 min: 90.9 % A and 9.1 % B; 5.74–7.74 min: 78.8 % A and 21.2 % B; 7.74–9.04 min: 40.4 % A and 59.6 % B; 9.04–10.0 min: 10 % A and 90 % B; 10.0–13.0 min: 99.9 % A and 0.1 % B). The column temperature was maintained at 35 °C. FAA levels were calculated by measuring the peak areas at 260 nm using a multimode microplate reader (SpectraMax iD3; Molecular Devices, San Jose, CA, USA). Amino acid standards, including L-glutamine, L-asparagine, L-tryptophan, and γ-aminobutyric acid (Sigma-Aldrich Co., St. Louis, MO, USA), were used for quantification.

2.6. FFA levels

Next, lipid extraction was performed as described by Folch et al. (1957). Briefly, the samples were mixed with chloroform/methanol (2:1, *w*/w) at a ratio of 1:4 (*w/v*) and homogenized for 1 min at 1296 ×g using Ultra-Turrax (T25 basic; IKA-Werke GmbH & Co. KG). Then, equal volume of 0.88 % KCl (w/v) was added to the dilution and centrifuged at 2 °C and 3000 ×*g* for 10 min using the Avanti J-E centrifuge (Beckman Coulter, Fullerton, CA, USA). The supernatant was removed and filtered through a Whatman No.1 filter paper (Whatman; Maidstone, UK). The filtrate was concentrated at 38 °C using the N2 gas blow concentrator (MGS-2200; Eyela Tokyo Rikakikai Co., Tokyo, Japan), as described by David and Wylie PL (2003). The concentrated lipid (200 μL) was further methylated with 2 mL of 0.5 N NaOH/methanol (*w*/w) and 14 % boron trifluoride/methanol solution (w/w), as described by David and Wylie PL (2003). The methylated lipids were mixed with 5 mL of distilled water and 2 mL of n-hexane and centrifuged at 2 °C and 3000 ×*g* for 5 min. The upper phase (1 μL) was injected into a GC system (CP-8400; Varian Inc., Palo Alto, CA, USA) equipped with the HP-Innowax column (30 m length × 0.32 mm id × 0.25 μm film thickness) for analysis. The GC conditions were as follows: injector at 260 °C with a split ratio of 1/10, carrier gas helium at 1 mL/min, oven program starting at 150 °C for 1 min, increasing to 200 °C at 15 °C/min, then to 250 °C at 2 °C/min, and holding at 250 °C for 10 min, and flame ionization detector at 280 °C. Each fatty acid peak was identified and quantified as a percentage of the total peak area using standards (47015-U; polyunsaturated fatty acid [PUFA] No. 2 Animal Source; Supelco, Bellefonte, PA, USA).

2.7. Sensory evaluation

This project was approved by the Kongju University Institutional Bioethics Committee (Authorization Number: KNU_IRB_2021-75The organization stated in advance that it would protect the rights and privacy of all participants. As a result, we received a positive response from the participants regarding the study, and individual consent forms were obtained. Participants responded, "I agree to participate in the sensory evaluation," and were allowed to withdraw at any time. The sensory evaluation panel consisted of eight individuals aged 20–30 who had previously consumed goat or lamb meat. Prior to sensory evaluation, the panelists were educated on the terminology and evaluation criteria related to goat meat, according to the Institutional Animal Care and Use Committee of Kongju National University (Authority No: KNU 2020–40). Sensory evaluation samples (3 × 1 × 1 cm) were roasted at 80 °C and cooled for 5 min before presentation. Each sample was randomly served with a 1-min interval between tests. Sensory attributes were rated on a 10-point scale, with scores for color, flavor, texture, juiciness, and overall liking ranging from 1 (extremely bad or undesirable) to 10 (extremely good or desirable). The scores for off-flavors and off-odors ranged from 1 (extremely unperceivable) to 10 (extremely perceivable). After evaluation, the average scores for each attribute were calculated and compared.

2.8. Statistical analyses

Using the SAS statistical software (version 9.4, SAS Institute Inc., Cary, NC, USA), we conducted one-way analysis of variance to analyze the experimental results. Duncan's multiple range test was used to verify the significant differences ($P < 0.05$) among the compared groups. Pearson correlation coefficient (r) was calculated using SAS PROC CORR to explore the correlation ($-1 < r < 1$) between meat quality and slaughter age, and its significance was analyzed ($P < 0.05$, $P < 0.01$, and $P < 0.001$).

3. Results and discussion

3.1. Color

Although color is not an indicator of the safety and quality of meat, consumers use it as a basis for purchasing decisions, perceiving it as a sign of meat integrity (Tomasevic et al., 2021). Color measurement results of black goat meat samples according to slaughter age are presented in Table 1. Lightness significantly decreased up to a slaughter age of 9 months ($P < 0.05$). Although lightness generally decreased with slaughter age, no significant differences were observed after 12 months ($P > 0.05$). Lightness exhibited a strong negative correlation with slaughter age ($r = -0.75$ and $P < 0.001$). In contrast, redness increased with slaughter age, with the 3-month-old sample exhibiting the lowest value ($P < 0.05$) and the 12–36-month-old samples exhibiting the highest values ($P < 0.05$). Additionally, a strong positive correlation was observed between redness and slaughter age ($r = +0.73$ and $P < 0.001$). These results are consistent with previous reports that the lightness decreases and redness increases with slaughter age (Deng et al., 2024). Heme iron levels increase with the animal slaughter age. Heme iron content is inversely related to meat lightness but directly related to redness (Calnan et al., 2016). Additionally, there have been studies showing that as age, more myoglobin is formed due to higher iron intake and exercise, which leads to these results (Ruedt et al., 2023). Abhijith et al. (2021) reported that the animals slaughtered at old ages exhibit higher number of type I muscle fibers and thicker perimysium than those slaughtered at young ages. These factors contribute to the lower lightness and higher redness of meat. Therefore, increasing the slaughter age of black goats decreases the lightness and increase the redness of meat. Yellowness decreased with increasing slaughter age, with the 3- and 6-month-old samples showing significantly higher yellowness than the 24- and 36-month-old samples ($P < 0.05$). A moderate negative correlation was observed between yellowness and slaughter age ($r = -0.68$ and $P < 0.001$). Therefore, young slaughter ages (3 and 6 months) negatively affect the consumer acceptance of meat. Chroma increased up to the slaughter age of 12 months. However, the 24- and 36-month old samples exhibited no significant differences compared with the 9- and 12-month samples ($P > 0.05$). Chroma showed a moderate positive correlation with slaughter age ($r = +0.62$ and $P < 0.01$). Hue angle decreased with the slaughter age, and no significant differences were observed after 12 months ($P < 0.05$). Hue angle exhibited a strong negative correlation with slaughter age ($r = -0.77$ and $P < 0.001$). In summary, color of the *triceps brachii* of black goats showed significant changes, starting from the slaughter age of 3–12 months, with no noticeable changes in meat color observed after the slaughter age of 12 months. Therefore, slaughter age of 12 months is appropriate for optimal color expression and meat stability.

3.2. Cooking yield and shear force

Cooking yields of black goat meat samples according to slaughter age are listed in Fig. 1. The cooking yield significantly increased with slaughter age ($P < 0.05$), exhibiting a strong positive correlation with slaughter age ($r = +0.90$ and $P < 0.001$). This increase is attributed to the differences in soluble collagen content according to the age of the animal. Young animals exhibit high collagen solubility due to protein breakdown by cathepsin B (Christensen et al., 2013). Soluble collagen is exuded from the muscle along with juice during cooking, leading to a reduction in cooking yield. Cooking yield is an indicator of meat quality, and high cooking yield is associated with better texture, juiciness, and overall palatability of the meat (Hoffman et al., 2020; Kopuzlu et al., 2018). Awan et al. (2014) reported that younger buffalo meat exhibited more myofibrillar protein contractions than the older buffalo meat. This contraction of myofibrillar proteins causes the moisture within the muscle to exude outward, thus reducing the cooking yield. Therefore, the increase in cooking yield with increasing slaughter age in black goats was possibly due to the decrease in soluble collagen content and

Table 1
Color of *m. triceps brachii* in black goats by slaughter age.

Color	Ages (month)						SEM[1]	r[2]
	3	6	9	12	24	36		
Lightness	42.48[a]	41.34[b]	39.20[c]	38.60[cd]	38.22[d]	38.02[d]	0.323	−0.75***
Redness	6.46[c]	7.56[b]	7.96[b]	8.57[a]	8.45[a]	8.70[a]	0.166	0.73***
Yellowness	7.04[a]	6.86[a]	6.74[ab]	6.70[ab]	6.40[b]	6.38[b]	0.064	−0.68***
Chroma	9.74[d]	9.94[cd]	10.38[bc]	10.92[a]	10.62[ab]	10.77[ab]	0.117	0.62**
Hue angle°	46.85[a]	42.39[b]	40.69[bc]	38.33[cd]	37.08[d]	36.45[d]	0.935	−0.77***

[a–d] Mean in the same row with different letters are significantly different ($P < 0.05$).
[1] SEM, standard error of the mean, $n = 30$.
[2] r, Pearson correlation coefficients; **, $P < 0.01$; ***, $P < 0.001$.

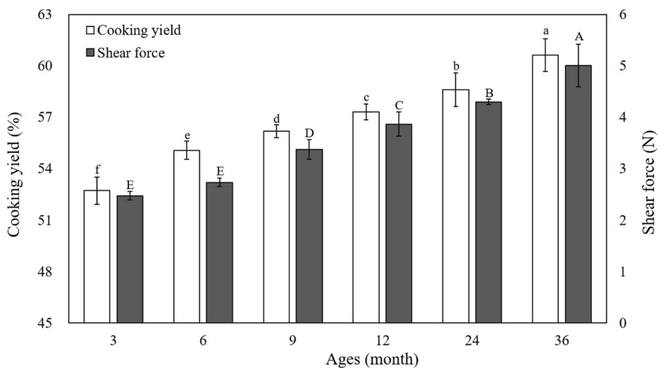

Fig. 1. Cooking yield and shear force of *m. triceps brachii* in black goats by slaughter age. $^{a–f}$ Mean in the cooking yield values with different letters are significantly different (P < 0.05). $^{A-E}$ Mean in the shear force values with different letters are significantly different (P < 0.05). r, Pearson correlation coefficients; ***, P < 0.001 in cooking yield and shear force.

myofibrillar protein contraction. Consequently, increasing slaughter age can enhance the sensory attributes, such as texture and juiciness, of meat.

Shear force of black goat meat samples increased significantly from the slaughter age of 6 months (P < 0.05), with no significant differences observed between the 3- and 6-month samples (P > 0.05). Shear force showed a strong positive correlation with slaughter age (r = +0.92 and P < 0.001). Insoluble collagen in the muscle is formed via crosslinking of collagen molecules, and the amount of crosslinking increases with age (Cho et al., 2017). The pyridinoline value, which increases with age, indicates the content of cross-linked collagen and is greatly influenced by age (Si et al., 2022). Most studies have shown that pyridinoline content is higher in older animals, suggesting that shear strength increases with age (Koulicoff et al., 2023; Li et al., 2022). Kadim et al. (2006) also reported that, as the age of the Omani Arabian camels increased, their sarcomere length and myofibrillar fragmentation index decreased, leading to increased shear force. Similarly, increase in the slaughter age of black goats is associated with high shear force. The study of Abdullah and Musallam (2007) on the relationship between shear force and sensory acceptability revealed that shear force >5.5 kg (53.94 N) negatively affects the sensory perception, whereas shear force <3.6 kg (35.30 N) is within the acceptable range of tenderness for goat meat. In this study, shear force of black goat meat across all slaughter ages was within the acceptable sensory range. Specifically, meat from goats slaughtered at 3–9 months of age was found to be tender. Therefore, slaughter age of 12 months is recommended to produce black goat meat with high sensory acceptability.

3.3. FAA levels

In black goat meat samples, 17 types of FAAs were detected based on the slaughter age. They were classified as umami (aspartic acid, asparagine, and glutamine), sweet (alanine, glycine, serine, and threonine), bitter (arginine, histidine, isoleucine, leucine, methionine, phenylalanine, tyrosine, tryptophan, and valine), and tasteless (cysteine) FAAs (Table 2). Umami and sweet FAA levels increased with slaughter age. FAA, one of the meat evaluation criteria, is known to be not only a component of protein but also plays an important role in cell signaling (Canfield & Bradshaw, 2019). In this study, each FAA showed a strong positive correlation with slaughter age: umami (r = +0.84 and P < 0.001) and sweet FAAs (r = +0.78 and P < 0.001). Umami is a key factor enhancing the palatability of food. It contributes to the overall taste, enhances the flavor characteristics, such as sweetness and saltiness, and suppresses the perception of bitterness, thereby controlling the undesirable bitter taste of meat (Wang et al., 2020). Glycine, a major component of sweet FAAs, enhances the sweetness of meat and improves the sweetness of reducing sugars, such as glucose, present in the meat (Dinh et al., 2018). Therefore, increase in umami and sweet FAA levels with increasing slaughter age enhances the flavor of black goat meat and suppresses the perception of bitterness, potentially increasing its consumer preference. Here, bitter FAA levels increased from the slaughter age of 9 months and showed a strong positive correlation with slaughter

Table 2
Free amino acids (FAA) composition of *m. triceps brachii* in black goats by slaughter age.

FAA (μmole/g dry weight)	taste	Ages (month)						SEM[1]	r[2]
		3	6	9	12	24	36		
Aspartic acid		0.05^{e}	0.08^{de}	0.16^{cd}	0.20^{bc}	0.27^{ab}	0.30^{a}	0.022	0.82***
Asparagine		0.08^{d}	0.12^{cd}	0.20^{bc}	0.21^{b}	0.26^{ab}	0.32^{a}	0.021	0.81***
Glutamine	umami	1.75^{b}	2.33^{b}	2.64^{ab}	2.93^{ab}	3.18^{ab}	3.80^{a}	0.203	0.70**
Total		1.88^{c}	2.53^{bc}	2.95^{bc}	3.34^{ab}	3.71^{ab}	4.40^{a}	0.242	0.84***
Total FAAs area (%)		11.90	12.16	9.86	10.25	10.83	10.74		
Alanine		0.14^{d}	0.17^{d}	0.36^{c}	0.41^{bc}	0.49^{ab}	0.59^{a}	0.041	0.88***
Glycine		0.88^{b}	1.08^{ab}	1.11^{ab}	1.30^{a}	1.40^{a}	1.39^{a}	0.063	0.62***
Serine	sweet	0.24^{c}	0.28^{c}	0.53^{b}	0.58^{b}	0.57^{b}	0.74^{a}	0.040	0.87***
Threonine		0.32^{c}	0.39^{c}	0.63^{bc}	0.75^{b}	0.85^{ab}	1.17^{a}	0.066	0.76***
Total		1.59^{d}	1.87^{cd}	2.63^{bc}	3.04^{ab}	3.39^{ab}	3.64^{a}	0.208	0.78***
Total FAAs area (%)		10.06	8.99	8.79	9.33	9.90	8.89		
Arginine		1.51^{c}	2.36^{b}	2.42^{b}	2.56^{b}	3.07^{ab}	3.59^{a}	0.161	0.79***
Histidine		0.06^{c}	0.08^{c}	0.14^{b}	0.17^{b}	0.19^{b}	0.25^{a}	0.014	0.83***
Isoleucine		0.08^{c}	0.12^{c}	0.25^{b}	0.25^{b}	0.27^{b}	0.34^{a}	0.022	0.83***
Leucine		0.14^{c}	0.21^{c}	0.51^{b}	0.54^{b}	0.59^{b}	0.75^{a}	0.053	0.83***
Methionine		0.11^{c}	0.13^{c}	0.25^{b}	0.29^{b}	0.35^{ab}	0.42^{a}	0.026	0.83***
Phenylalanine	bitter	0.08^{d}	0.10^{d}	0.18^{c}	0.20^{bc}	0.24^{b}	0.31^{a}	0.019	0.91***
Tyrosine		9.40^{b}	12.22^{b}	18.31^{a}	19.90^{a}	21.28^{a}	24.26^{a}	1.371	0.76***
Tryptophan		0.002^{c}	0.004^{c}	0.010^{b}	0.013^{ab}	0.016^{a}	0.018^{a}	0.001	0.79***
Valine		0.08^{c}	0.08^{c}	0.16^{b}	0.18^{b}	0.25^{b}	0.25^{a}	0.016	0.81***
Total		11.47^{c}	15.31^{c}	22.45^{b}	24.22^{ab}	25.06^{ab}	30.34^{a}	1.622	0.79***
Total FAAs area (%)		72.59	73.61	75.59	74.36	73.17	74.07		
Cysteine		0.86^{c}	1.09^{c}	1.88^{b}	1.97^{b}	2.09^{ab}	2.58^{a}	0.148	0.79***
Total	tasteless	0.86	1.09	1.88	1.97	2.09	2.58		
Total FAAs area (%)		5.44	5.24	6.29	6.05	6.10	6.30		

$^{a–e}$ Mean in the same row with different letters are significantly different (P < 0.05).
[1] SEM, standard error of the mean, n = 30.
[2] r, Pearson correlation coefficients; **, P < 0.01; ***, P < 0.001.

age (r = +0.79 and $P < 0.001$). Tasteless FAA cysteine levels increased from the slaughter age of 9 months, exhibiting a strong positive correlation with slaughter age (r = +0.79 and P < 0.001). Cysteine is a sulfur-containing amino acid that has minimal direct impact on the taste of meat. However, it is a key precursor of sulfur-containing methyl compounds that participates in the Maillard reaction during cooking to form volatile compounds, such as 2-methyl-3-furanthiol, 2-furfurylthiol, 3-thiophenethiol, and 3-mercapto-2-pentanone. These compounds contribute to the distinct aroma of cooked meat (Ramalingam et al., 2019; Zhao et al., 2019). Therefore, increase in FAA content in *triceps brachii* of black goats with increasing slaughter age enhances the consumer value of meat by improving its sensory attributes, such as flavor and aroma. Although the overall percentage of total FAAs increased with slaughter age, the percentages of umami and sweet FAAs decreased and that of bitter FAAs increased with slaughter age. Therefore, although the total FAA content increases with the slaughter age of black goats, predominance of bitter FAAs affects their sensory qualities.

3.4. FFA levels

Goat meat exhibits higher unsaturated fatty acid (UFA) levels and lower saturated fatty acid (SFA) levels than the meat from other livestock species, making it nutritionally superior (Pisinov et al., 2021). Table 3 presents the composition of FFAs in black goat meat samples according to their slaughter age. SFA levels decreased with increasing slaughter age, exhibiting a strong negative correlation with slaughter age ($r = -0.81$ and $P < 0.001$). Palmitic acid, a representative SFA, negatively affects meat (Lee et al., 2019). Therefore, decrease in SFA levels enhances the sensory quality of meat. Here, UFA levels increased with increasing slaughter age, showing a strong positive correlation with slaughter age (r = +0.79 and $P < 0.001$). Additionally, monounsaturated fatty acid (MUFA) levels were significantly increased at the slaughter age of 36 months ($P < 0.05$), showing an increasing trend from 9 months of age. MUFA levels also exhibited a strong positive correlation with the slaughter age (r = +0.83 and $P < 0.001$). UFAs contribute to the distinctive flavor of meat via oxidation, leading to the formation of substances, such as aldehydes, ketones, phenols, and esters. High MUFA levels decrease the melting point of fat, contributing to the tenderness and flavor of meat (He et al., 2022; Hwang & Joo, 2017). Therefore, increasing slaughter age positively impacts the sensory qualities, such as flavor, of meat. Oleic acid, a major fatty acid in MUFA (r = +0.82 and P < 0.001), enhances the tenderness and juiciness of meat, influencing its succulence, flavor, and color (D'Alessandro et al., 2015). In the 18-carbon fatty acid group, stearic acid (18:0) melts at 69.6 °C, oleic acid (18:1) melts at 13.4 °C, and 18:2 and 18:3 melt at −5 and − 11 °C, respectively. High UFA levels decrease the melting point of fat tissues in meat (Wood et al., 2004). Therefore, increased oleic acid levels and decreased myristic and palmitic acid levels can enhance the perceived juiciness and flavor of *triceps brachii* during cooking. No significant differences in PUFA levels were observed across all tested slaughter ages ($P > 0.05$). Therefore, slaughter age ≥ 9 months is recommended as it changes the fatty acid composition to enhance the sensory quality of meat.

3.5. Sensory evaluation

Sensory evaluation results of black goat meat according to slaughter age are presented in Table 4. Color increased with the slaughter age up to 12 months, and no significant differences were observed between the slaughter ages of 9 and 12 months ($P > 0.05$). Additionally, no significant correlation was observed between goat meat color and slaughter age (P > 0.05). Flavor increased with the slaughter age up to 9 months,

Table 3
Free fatty acids (FFA) composition of *m. triceps brachii* in black goats by slaughter age.

FFA (%)	Ages (month)						SEM[1]	r[2]
	3	6	9	12	24	36		
C14:0 (Myristic acid)	8.91[a]	5.30[b]	3.41[c]	2.93[c]	2.90[c]	2.45[c]	0.533	−0.62**
C16:0 (Palmitic acid)	30.03[a]	27.85[ab]	26.62[bc]	23.73[c]	26.22[bc]	24.80[bc]	0.647	−0.52*
C16:1n7 (Palmitoleic acid)	1.93	1.96	2.04	1.79	2.08	2.10	0.060	0.25
C18:0 (Stearic acid)	15.60	16.52	15.97	15.45	15.35	14.28	0.537	−0.29
C18:1n7 (Vaccenic acid)	0.06[a]	0.05[ab]	0.02[c]	0.02[c]	0.04[b]	0.04[b]	0.004	−0.003
C18:1n9 (Oleic acid)	38.81[d]	40.82[cd]	43.67[bc]	45.67[ab]	46.99[ab]	49.29[a]	1.023	0.82***
C18:2n6 (Linoleic acid)	4.22	4.46	4.62	4.92	4.91	4.81	0.122	0.32
C18:3n3 (α-Linolenic acid)	0.12[c]	0.13[bc]	0.15[abc]	0.27[ab]	0.29[a]	0.15[abc]	0.022	0.29
C18:3n6 (γ-Linolenic acid)	0.01	0.01	0.02	0.02	0.02	0.01	0.002	0.04
C20:1n9 (Gondoic acid)	0.09	0.07	0.07	0.07	0.09	0.08	0.003	0.00
C20:4n6 (Arachidonic acid)	1.70[b]	2.00[b]	2.00[ab]	2.74[a]	1.58[ab]	1.67[b]	0.113	−0.27
C20:5n3 (Eicosapentaenoic acid)	0.08[ab]	0.08[ab]	0.09[ab]	0.14[a]	0.14[a]	0.05[b]	0.009	−0.16
C22:4n6 (Docosatetraenoic acid)	0.17[ab]	0.17[ab]	0.10[b]	0.17[ab]	0.18[a]	0.15[ab]	0.011	0.06
C22:6n3 (Docosahexaenoic acid)	0.05	0.05	0.05	0.04	0.04	0.04	0.003	−0.44
SFA[3]	51.93[a]	49.18[ab]	46.64[bc]	42.22[de]	44.29[cd]	40.02[e]	1.209	−0.81***
UFA[4]	47.19[d]	49.72[cd]	52.76[bc]	55.74[ab]	54.37[abc]	59.17[a]	1.153	0.79***
MUFA[5]	40.89[d]	42.90[cd]	45.79[bc]	47.54[b]	47.14[b]	51.58[a]	0.980	0.83***
PUFA[6]	6.30	6.81	6.97	7.46	7.24	7.07	0.217	0.20
UFA/SFA	0.91[d]	0.99[d]	1.09[cd]	1.33[ab]	1.23[bc]	1.48[a]	0.061	0.84***
MUFA/SFA	0.70[e]	0.87[de]	0.95[cd]	1.13[b]	1.07[bc]	1.29[a]	0.049	0.86***
PUFA/SFA	0.12[c]	0.14[bc]	0.14[bc]	0.19[a]	0.16[ab]	0.19[a]	0.009	0.65*
∑n-3[7]	0.25[b]	0.27[b]	0.30[ab]	0.48[a]	0.46[a]	0.24[b]	0.033	0.11
∑n-6[8]	6.05	6.55	6.73	7.78	6.83	7.34	0.217	0.39
∑n-6/∑n-3	24.53[ab]	25.03[ab]	21.08[ab]	19.78[ab]	14.86[b]	30.46[a]	1.592	0.11

[a–e] Mean in the same row with different letters are significantly different ($P < 0.05$).
[1] SEM, standard error of the mean, n = 30.
[2] r, Pearson correlation coefficients; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.
[3] SFA, saturated fatty acids (C14:0 + C16:0 + C18:0).
[4] UFA, unsaturated fatty acids (C16:1n7 + C18:1n7 + C18:1n9 + C18:2n6 + C18:3n3 + C18:3n6 + C20:1n9 + C20:4n6 + C20:5n3 + C22:4n6 + C22:6n3).
[5] MUFA, monounsaturated fatty acids (C16:1n7 + C18:1n7 + C18:1n9 + C20:1n9).
[6] PUFA, polyunsaturated fatty acids (C18:2n6 + C18:3n3 + C18:3n6 + C20:4n6 + C20:5n3 + C22:4n6 + C22:6n3).
[7] ∑n-3 (C18:3n3 + C20:5n3 + C22:6n3).
[8] ∑n-6 (C18:2n6 + C18:3n6 + C20:4n6 + C22:4n6).

Table 4
Sensory evaluation of *m. triceps brachii* in black goats by slaughter age.

Traits[1]	Ages (month)						SEM[2]	r[3]
	3	6	9	12	24	36		
Color	7.40[c]	7.90[bc]	8.63[ab]	9.13[a]	8.67[a]	8.60[ab]	0.152	0.37
Flavor	7.50[b]	8.13[ab]	8.75[a]	8.90[a]	8.20[ab]	8.14[ab]	0.122	−0.03
Off-flavor	7.67[b]	7.79[b]	8.21[ab]	8.33[ab]	8.88[a]	8.80[a]	0.131	0.56***
Juiciness	7.88[d]	8.07[cd]	8.60[bc]	8.92[ab]	9.25[a]	9.00[ab]	0.113	0.62***
Texture	8.13[c]	8.25[c]	8.90[a]	9.00[a]	8.67[ab]	8.33[bc]	0.086	0.06
Overall acceptability	7.90[d]	8.00[cd]	8.70[ab]	9.17[a]	8.63[abc]	8.38[bcd]	0.112	0.21

[a–d] Mean in the same row with different letters are significantly different ($p < 0.05$).
[1] Color, flavor, texture, juiciness, overall acceptability (10 = extremely good or desirable, 1 = extremely bad or undesirable); off-flavor (10 = extremely felt, 1 = extremely not felt).
[2] SEM, standard error of the mean, $n = 18$.
[3] r, correlation coefficients; *** $p < 0.001$.

with no significant differences observed thereafter ($P > 0.05$). Off-flavor was significantly stronger at slaughter ages of 24 and 36 months than at slaughter ages of 3 and 6 months ($P < 0.05$), showing a moderate positive correlation with slaughter age ($r = +0.56$ and $P < 0.001$). This is attributed to the accumulation of myoglobin in the muscles due to the aging of black goats, as heme iron in myoglobin contributes to the metallic off-flavor of meat, thereby deteriorating its sensory quality (Da Silva et al., 2020; Gerhard, 2020). Borgogno et al. (2015) revealed that metallic flavor in goat meat is associated with the iron content of myoglobin, which influences the meat redness. Therefore, accumulation of myoglobin in the muscle as the goat age increases possibly contributed to the off-flavor observed at the slaughter ages of 24 and 36 months. The meat texture was significantly better in the goats slaughtered at 9 and 12 months than those slaughtered at 3, 6, and 36 months ($P < 0.05$), but no significant differences were observed in the meat of goats slaughtered at 24 months and at 9, 12, and 36 months ($P > 0.05$). Therefore, slaughter ages between 9 and 24 months are recommended to achieve positive textural attributes of black goat meat. Juiciness ratings increased with slaughter age up to 24 months, with no significant differences noted between goats slaughtered at 36 months and those slaughtered between 9 and 24 months ($P > 0.05$). Juiciness was positively correlated with age at slaughter ($r = +0.62$ and $P < 0.001$). The moisture retained in meat after cooking is a major factor contributing to its juiciness, and cooking yield increases with the slaughter age, thereby leading to higher juiciness ratings (Kopuzlu et al., 2018; Hoffman et al., 2020). Moreover, increase in the percentage of MUFAs, such as oleic acid, among all FFAs (%) was associated with high juiciness ratings. Overall acceptability increased up to a slaughter age of 12 months and decreased thereafter, but it was not significantly correlated with slaughter age ($P > 0.05$). Similarly, Hossain et al. (2021) used Jamuna Basin lambs and reported that meat of 9- and 12-month-old lambs exhibited superior sensory qualities than the meat of 6-month-old lambs, suggesting that optimal slaughter age enhances consumer acceptance. In this study, very young (3 and 6 months) and old (36 months) slaughter ages decreased the overall sensory acceptance of meat. In contrast, meat obtained at slaughter ages between 9 and 24 months exhibited significantly better color, flavor, texture, juiciness, and overall liking. Therefore, slaughter ages of 9 and 12 months in the 9–24 month range are favorable to enhance the sensory attributes of black goat meat.

4. Conclusion

In conclusion, this study confirmed that the quality and sensory characteristics of black goat meat vary according to slaughter age. Color changes were observed between 3 and 12 months of age, but no further changes were noted after 12 months. Additionally, although cooking yield increased with age, shear force also increased, leading to the recommendation of selecting younger animals for slaughter. While all FAA levels increased with slaughter age, umami and sweet FAA levels decreased, and bitter FAA levels increased. The analysis of FFA composition showed a decrease in SFA and an increase in UFA and MUFA starting from 9 months of age. Sensory evaluations according to slaughter age indicated that meat from animals between 9 and 24 months of age received high ratings for color, flavor, texture, juiciness, and overall preference, with the highest values observed at 12 months. Overall, these findings suggest that the optimal slaughter ages for black goat meat production are 9 and 12 months, and the study's data may serve as a foundational resource for the commercialization of black goat meat.

Ethical statements

This project was approved by the Kongju University Institutional Bioethics Committee (Authorization Number: KNU_IRB_2021-75The organization stated in advance that it would protect the rights and privacy of all participants. As a result, we received a positive response from the participants regarding the study, and individual consent forms were obtained. Participants responded, "I agree to participate in the sensory evaluation," and were allowed to withdraw at any time. The goat meats evaluation was safe for consumption.

CRediT authorship contribution statement

Sol-Hee Lee: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Hack-Youn Kim:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that they have no received no assistance from AI and AI-assisted technologies during the writing process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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