JAST (Journal of Animal Science and Technology) TITLE PAGE

ARTICLE INFORMATION	Fill in information in each box below
Article Type	Research article
Article Title (within 20 words without abbreviations)	Physicochemical traits, flavor, and bioactive compound characteristics of imported frozen Australian goat meat: comparative analysis across muscle cuts and sexes
Running Title (within 10 words)	Goat meat physicochemical and bioactive profile by cut and sex
Author	Kwan-Woo Kim1#, Joko Sujiwo2#, Yousung Jung2, Dongwook Kim2, Soomin Oh2, Dowon Jeong2, Jinwoo Park2, Aera Jang2 # These authors contributed equally to this work
Affiliation	1 Animal Genetic Resources Research Center, National Institute of Animal Science, Rural Development Administration, Hamyang 50000, Republic of Korea 2 Department of Applied Animal Science, Kangwon National University, Chuncheon 24341, Republic of Korea
ORCID (for more information, please visit https://orcid.org)	Kwan-Woo Kim (https://orcid.org/0000-0003-2729-2181) Joko Sujiwo (https://orcid.org/0000-0003-2078-3922) Yousung Jung (https://orcid.org/ 0000-0003-2095-2394) Dongwook Kim (https://orcid.org/0000-0002-5496-1961) Soomin Oh (https://orcid.org/0009-0006-2403-4813) Dowon Jeong (https://orcid.org/0009-0003-2011-198X) Jinwoo Park (https://orcid.org/0009-0008-6602-7261) Aera Jang (https://orcid.org/0000-0003-1789-8956)
Competing interests	No potential conflict of interest relevant to this article was reported.
Funding sources State funding sources (grants, funding sources, equipment, and supplies). Include name and number of grant if available.	This work was funded by the “Cooperative Research Program for Agriculture Science and Technology Development (Project No. PJ01723301)" Rural Development Administration, Republic of Korea
Acknowledgements	Not applicable.
Availability of data and material	Upon reasonable request, the datasets of this study can be available from the corresponding author.
Authors' contributions Please specify the authors’ role using this form.	Conceptualization: Kim KW, Jang A. Data curation: Sujiwo J, Jung Y, Kim D, Oh S, Jeong D, Park J. Formal analysis: Sujiwo J, Jung Y, Kim D, Oh S, Jeong D, Park J. Methodology: Kim KW, Kim D, Jang A. Software: Sujiwo J, Jung Y, Oh S, Jeong D. Validation: Kim KW, Jang A. Investigation: Kim KW, Kim D, Jang A. Writing - original draft: Kim KW, Sujiwo J, Jang A. Writing - review & editing: Kim KW, Sujiwo J, Jung Y, Kim D, Oh S, Jeong D, Park J, Jang A.
Ethics approval and consent to participate	This study was approved by the Institutional Review Board of KNU (No. KWNUIRB-2023-02-010-002).

CORRESPONDING AUTHOR CONTACT INFORMATION

For the corresponding author (responsible for correspondence, proofreading, and reprints)	Fill in information in each box below
First name, middle initial, last name	Aera Jang
Email address – this is where your proofs will be sent	ajang@kangwon.ac.kr
Secondary Email address	ajang2020@naver.com
Address	College of Animal Life Sciences, Building 2, Room 201, Department of Applied Animal Science, Kangwon National University, 1 Kangwondaehakgil, Chuncheon-si, Gangwon state, 24341, Korea.
Cell phone number	+82-10-9017-8643
Office phone number	+82-33-250-8643
Fax number	+82-33-251-7719

Physicochemical traits, flavor, and bioactive compound characteristics of imported frozen Australian goat meat: comparative analysis across muscle cuts and sexes

Abstract

The physicochemical, flavor-related compounds, and sensory characteristics of imported frozen goat meat were evaluated by comparing variations among sex and cut types. Female rib cuts had a lower moisture content than those of males. Protein levels were high in the rib and loin cuts of males, whereas females exhibited increased fat levels in these same cuts. Increased sodium levels were observed in the shoulders and loins of females. Among the different cuts, female ribs exhibited the highest values of cooking loss, as well as cholesterol and collagen contents. Sex and meat cuts influenced dipeptides and α-tocopherol levels. Multivariate analysis revealed evident groupings based on meat cut and sex, with dipeptides, nucleotide metabolites, zinc, and certain fatty acids identified as key differentiating factors. Male ribs contained high levels of ketones, whereas female shoulders had increased concentrations of sulfur compounds. The female rib samples demonstrated high overall acceptability in the sensory evaluation. In conclusion, both cut and sex significantly influenced the physicochemical traits, flavor compounds, bioactive profiles, and sensory qualities of imported frozen goat meat. Although this study provides fundamental data on imported frozen goat meat, further studies are required to validate these findings across various breeds, countries, and production systems.

Keywords: Goat meat, Boer goat, Frozen meat cuts, Sex, Bioactive compounds, Flavor compounds

Introduction

Goat meat is increasingly being considered as a nutritious alternative to traditional red meat, providing a lean protein source with favorable health attributes. Compared to those of beef and lamb, goat meat contains lower cholesterol, reduced saturated fat, and fewer calories, with levels comparable to those of chicken, while providing high-quality protein, essential minerals, and unsaturated fatty acids [1]. Owing to its digestibility and hypoallergenic characteristics, it is considered suitable for use in specialized diets [2]. In many parts of Asia and Africa, smallholder goat farming systems significantly contribute to the total production, making goat meat an essential source of animal protein and an economic livelihood.

South Korea's goat meat market relies heavily on imports from Australia. Therefore, Australian goat meat was used in this study. A Korea Rural Economic Institute report indicates that Australia supplied nearly all (95–100%) of South Korea's goat meat imports from 2015 to 2024, with only a small proportion originating from New Zealand. [3]. Rising consumer demand has driven a substantial increase in Australian goat carcass imports. However, frozen storage and long-distance transport can induce quality degradation through ice-crystal damage, protein denaturation, lipid oxidation, and drip loss, potentially affecting the meat's nutritional and sensory attributes [4].

The marketability of goat meat is primarily influenced by its overall flavor profile. Although goat meat is typically associated with a distinctive "goaty/sweaty" aroma that some consumers find undesirable [1], a comprehensive flavor assessment should consider its fatty acid composition and nucleotide-derived metabolites, which influence taste and odor perceptions. Accordingly, this study analyzed volatile organic compounds (VOCs), fatty acids, and nucleotide metabolites to identify the key compounds that influence the flavor differences.

In addition, the bioactive constituents were evaluated. These compounds contribute to the health-promoting properties of meat, including its oxidative stability, anti-inflammatory potential, and disease prevention. Their evaluation is critical for validating the nutritional claims and marketability of goat meat, particularly in frozen imported products, where extended storage and transportation may alter the quality through oxidative stress or enzymatic degradation.

Moreover, intrinsic factors, such as anatomical cuts and animal sex, influence moisture retention, fat distribution, bioactive compounds, and VOC profiles [5–8]. However, several studies have focused on fresh, domestically produced goat meat with limited investigation of variations across different cuts and sexes within the

same study [9–11]. The present study addresses this critical knowledge gap by examining frozen imported goat meat while considering the effects of sex and cut types.

Considering the increasing demand for high-quality frozen goat meat in South Korea, a comprehensive evaluation of these factors is vital. Therefore, this study aimed to evaluate the physicochemical properties, flavor profile, bioactive properties, and sensory characteristics of imported frozen goat meat and compare variations among cut types and sexes. These findings enhance our understanding of the quality attributes of imported frozen goat meat of different sexes and cuts, thereby supporting industry stakeholders and consumers in making informed decisions. To contextualize the findings for the South Korean market, key quality attributes observed in the imported product were benchmarked against published data on domestically raised Korean goats.

Materials and methods

Sample preparation

The samples used were imported frozen Boer goat meat originating from Australia and were procured as commercially distributed primal cuts (shoulder, rib, and loin) rather than as whole carcasses. The products were maintained frozen, with an interval of 4–7 months between initial freezing and delivery to the laboratory. Following arrival, the goat meat was maintained at –18 °C until further processing. Ten animals (five castrated males and five females) were included as biological replicates, and for each animal the shoulder, rib, and loin cuts were obtained (Fig. 1) as described previously [10,11]. Goat meat from Australia is commonly traded as frozen whole carcass or six-way cut carcass pieces and is subsequently distributed as cut portions in destination markets.

Given that each primal cut comprises multiple muscles, the cut was treated as the experimental unit across all measurements. The experimental unit was representative of marketed cuts rather than a single named muscle. Prior to homogenization, each cut was thawed under refrigeration and deboned in the laboratory. For all cuts of each carcass, a cut-level composite was prepared by trimming the visible external fat and connective tissue and mincing to homogeneity using a SMX-SG45HJ meat mincer (Shinil, Cheonan, Korea). This composite was stored at −18 °C and used for compositional and biochemical analyses. For physical and sensory measurements, samples were taken from the central region of each cut. Each carcass constituted one biological experimental unit; for each sex × cut (n = 5), technical replicates were averaged within carcasses prior to statistical analysis.

Proximate composition

The proximate composition of each meat cut was determined according to the AOAC guidelines [12]. As each primal cut consists of multiple muscles, all values reported here reflect cut-level measurements as explained in Section 2.1. Moisture was measured by oven-drying samples (105 °C, 16 h). Crude protein was determined using the Kjeldahl method (conversion factor 6.25), crude fat by Soxhlet ether extraction, and crude ash by incineration (550 °C, 12 h).

Mineral analysis

The mineral content was analyzed using wet digestion according to the Food Code test method [13]. Samples (5 g) were digested with nitric and perchloric acids, evaporated to dryness, dissolved in diluted hydrochloric acid, and filtered (0.45 μm). The mineral content was measured using Agilent 5900 inductively coupled plasma optical emission spectroscopy (Agilent Technologies, Santa Clara, CA, USA).

pH, cooking loss, shear force, and instrumental color

pH was measured using a homogenate (10 g sample blended with 90 mL distilled water for 30 s) and an Orion 230A pH meter (Thermo Fisher Scientific, Waltham, MA, USA). pH was measured at 20 ± 2 °C using a bench-top meter with automatic temperature compensation, two-point calibrated daily with pH 4.01 and 7.00 buffers. Cooking loss was calculated as the percentage of weight loss after cooking the meat samples in polyethylene bags at 75 °C for 45 min in a water bath. For each sex × cut (n = 5 carcasses), two steaks per carcass were inserted together in one bag; the five bags (10 steaks) were cooked simultaneously in a single run using the same water bath. For shear force (SF) measurement, the same cooked steaks were cut into three rectangular strips (1 × 1 × 3 cm; thickness × width × length) with the 3-cm axis parallel to the muscle fibers. The three strips were pooled across the two steaks of each carcass × cut (technical replicates). SF was measured using a TA1 texture analyzer (Lloyd Instruments, Berwyn, IL, USA) with a V-blade, 50 mm/min crosshead speed, and a 500 N load cell. The three strip-level values were averaged to obtain one carcass-level SF value. Instrumental color (CIE L^*, a^*, and b^*) was assessed using a Chroma Meter CR-400 (Konica Minolta, Osaka, Japan), calibrated with a standard white plate (Y: 93.60, x: 0.3134, y: 0.3194) and with illuminant C, 2° standard observer, and an aperture of φ8 mm (measurement) / φ11 mm (illumination), after a 20-min bloom at 4±1 °C.

Water holding capacity (WHC)

Briefly, 0.5 g of muscle tissue (free of connective tissue) was placed in a plastic centrifuge tube filter Costar Spin-X (Corning, Corning, NY, USA), heated in a water bath at 80 °C for 20 min, cooled at room temperature (25 ± 2 °C) for 10 min, and then centrifuged at 2,000 × *g* for 20 min at 4 °C. The WHC (%) was calculated as follows: WHC (%) = [(sample moisture content–water loss)/sample moisture content]×100.

where water loss (%) = [(weight before centrifugation – weight after centrifugation)/(sample weight×fat factor)]×100 and fat factor = 1 – (crude fat/100).

Cholesterol determination

A 2 g sample containing 5-cholestane (internal standard) was saponified in ethanol and KOH and then extracted with n-hexane. The hexane extract was concentrated, derivatized in dimethylformamide, and analyzed using a 7890N gas chromatograph (GC) (Agilent Technologies, Santa Clara, CA, USA) equipped with an HP-5 column (30 m × 0.33 mm × 0.25 μm). Helium (1.0 mL/min, split ratio 1:12.5) was the carrier gas; injector/detector temperatures were 250/300 °C. The column temperature was maintained at 190 °C (2 min), then increased to 230 °C at 20 °C/min (3 min), followed by an increase to 270 °C at 40 °C/min (25 min). Cholesterol was quantified as mg/100 g of meat.

Collagen determination

Collagen content was determined based on hydroxyproline [8]. A 4 g sample was hydrolyzed in 7N sulfuric acid (105 °C, 16 h) and diluted to 500 mL. A diluted aliquot was incubated with chloramine-T (pH 6.0, acetate-citrate buffer, 20 min, 23 °C) and Ehrlich's reagent (60 °C, 15 min). The absorbance at 558 nm was measured using a SpectraMax M2e microplate reader (Molecular Devices, San Jose, CA, USA). The hydroxyproline concentration, obtained from a standard curve, was multiplied by 8.0 to yield collagen content (mg/100 g).

L-carnitine determination

L-carnitine levels were measured according to a previously described method [8]. Briefly, 5 g of the meat sample was homogenized in 0.3M $HClO_4$, centrifuged, and filtered. An aliquot was neutralized with 1.2M K_2CO_3, centrifuged, and filtered again (0.45 μm). The extract or standard (50 μL) was mixed with reaction buffer (containing DTNB,

acetyl-CoA, EDTA, and Tris–HCl), incubated at 37 °C for 10 min, and the initial absorbance was recorded at 415 nm. After adding carnitine acetyltransferase and incubating (37 °C, 30 min), the final absorbance was measured. L-carnitine levels were quantified using a standard curve.

Coenzyme Q10 (CoQ10) content analysis

Approximately 10 g of each sample was homogenized in 90 mL ethanol, agitated for 1 h, and adjusted to a final volume of 100 mL using additional ethanol. The mixture was filtered through a 0.22 μm membrane. Quantification was conducted via 1260 Infinity HPLC (Agilent Technologies, Santa Clara, CA, USA) fitted with a ZORBAX Eclipse XDB-C18 column (4.6 mm × 150 mm, 3.5 μm). An isocratic mobile phase of methanol and ethanol (2:3, v/v) was applied at 1.5 mL/min, with the column temperature maintained at 40 °C. Detection was performed at 275 nm using a diode array detector. The CoQ_{10} concentrations were derived from calibration curves generated using commercial standards.

Dipeptide (anserine and carnosine) determination

Meat samples (2.5 g) were homogenized in 0.01N HCl, centrifuged (3,000 × *g*, 30 min), filtered, mixed with acetonitrile, chilled, and centrifuged again (10,000 × *g*, 10 min). The supernatant was filtered (0.22 μm) and analyzed by HPLC. An Atlantis HILIC silica column, 4.6 × 150 mm, 3 μm; 35 °C was used. Gradient elution (0–100% B; 13 min; 1.4 mL/min) was performed using two mobile phases: (A) 0.65 mM ammonium acetate (pH 5.5) in water-acetonitrile (25:75) and (B) 4.55 mM ammonium acetate (pH 5.5) in water-acetonitrile (70:30). The detection wavelengths were 214 nm (carnosine and anserine) and 236 nm (creatinine). Quantification was performed based on the external standard curves.

α-tocopherol content determination

The samples were prepared according to the Korean Food Code [14]. Minced meat (10 g) was mixed with 30 mL ethanol, 1 mL 10% pyrogallol–ethanol, and 3 mL 90% KOH and then saponified at 95 °C for 30 min. After cooling, the digest was transferred to a separatory funnel, diluted with 30 mL of water, and extracted with diethyl ether. The ether phase was dried over anhydrous Na_2SO_4, evaporated, redissolved in methanol, and filtered (0.45 μm). HPLC conditions were involved separation on a ZORBAX Eclipse XDB-C18 column (250 × 4.6 mm, 5 μm, 28 °C) with a

methanol/acetonitrile gradient (50% methanol to 100% over 12 min, total run 22 min) at 1.0 mL/min. Detection was performed at 295 nm (UV–vis), with an injection volume of 10 µL.

Fatty acids composition determination

Lipids from 5 g minced meat were extracted with 30 mL of chloroform:methanol (2:1, v/v) containing butylated hydroxyanisole, washed with 0.88% KCl, and the chloroform layer was evaporated under N_2. Aliquots (40 µL) were saponified (0.5N NaOH, 100 °C, 5 min) and methylated (10% BF3-MeOH, 100 °C, 2 min). After phase separation with iso-octane/saturated NaCl, fatty acid methyl esters were quantified on a GC equipped with an Omegawax 250 column (30 m × 0.25 mm × 0.25 µm; Supelco). Helium (1.2 mL/min, split 1:100) was the carrier gas; injector/detector temperatures were 250/260 °C. The oven was programmed from 150 °C (2 min) to 220 °C at 4 °C/min, then maintained for 30 min. FA were identified using polyunsaturated fatty acids (PUFA) No. 2 animal standards. Peak areas were normalized to 100% and expressed as % of total identified FA. Where applicable, fatty acid methyl esters (FAME) were converted to FA (i.e., without methyl groups) prior to normalization using the Sheppard factors recommended by FAO/INFOODS [15]. For absolute contents, individual FA (mg/100 g muscle) were calculated from %FA and the total lipid content (g/100 g muscle, proximate analysis) according to the FAO/INFOODS framework:

FA (mg/100 g) = fat (g/100 g) × XFA × (%FA/100) × 1000, where XFA is the fatty acid conversion factor of 0.916 was applied for lean ruminant meat [15].

Nucleotide metabolites analysis

Minced meat (5 g) was extracted twice with 0.7M perchloric acid (25 mL, then 20 mL), centrifuged (2,000 × *g*, 15 min, 4 °C), and the combined supernatants were neutralized to pH 6.5 with 5N KOH and diluted to 100 mL. After chilling and filtration (0.22 µm), the analysis was performed on HPLC equipped with a Nova-Pak C18 column, using 1% trimethylamine–phosphate buffer (pH 6.5) as the mobile phase and UV detection at 254 nm. Quantification was performed using external standards of hypoxanthine, inosine, inosine monophosphate, adenosine monophosphate, adenosine diphosphate, and adenosine triphosphate (Sigma-Aldrich).

VOCs analysis

Samples were sealed in 20 mL glass vials fitted with septa and aluminum caps. The vials were incubated at 60 °C for 25 min. Volatiles were then adsorbed onto a 50/30 μm DVB/Carboxen/PDMS-coated fiber (Supelco, Bellefonte, PA, USA) exposed to the vial headspace for 30 min. VOCs were analyzed on an Agilent 8890 GC–5977B MSD (Agilent Technologies, Santa Clara, CA, USA) fitted with a DB-5MS column (30 m × 0.25 mm, 0.25 μm). Helium (1.3 mL/min) was used as the carrier gas. The injector and MS detector temperatures were set to 250 and 280 °C, respectively. The oven was maintained at 40 °C for 10 min, increased at 5 °C/min to 250 °C, and maintained for 5 min, after which VOCs were desorbed from the SPME fiber in the injector for 15 min. The compounds were identified using linear retention indices (alkanes C10–C26) and NIST 20 mass spectral matching. The data are presented as the intensity in peak area units × 10^6.

Sensory evaluation

A total of 58 panellists from Kangwon National University (KNU) completed the sensory evaluation across two sessions (24 unique panellists in Session 1 and 34 in Session 2). In each session, all six treatments (Sex × Cut: male-shoulder, male-rib, male-loin, female-shoulder, female-rib, female-loin) were served together but evaluated sequentially in a randomized tasting order, each sample coded with a random three-digit number. Panellists clean their palates with water between samples. The samples were pan-broilled to an internal temperature of 72 ± 3 °C and cut into 2 × 2 × 1 cm pieces. The panelists cleansed their palates with water between sample tastings. Using a 9-point hedonic scale, the panelists evaluated seven attributes: peculiar odor refers to the intensity of non-typical goat-specific odors perceived as undesirable (1 = very weak, 9 = very strong), appearance, taste, aroma, overall acceptability (1 = very poor, 9 = excellent), tenderness, and juiciness (1 = very tough/very dry, 9 = very tender/very juicy). This study was approved by the Institutional Review Board of KNU (No. KWNUIRB-2023-02-010-002). All the participants provided verbal informed consent.

Statistical analysis

All data were processed using the SAS 9.4 (SAS Institute, Cary, NC, USA). To evaluate the six Sex and Cut combinations data were analyzed using one-way ANOVA (PROC GLM) with Tukey's HSD test at the 0.05 significance level. The results are expressed as least square means and pooled standard error of the mean (SEM).

Additionally, main effects and their interaction were tested using a linear mixed model (PROC MIXED) with Sex, Cut, and Sex×Cut as fixed effects. Animal (carcass ID) was included as a random effect, with animals nested within sex. Denominator degrees of freedom were estimated using the Kenward–Roger method. The *p*(Sex), *p*(Cut), and *p*(Sex×Cut) reported in the tables are Type III tests from this mixed model.

For the sensory data, a linear mixed model was used with Sex, Cut, and Sex×Cut as fixed effects; Session (two levels) as a random blocking factor; and Panellist nested within Session as a random effect to account for repeated ratings. A compound-symmetry covariance structure was assumed for within-panellist correlations, denominator degrees of freedom were estimated using the Kenward–Roger method.

Multivariate patterns were explored via partial least squares discriminant analysis (PLS-DA) in MetaboAnalyst 6.0. Two models were built, with the first using all physicochemical traits and flavor-related compounds, and the second including only VOCs. Variable-importance (VIP) scores identified key discriminators (VIP≥1.0), and two-dimensional biplots illustrated sample clustering and variable loadings.

Results and discussion

Proximate composition

Table 1 summarizes the proximate composition of goat meat (LS-means ± SEM). Moisture showed significant Sex×Cut interaction (P = 0.006), with the lowest value in Female–Rib (68.8%) and the highest in shoulders (Male–Shoulder 76.4%; Female–Shoulder 76.0%). A sex difference was evident in the rib (Male > Female), whereas shoulder and loin did not differ by sex. Aligns with Ali et al. [9], which also reported that rib cuts have relatively low moisture content. In this study, moisture ranged from 68.8 to 76.4%, which largely within values reported for Korean native black goat (65.98–75.99%) [9].

In crude protein content Sex (P = 0.010), Cut (P < 0.001), and Sex×Cut (P = 0.015) were significant. Male–Loin showed the highest protein (20.6%), while Female–Rib was the lowest (17.9%). However, shoulder did not differ by sex, and loin also showed no significant sex difference. The protein ranged from 17.9 to 20.6%, which is slightly lower than those reported for Korean native goats, which typically range between 19.74 and 23.40% [9].

Fat showed significant effects of Cut (P < 0.001), Sex (P = 0.005), and Sex×Cut (P = 0.004). Female–Rib had the greatest fat (12.4%), followed by Female–Loin (6.8%) and Male–Rib (6.4%); shoulders were leanest (Male 2.5%,

Female 3.0%). Thus, the order was generally Rib > Loin > Shoulder in both sexes, with sex differences pronounced in rib (Female > Male). This hierarchy matches earlier observations that rib cuts tend to carry more lipid than shoulder/loin in native Korean goats [9]. Notably, the fat content observed in this study (2.5–12.4%) falls within, but toward the lower end of, the range reported for Korean native black goats (1.82–14.06%) [9].

In crude ash value there was no meaningful effects of Sex, Cut, or Sex×Cut were detected (all P>0.14); values were narrowly distributed (0.91–1.11%), consistent with prior reports in Korean goat meat [9].

Mineral profile

Table 2 presents least-squares means and the significance of Sex, Cut, and their interaction. No significant Sex effect or Sex×Cut interaction was detected for any mineral. These findings indicate that mineral composition was primarily influenced by the cut of meat rather than by sex or their interaction. All minerals showed no sex effects. Significant effects of Cut were observed for potassium (K), phosphorus (P), sodium (Na), and magnesium (Mg) (all p(C)<0.001). K was the most abundant element, followed by phosphorus P, Na, Mg, calcium (Ca), zinc (Zn), iron (Fe), copper (Cu), and manganese (Mn).

K was most abundant (273.8–322.1 mg/100 g), consistent with levels reported in previous studies [8], but lower than the 420.8–499.3 mg/100 g observed in the Korean native black goat range [16]. K content was lower in the ribs than in the shoulder and loin across sexes. P was the second most abundant (163.2–188.4 mg/100 g), which was slightly lower than the levels observed in Saanen goat (212–275 mg/100 g) [17]. Na content ranged from 62.5 mg/100 g (male shoulder) to 74.3 mg/100 g (female rib), which was slightly lower than the levels of Korean black goats (76.03–94.97 mg/100 g; [5]). Mg ranged from 18.1 mg/100 g (female rib) to 21.9 mg/100 g (male shoulder), consistent with previous findings of 20.4–28.9 mg/100 g [17]. Ca ranged from 5.4 mg/100 g (female shoulder) to 7.2 mg/100 g (female rib), similar to the findings by Kim et al. [8] (5.22–6.09 mg/100 g) but lower than the results by Joo et al. [16] (11.98–13.3 mg/100 g). Fe ranged from 2.0 mg/100 g (female rib) to 3.2 mg/100 g (male shoulder), which was slightly higher than the values reported for Korean black goats (1.35–1.48 mg/100 g) [5]. Supporting the view that goat meat provides a relevant source of bioavailable iron [8]. Cu (0.10–0.12 mg/100 g) and Mn (0.02–0.03 mg/100 g) were the least abundant, consistent with those of [17], who reported Cu levels ranging from 0.074 to 0.230 mg/100 g and Mn levels from 0.007 to 0.021 mg/100 g.

Overall, the results indicate that the distribution of minerals in goat meat is primarily influenced by the anatomical location of the cut. Specifically, rib cuts exhibited lower levels of intracellular minerals such as potassium, phosphorus, and magnesium, which aligns with their higher fat content and lower moisture levels. However, sodium levels did not follow this pattern. This trend is consistent with observations reported in a study on cattle by [18]. The observed cut-dependent patterns indicate structural and metabolic differentiation among goat muscles. These differences are consistent with the oxidative or glycolytic classification of muscles, which is based on their metabolic, chromatic, and contractile characteristics [19].

Physicochemical traits, cholesterol, and collagen content

Physicochemical traits (pH, WHC, cooking loss, and shear force), cholesterol and collagen are shown in Table 3. Sex had no effect on pH, whereas Cut was significant (p(C)<0.001) when pooled across sex. This absence of a sex-related difference in pH is consistent with the findings reported by Ahmad et al. [20] for frozen goat meat. Measured pH in this study (6.2–6.5) was slightly higher than the optimal 5.5–6.2 range [21]. When compared with Korean native black goats, which typically exhibit pH values between 5.83 and 6.10 [6], the observed range in imported frozen samples is marginally elevated, suggesting potential effects of freezing and storage duration on ultimate pH. This aligns with a statement by Ahmad et al. [20], who noted that frozen storage can increase the pH of goat meat. Additionally, goats are prone to perimortem stress, leading to faster glycogen loss and a high final pH [22]. Collectively, these factors support the observation that goat meat typically exhibits a higher ultimate pH than the optimal range of 5.4–5.7 commonly reported for other livestock species [21]. WHC did not differ significantly by Sex, Cut, or their interaction (p(S)=0.624; p(C)=0.123; p(S×C)=0.482), with values spanning 51.6–57.7%. These values were higher than those reported by Lamri et al. [23], who found a WHC range of 29.73–31.12%, and also exceed the typical range observed in Korean native black goats (28–35%) [24], but aligned with the findings of Apata [25], who observed a WHC of 57.53% in goat meat after 21 days of frozen storage. The elevated WHC value can plausibly be explained, at least in part, by the high pH value. When the pH rises above the isoelectric point of myofibrillar proteins, the proteins acquire a greater net negative charge. This increased charge causes electrostatic repulsion among the protein filaments, leading to swelling of the myofibrillar lattice. Such swelling creates more space for water molecules, thereby enhancing water retention and resulting in high WHC value [24].

Cooking loss was influenced by Cut (p(C)<0.001) but not by Sex or Sex×Cut (p(S)=0.450; p(S×C)=0.365). Across combinations, ribs showed the greatest value (39.5–40.6%), shoulders were intermediate (35.3–35.7%), and loins were lowest (31.5–32.9%). These values were slightly above the 30.10–35.70% range reported by Xiao et al. [26]. The variation among cuts likely indicates differences in muscle fiber and collagen content, as the ribs showed the highest collagen levels. Rib cuts, which are rich in tendons, epimysium, and perimysium, contain more connective tissue, contributing to increased collagen content [27,28]. This dense connective matrix may lead to increased water loss during cooking. Gawat et al. [21] also observed significant differences in cooking loss among goat muscle samples, which supports the cut-specific trends observed in this study. Shear force did not differ by Sex, Cut, or their interaction (p(S)=0.124; p(C)=0.445; p(S×C)=0.768), with means ranging from 32.6 to 39.9 N. Previous studies have reported shear force values of 61.8–71.5 N for Boer crossbred goats [21] and 48.37–71.69 N for Xinjiang goats [26], both of which were slightly higher than the values observed in this study.

For cholesterol, a main effect of Cut was observed (p(C)=0.025), while Sex and Sex×Cut were not significant (p(S)=0.119; p(S×C)=0.202). The highest concentrations occurred in ribs (Male 56.1; Female 64.1 mg/100 g), followed by loins (Male 55.0; Female 61.0 mg/100 g), with shoulders being lowest (Male 53.1; Female 52.0 mg/100 g). These cholesterol levels were consistent with those observed for Thai × Anglo-Nubian crossbreeds (62.42–69.02 mg/100 g) and Boer goats (55.2–88.4 mg/100 g across cuts) [11]. Cholesterol, a key lipid in cell membranes, is typically higher in cuts with more fat or marbling. In this study, rib cuts exhibited higher fat content, consistent with previous findings that cuts such as ribeye have increased cholesterol levels [29].

Total collagen differed by Cut (p(C)<0.001) but not by Sex or Sex×Cut (p(S)=0.204; p(S×C)=0.243); ribs had greater collagen (Male 1.2; Female 1.1 g/100 g) than shoulders (both 0.7 g/100 g) and loins (0.8–0.9 g/100 g). Collagen levels in this study (0.7–1.2 g/100 g) are comparable to those previously reported for goat meat including Korean goat (0.59–1.68 g/100 g) [8,24]. The consistently high collagen measured in the rib (intercostal) muscles of goats likely reflects their respiratory function and the repetitive mechanical loading of the thoracic wall. This aligns with the dense collagen network documented in respiratory muscles [30] and supports the general principle that higher functional demand results in greater intramuscular connective tissue [31]. The lack of sex-based collagen differences is consistent with the results observed in alpine crossbred kids, which also showed no sex effect [32]. These results highlight the importance of cut-specific profiling for the texture control and nutritional applications of goat meat products.

Instrumental color

Table 4 displays the instrumental color values of goat meat. For lightness (CIE *L**), a significant Sex×Cut interaction was detected (p(S×C)=0.002) alongside a main effect of Cut (p(C)<0.001), whereas Sex was not significant (p(S)=0.530). Within males, Rib was lighter than Loin (39.8 vs 33.5), with Shoulder intermediate (36.3). Among female samples, differences between cuts were not statistically significant (36.3–38.5). Accordingly, the interaction effect indicated that cut-related differences were more distinct in males than in females. Overall, *L** values were slightly below the 39.8–41.4 range reported for Boer goat meat [21].

Redness, expressed as CIE *a**, was not influenced by the interaction between sex and cut (P = 0.703); therefore, the main effects were interpreted. Overall, females exhibited higher redness than males (P = 0.006). Across anatomical cuts, rib and shoulder were the reddest, whereas loin was consistently the least red when averaged over sexes (P < 0.001). Across all sex and cut combinations, redness value ranged from 16.9 to 21.6. These values are consistent with previous results on Boer goat meat (18.50–20.60) [33]. Variations in *a** values may result from differences in muscle fiber composition across cuts, which influence myoglobin oxidation rates. Elevated redness in goat meat is positively correlated with a higher proportion of type I fibers and negatively correlated with type IIB fibers [34].

For yellowness (CIE *b**), no statistically significant effects were detected (p(S)=0.085; p(C)=0.323; p(S×C)=0.416), with values narrowly distributed from 8.2 to 9.8. These values were slightly lower than the 10.9–12.6 range reported by Ryan et al. [33]. Overall, cut type had a stronger effect on meat color than that of sex, with loins consistently showing lower lightness and redness. The lack of *b** differences is consistent with the findings of Gawat et al. [21], who reported minimal sex-related variations in yellowness.

When compared with Korean native black goats, which typically exhibit L* values of 30.47–34.64, a* values of 18.08–20.35, and b* values of 4.77–7.13 [9], the imported frozen samples in this study demonstrated higher lightness and yellowness but comparable redness, suggesting that breed and storage conditions may influence chromatic attributes.

Bioactive compounds

Table 5 summarizes key bioactive compounds in imported Australian goat meat, including l-carnitine, CoQ10, anserine, carnosine, and α-tocopherol. Based on linear-mixed model bioactive compounds were influenced mainly by Cut (all p(C) <0.05). L-carnitine and CoQ10 showed clear cut-only effects (p(C)=0.001 and <0.001, respectively. The dipeptides (carnosine and anserine) displayed strong Cut effects (both p(C)<0.001) together with significant Sex×Cut

interactions (both $p(S\times C)<0.001$). The α-Tocopherol was the only trait with a pronounced Sex effect ($p(S)<0.001$) in addition to Cut ($p(C)=0.004$) and interaction ($p(S\times C)=0.005$). Overall, cut dictates the distribution of most bioactives, while sex chiefly elevates vitamin E and modulates dipeptide levels via interaction effects.

For L-carnitine, linear-mixed model showed a cut main effect with no Sex or Sex×Cut effects. Although Tukey's HSD pairwise comparisons among the six Sex × Cut combinations did not reveal statistically significant differences, the overall Cut effect remained significant, indicating substantial variation among cuts (Table 5). In this study, L-carnitine levels ranged from 2.8 to 3.6 μmol/g, consistent with previous findings of 2.80–3.29 μmol/g [35].

For CoQ10 no effects of sex or the interaction were detected, while a significant cut effect was present. Values ranged from 2.1 to 3.2 mg/100 g, with the shoulder showing the highest concentration, the rib the lowest, and the loin at an intermediate level. No sex differences were observed, which is consistent with the findings of Purchas et al. [36], who also observed no sex-based CoQ10 differences in lambs. The results in this study are slightly higher than those reported by Kim et al. [35], who observed values ranging from 1.43 to 1.70 mg/100 g in goat meat.

Carnosine and anserine showed a significant interaction between sex and cut ($p(S\times C) < 0.001$) together with a main effect of cut ($P < 0.001$), whereas the main effect of sex was not significant when averaged over cuts (carnosine $P = 0.236$; anserine $P = 0.604$). For carnosine, the male loin displayed the highest concentration (307.6 mg/100g) and was significantly greater than the male shoulder and rib (120.5 and 106.1 mg/100g, respectively) and also greater than all three female cuts (shoulder 119.6, rib 173.2, and loin 189.2 mg/100g). Across all combinations, carnosine ranged from 106.1 to 307.6 mg/100g. These values exceed those reported by Kim et al. [8], ranging from 49.54–65.25 mg/100g. Similar cut-based variations in the carnosine and CoQ10 levels have been reported in lambs [36].

For anserine, the male loin (325.2 mg/100g) significantly exceeded all other groups except the female loin. The female loin (257.8 mg/100g) was significantly higher than the male shoulder (134.8 mg/100g), the male rib (107.3 mg/100g), and the female shoulder (148.0 mg/100g), but did not significantly differ from the female rib (191.4 mg/100g). Across combinations, anserine ranged from 107.3 to 325.2 mg/100g. The anserine concentrations in this study were higher than those reported previously, ranging from 66.32 to 81.93 mg/100g [8].

Overall, α-tocopherol concentrations were greater in females than in males. In females, the shoulder was 79.7 μg/100g and the loin was 73.0 μg/100g, while the rib was the lowest within females (48.2 μg/100g). In males, the loin, rib, and shoulder were 56.0, 40.6, and 33.8 μg/100 g, respectively, with no significant differences among cuts. Across combinations, values ranged from 33.8 to 79.7 μg/100g. These results are consistent with previously reported

variability. For example, Jacobson and Pethick [37] reported α-tocopherol levels in goat meat ranging from <100 to 3,700 μg/100g. The concentrations in this study (33.8–79.7 μg/100g) are relatively low, possibly due to differences in diet, breed, or environment. However, these values are comparable to those reported for lamb loin α-tocopherol levels, ranging from 84 to 162 μg/100g [38], indicating potential similarities in Vitamin E retention across species under certain conditions.

Compared with Korean native black goat (KNBG) loin [35], the imported Australian goat meat in this study showed a different range of key bioactives. CoQ10 in imported goat meat ranged from 2.1 to 3.2 mg/100 g, exceeding the KNBG range of 1.30 to 1.70 mg/100 g. L-carnitine ranged from 2.8 to 3.6 μmol/g, which is comparable to KNBG (2.80–3.93 μmol/g). The largest gap was observed for dipeptides, imported goat meat showed carnosine of 106.1–307.6 mg/100 g and anserine of 107.3–325.2 mg/100 g, which exceeded the KNBG ranges (carnosine 39.67–54.44 mg/100 g; anserine 44.30–54.99 mg/100 g). Overall, imported Australian goat meat appears to provide greater dipeptide and CoQ10 concentrations than KNBG, while showing comparable L-carnitine.

Fatty acids profile

Table 6 presents the fatty acid (FA) content of frozen Australian goat meat. For most FA, Cut was significant (p(C)<0.001), and many traits also exhibited a significant interaction between sex and cut (p(S×C)<0.05). Among all groups, the female rib cut exhibited the highest total FA content, which aligns with its previously reported elevated crude fat level (12.4% compared to 2.5–6.8%). Specifically, it contained 5,884.8 mg/100 g of saturated fatty acids (SFA) and 5,477.3 mg/100 g of unsaturated fatty acids (UFA), surpassing the values observed in other cuts.

Within SFA, the female rib had the greatest myristic acid (C14:0, 305.35 mg/100 g), palmitic acid (C16:0, 2,874.05 mg/100 g), and stearic acid (C18:0, 2,705.40 mg/100 g). These values were similar to those previously reported for the fatty acid content of Korean native goat meat [39]. The C16:0 and C18:0 were predominant, consistent with previous findings [40]. These patterns were reflected in the SFA sum, which ranked the female rib above the other combinations.

The female rib cut exhibited markedly elevated levels of monounsaturated fatty acids (MUFA), with oleic acid (C18:1 n-9) reaching 4,320.26 mg/100 g, the highest concentration among all sample groups. As the predominant MUFA in goat meat [40], C18:1 n-9 was also the most abundant unsaturated fatty acid identified in this study. Vaccenic acid (C18:1 n-7) and eicosenoic acid (C20:1 n-9) also showed peak levels in the female rib, at 356.09 and 66.86

mg/100 g, respectively. Reflecting these values, the total MUFA content in the female rib was the highest recorded, at 4,930.91 mg/100 g, exceeding all other groups.

Within polyunsaturated fatty acids, the female rib exhibited the greatest total (546.36 mg/100 g) but did not differ significantly from the male rib (373.87 mg/100 g); it exceeded the remaining four combinations (male shoulder, male loin, female shoulder, and female loin). For individual constituents, α-linolenic acid (C18:3n-3), γ-Linolenic acid (C18:3n-6) and docosahexaenoic acid (C22:6n-3) in the female rib exceeded all other groups. By contrast, linoleic acid (C18:2n-6), adrenic acid (C22:4n-6), dihomo-γ-linolenic acid (C20:3n-6), and docosapentaenoic acid (C22:5n-3) in the female rib exceeded male shoulder, male loin, female shoulder, and female loin, but did not differ significantly from the male rib. For eicosapentaenoic acid (C20:5n-3), only a sex main effect was detected ($P = 0.042$), indicating that females exceeded males when averaged across cuts, and no cut or interaction effects were resolved. No significant differences in arachidonic acid (C20:4n-6) levels were observed among the meat cuts. In general, the PUFA profile identified in the present study showed a similar distribution pattern to that of Korean native goats as described by Moon et al. [39].

Lipid ratios paralleled the component profiles. For the MUFA/SFA ratio, the female shoulder (1.11) and the female loin (0.98) did not differ significantly; both exceeded the male rib and the male loin (0.77 each), and the female shoulder exceeded the male shoulder (0.85) and the female rib (0.84), whereas the female loin did not differ from the male shoulder or the female rib. For the PUFA/SFA ratio, the shoulders (male 0.25; female 0.25) exceeded the four remaining combinations (male rib 0.13, male loin 0.14, female rib 0.09, female loin 0.12), and no sex difference was detected for this ratio. Although the fatty acid profile observed in this study was slightly elevated compared to earlier research on Brazilian goat meat by [41], the PUFA to SFA ratio remained consistent.

For comparison with Korean goat meat, the KNBG fatty acid composition was reported by Ali et al. [9]. In terms of fatty acid composition (%), Australian goat meat in the present study showed SFA 42.38–53.20% and UFA 46.80–57.62%, indicating a higher SFA and lower UFA than KNBG overall (SFA 35.35–41.95%; UFA 49.16–55.80%). The MUFA in Australian goat meat (40.38–47.08%) was generally lower than KNBG (42.89–49.80%), while PUFA was broadly comparable (Australian 4.81–11.26% vs KNBG 6.00–11.10%). For the loin, Australian goat meat showed SFA 47.96–52.45% and UFA 47.55–52.04%, compared with KNBG loin (SFA 37.65%; UFA 55.80%), and it also had lower UFA/SFA (0.91–1.08 vs 1.50), MUFA/SFA (0.77–0.98 vs 1.32), and PUFA/SFA (0.12–0.14 vs 0.16). For the rib, Australian goat meat showed SFA 51.79–53.20% and UFA 46.80–48.21%, compared with KNBG rib (SFA 41.95%;

UFA 49.16%), with lower UFA/SFA (0.88–0.93 vs 1.18), MUFA/SFA (0.77–0.84 vs 1.02), and PUFA/SFA (0.09–0.13 vs 0.15). Overall, KNBG exhibited a lipid profile that was more unsaturated than imported Australian goat meat.

Nucleotide metabolite

Nucleotide metabolites were summaries in Table 7. Based on the linear-mixed model analysis, cut was the primary determinant, showing significant effects for ATP (p=0.005), GMP (p=0.001), IMP (p<0.001), ADP (p=0.004), hypoxanthine (p<0.001), and inosine (p<0.001), while AMP showed no Cut effect (p=0.123). Sex effects were largely absent, except for ATP (p(S)=0.005), with all other nucleotides having p(S) > 0.20. Sex×Cut interactions were generally not significant; only AMP exhibited an interaction (p(S×C)=0.017). Overall, nucleotide variation was driven mainly by Cut, with minimal contributions from Sex and Sex×Cut.

When averaged across cuts, adenosine triphosphate (ATP) concentrations were higher in females than in males; conversely, when averaged across sexes, the rib cut contained less ATP than the shoulder and loin. Increased ATP levels may indicate reduced post-mortem degradation and delayed flavor development [7]. Across combinations, ATP ranged from 3.2 to 6.2 mg/100 g.

Inosine monophosphate (IMP), the primary umami contributor, was the dominant nucleotide across all cuts, peaking in the loin, whereas the shoulder and rib contained approximately half of those levels. Guanosine monophosphate (GMP) showed a similar trend, synergistically enhancing the umami taste with IMP. These results suggest that the loin has the highest innate umami potential in both sexes. Values spanned from 63.7 to 117.0 mg/100 g for IMP and 1.7–2.8 mg/100 g for GMP.

In contrast, inosine (produced from IMP breakdown) was relatively high in the shoulders and ribs, particularly in females. Increased levels of inosine, which is subsequently degraded into hypoxanthine, are frequently associated with aged or slightly bitter flavor notes as the meat matures [42]. Hypoxanthine, which is associated with bitterness at elevated levels, was not significantly different among the group. The ratio of flavor-enhancing compounds (IMP + GMP) to degradation products indicated that the loin cut had the most favorable balance, characterized by relatively high levels of IMP and GMP alongside low inosine content.

Nucleotide profiling showed that cut considerably influenced flavor precursors than sex. Loin has the highest umami potential, while shoulder and rib may develop stronger aged or bitter notes during storage. These trends are

consistent with previous studies linking muscle type to nucleotide breakdown and flavor [7]. Overall, the nucleotide metabolite contents in this study are comparable to the values reported for goat meat by Indriani et al. [7].

Compared with Korean goat meat [6], IMP in imported Australian goat meat (63.7–117.0 mg/100 g) was broadly comparable in range to the Korean black goat values (61.24–93.53 mg/100 g), but the Australian dataset reached a greater maximum, driven by the loin. In contrast, the degradation-related compounds were clearly shifted upward in the Australian meat: inosine (75.8–105.5 mg/100 g) and hypoxanthine (2.0–3.6 mg/100 g) exceeded the Korean black goat ranges (56.67–67.84 mg/100 g and 0.91–1.65 mg/100 g, respectively). Overall, while IMP levels were generally comparable between datasets, imported Australian goat meat showed a greater accumulation of breakdown products, suggesting a profile that may lean more toward aged/bitter flavor notes than Korean black goat meat.

Comprehensive multivariate analysis of physicochemical and compositional traits for sex-based and meat cuts discrimination

PLS-DA revealed apparent clustering of male and female goat meat cuts based on their physicochemical and bioactive traits (Fig. 2). The sex-based biplot (Fig. 2A) showed separation along components 1 (15.4%) and 2 (19.6%), explaining 35.0% of the variance. Key discriminators included total MUFA and eicosenoic acid, with VIP scores of 2.10 and 2.03, respectively (Fig. 3A).

Cut-specific PLS-DA in males (Fig. 2B) showed a prominent separation of the shoulder and loin along components 1 (25.6%) and 2 (17.1%), with the rib overlapping the shoulder. Shoulder cuts were characterized by increased DPA, EPA, and PUFA/SFA ratios (VIP>1.4; Fig. 3B). Loin cuts were distinguished by elevated levels of carnosine, anserine, and α-tocopherol (VIP>1.6), highlighting the role of these antioxidants in loin differentiation. Similarly, Kim et al. (2019) observed higher carnosine and anserine levels in Korean goat loins than in other cuts. This is due to the fiber-type composition, as carnosine accumulates in fast-twitch (Type II) fibers, which are dominant in the loin, whereas oxidative (Type I) muscles, such as the shoulder, contain less carnosine [43]. Thus, muscle anatomy and metabolism influence the distribution of bioactive compounds.

In females (Fig. 2C), shoulder, rib, and loin cuts formed distinct clusters. Shoulder cuts showed higher levels of zinc, hypoxanthine, inosine, and various fatty acids, whereas loins had more anserine and IMP, which is consistent with the data in Table 7. Heatmap analysis (Fig. 3B-C) supported the PLS-DA, primarily clustering samples by cut within each sex. In males (Fig. 3B), key drivers (VIP>1.2) included carnosine, IMP, anserine, α-tocopherol, DPA,

PUFA/SFA ratio, arachidonic acid, total PUFA, CIE *b** value, EPA, SFA, UFA, pH, linoleic acid, and α-linolenic acid. In females (Fig. 3C), clustering was dominated by anserine, zinc, dihomo-γ-linolenic acid (DGLA), total PUFA, docosahexaenoic acid (DHA), hypoxanthine, PUFA/SFA ratio, inosine, IMP, linoleic acid, palmitic acid, arachidonic acid, carnosine, DPA, and EPA. These patterns showed that dipeptides, nucleotide metabolites, zinc, and specific long-chain fatty acids are strong markers for distinguishing goat meat cuts. Similarly, Wang et al. [44] observed that flavor precursors, including specific fatty acids, effectively differentiated lamb muscles, consistent with the results of the present study.

VOCs profile

A total of 161 VOCs were identified in the imported frozen Boer goat meat, including eight acids, 30 alcohols, 9 aldehydes, 26 esters, 68 hydrocarbons, 6 ketones, 10 nitrogen compounds, one sulfur compound, and three others (Supplementary Table S1). Several VOCs identified in this study have been detected in goat meat from different regions and systems. Octanoic acid, hexanoic acid, decanal, and carbon disulfide have been reported in ThaiAnglo-Nubian goats [7]. The 1-octen-3-ol and 2,3-butanedione appeared in both Thai × Anglo-Nubian [7] and European local breeds [45]. Common aldehydes such as nonanal and octanal were observed in suckling Spanish goat kids [46], Chinese indigenous goats [47], European goats [45], and the Thai × Anglo-Nubian crossbreds [7]. The repeated detection of these compounds across breeds, ages, and regions highlights their reliability as universal markers of lipid oxidation in goat meat and supports their use in cross-study flavor comparisons.

Overall, VOC class comparisons by sex and cut type showed minimal differences. However, ketones were highest in male rib cuts, suggesting stronger lipid oxidation in this fat-rich area. Moreover, sulfur compounds, including carbon disulfide, were increased in female shoulder cuts (Fig. 4). Carbon disulfide, as a representative sulfur compound, may originate from multiple pathways, including microbial catabolism of sulfur-containing substrates and non-microbial degradation during storage and handling. Previous work has reported the appearance of trace carbon disulfide at early stages of psychotropic spoilage [48]. Ercolini et al. [48] reported viable bacterial counts ranging from 2.56 to 5.00 log CFU/g when trace amounts of carbon disulfide were initially detected. In the present study, because microbiological counts were not measured, it cannot be determined whether the cut- or sex-related differences in carbon disulfide reflect differential microbial contamination. The absence of microbiological testing is therefore considered a limitation of this study. Rather, the detection of carbon disulfide may reflect early freshness decline

associated with prolonged frozen storage and thawing/cold-chain conditions [49], together with differences in precursor availability among cuts. Accordingly, carbon disulfide should be interpreted as a potential indicator of early freshness deterioration under frozen storage and handling conditions, rather than as definitive evidence of microbial spoilage.

PLS-DA revealed an evident sex-based separation in the VOC profiles (Fig. 5A). The key contributors included (Z)-2-tridecene, 1-heptadecyne, and pentadecanal, all with VIP scores > 1.0 (Fig. 6A). Although generally odor-neutral or mildly waxy, increased long-chain hydrocarbons in female meat indicate increased lipid oxidation, aligning with increased intramuscular fat in female carcasses (Table 1). These VOCs may serve as markers of oxidative status for sex differentiation rather than as direct aroma contributors.

VOC profiling of male cuts showed apparent differences among the loins, ribs, and shoulders (Fig. 5B). The loins had higher levels of methylazoxymethanol acetate, carbonic acid decyl vinyl ester, and methane dichloronitro. Shoulders showed a distinct contribution of sulfur-related volatiles, including carbon disulfide, which may reflect cut-specific precursor composition such as connective tissue-rich matrices or storage-related reactions. A microbial contribution during thawing cannot be excluded, although this cannot be confirmed without microbiological measurements. This compound has a sulfurous, fruity, burnt, and cabbage-like aroma [7]. VIP analysis (Fig. 6B) confirmed the discriminative value. Notably, Propanoic acid, 2-methyl-, 3-hydroxy-2,2,4-trimethylpentyl ester also showed strong cut specificity, with a VIP score of 2.22 for the shoulder.

In female goats, the VOC profiles varied significantly by cut (Fig. 5C). The loin showed increased levels of hydrocarbons such as decane, 4-methyl-; undecane, 2,6-dimethyl-, and nonane, 2,6-dimethyl-, likely from lipid oxidation. The ribs contained more ketones, particularly 2-pentanone, 4-hydroxy-4-methyl-, indicating typical oxidative lipid degradation. VIP analysis identified 15 key VOCs that differentiated female cuts (Fig. 6C), with scores from 1.53 to 1.86. Propanoic acid, 2-methyl-, 2-ethyl-3-hydroxyhexyl ester confirmed its value as a consistent cut discriminator across the sexes.

The consistent and strong discriminative presence of propanoic acid, 2-methyl-, 2-ethyl-3-hydroxyhexyl ester (also known as 2-ethyl-3-hydroxyhexyl 2-methylpropanoate) in shoulder cuts of both sexes highlights their potential significance. It has rarely been reported in meat. Therefore, it may serve as a biomarker for shoulder meat identification. However, further studies across goat breeds and production systems are required to confirm its role and determine its biochemical origin in goat muscle.

Overall, VOC profile variations highlighted complex biochemical processes shaped by sex and cut. Key discriminators, particularly propanoic acid, 2-methyl-, 2-ethyl-3-hydroxyhexyl ester, provide valuable insights into distinguishing meat cuts. These findings support efforts by the meat industry to optimize quality, develop targeted products, and improve consumer acceptance through better sensory management.

Sensory attributes

Table 8 shows the sensory attributes evaluation results. Overall, panelists preferred meat from female goats, with rib cuts generally receiving the highest scores across attributes. In contrast, shoulder cuts from male goats were the least favored. The main effects of sex and cut significantly influenced juiciness, taste, tenderness, and overall acceptability, while a significant sex × cut interaction was observed only for tenderness ($p<0.05$). Appearance did not differ ($p>0.05$), likely reflecting standardized cooking/serving conditions that minimize visual cues once doneness and surface browning are controlled. Sex was influenced “peculiar (goaty) odor,” which was lower (more desirable) in females across cuts, yielding a strong Sex effect without a Cut or interaction effect. This stronger “goaty” note in males is consistent with previous findings in Korean native goats [6]. Overall, sensory perception varied according to the cut and sex. The ribs were the most preferred, and the shoulder the least preferred. The female samples scored higher in flavor and texture, leading to better overall acceptability. These differences likely result from variations in the flavor precursors and intramuscular fat distribution. Although lipid oxidation can produce unwanted off-odors, the goat meat aroma is mainly attributable to lipid-derived volatiles [6]. Moreover, the pattern of significance indicates that differences between sexes drive the outcomes more than differences among cuts or their interaction. Across traits, the Sex term reached significance more frequently and with larger, more consistent effect sizes, whereas Cut effects were lower and the Sex×Cut term was limited. In practical terms, between-sex mean separations are wider and more stable than the differences among cuts. Accordingly, strategies to improve sensory quality in imported goat meat should prioritize managing sex and physiological status first, with cut selection serving a secondary, trait-dependent role.

Conclusion

Frozen goat meat imported from Australia can be classified based on sex and anatomical cut using integrated physicochemical, bioactive, nucleotide, fatty acid, and VOC. PLS-DA revealed evident differences between male and female meat, which were significantly influenced by lipid-related variables, including total MUFA, the MUFA/SFA ratio, eicosanoic acid, oleic acid, adrenic acid, and γ-linolenic acid, as well as α-tocopherol and Fe content. Additionally, for the classification of anatomical cuts, the discrimination in male samples was significantly driven by carnosine, anserine, IMP, α-tocopherol, and DPA. In contrast, the classification of female samples was determined by anserine, Zn, DGLA, DHA, and total PUFA (VIP score > 1.55). Complementing these multivariate classifications, linear mixed-model analyses showed Cut as the primary determinant of non-sensory traits. By contrast, Sex effects and Sex×Cut interactions were smaller, and only sensory traits deviated by showing broader Sex influence alongside contributions from Cut.

The findings of this study have practical implications for producers in the meat import-export industry and provide nutritionally relevant information to consumers. Female goat meat, particularly shoulder and loin cuts, exhibited higher concentrations of α-tocopherol than those of male goats, indicating increased antioxidant potential. Conversely, male goat meat, particularly loins, contained higher levels of dipeptides. Based on anatomical cut analysis, loins from both sexes consistently showed the highest levels of IMP, a key biochemical indicator of umami taste. This cut also has the potential for high antioxidant activity owing to the relative abundance of α-tocopherol and dipeptides. However, the shoulder cut contained a higher proportion of PUFA than other cut types. Furthermore, under suboptimal storage conditions, shoulder cuts tend to generate sulfur-containing volatile compounds that can act as early indicators of freshness loss. Thus, proper storage conditions are essential to maintain product quality and stability.

This study provides preliminary information on the potential biomarkers for the classification of imported frozen goat meat. However, the study was limited to samples from a single country of origin and had insufficient information on production systems, including feeding management. Therefore, future investigations are critical to verify the robustness of these results and to inform evidence-based practices within the meat industry.

References

1. Gawat M, Boland M, Singh J, Kaur L. Goat meat: production and quality attributes. Foods. 2023;12:3130. https://doi.org/10.3390/foods12163130

2. Bae IS, Hoa VB, Lee JA, Park WS, Kim DG, Kim HW, et al. Skin function improvement and anti-inflammatory effects of goat meat extract. Foods. 2024;13:3934. https://doi.org/10.3390/foods13233934

3. Lee YG, Song WJ, Choi JY. Analysis of goat industry trends and challenges [Internet]. Korea Rural Economic Institute (KREI); 2025 [cited 2025 Dec 19]. Report No.: P2024-12. https://repository.krei.re.kr/handle/2018.oak/32251?mode=full

4. Leygonie C, Britz TJ, Hoffman LC. Meat quality comparison between fresh and frozen/thawed ostrich M. iliofibularis. Meat Sci. 2012;91:364–8. https://doi.org/10.1016/j.meatsci.2012.02.020

5. Anneke, Kim HJ, Kim D, Shin DJ, Do KT, Yang CB, et al. Characteristics of purified horse oil by supercritical fluid extraction with different deodorants agents. Food Sci. Anim. Resour. 2024;44:443–63. https://doi.org/10.5851/kosfa.2024.e19

6. Aung SH, Abeyrathne EDNS, Hossain MA, Jung DY, Kim HC, Jo C, et al. Comparative quality traits, flavor compounds, and metabolite profile of Korean native black goat meat. Food Sci Anim Resour. 2023;43:639-58. https://doi.org/10.5851/kosfa.2023.e25

7. Indriani S, Srisakultiew N, Sangsawad P, Paengkoum P, Pongsetkul J. Characterization of the non-volatiles and volatiles in correlation with flavor development of cooked goat meat as affected by different cooking methods. Food Sci. Anim. Resour. 2024;44:662–83. https://doi.org/10.5851/kosfa.2024.E10

8. Kim HJ, Kim HJ, Jang A. Nutritional and antioxidative properties of black goat meat cuts. Asian-Australas J Anim Sci. 2019;32:1423-9. https://doi.org/10.5713/ajas.18.0951

9. Ali M, Choi YS, Nam KC. Physicochemical attributes, free amino acids, and fatty acids of the five major cuts from Korean native black goat. Anim. Ind. Technol. 2021;8:23–33. https://doi.org/10.5187/ait.2021.8.1.23

10. Luasiri P, Sangsawad P, Pongsetkul J, Paengkoum P, Nakharuthai C, Suwanangul S, et al. Exploration of nutritional and bioactive peptide properties in goat meat from various primal cuts during in vitro gastrointestinal digestion and absorption. Anim Biosci. 2024;37:1096-1109. https://doi.org/10.5713/ab.23.0352

11. Saengsuk N, Sangsawad P, Paengkoum P, Pongsetkul J. Lipid and volatile profiles of various goat primal cuts: aspects of nutritional value and flavor/taste attributes. Foods. 2024;13:492. https://doi.org/10.3390/foods13030492

12. AOAC. Official methods of analysis of AOAC International. 16th ed. Arlington (VA): AOAC International; 1995.

13. MFDS. Ministry of Food and Drug Safety (MFDS): Food and food additives codex minerals analysis method [Internet]. 2022 [cited 2025 Feb 24]. https://www.foodsafetykorea.go.kr/foodcode/01_03.jsp?idx=304. Accessed 24 Feb 2025

14. MFDS. Ministry of Food and Drug Safety (MFDS): Food and food additives codex for Vitamin E analysis method [Internet]. 2022 [cited 2025 May 1]. https://www.foodsafetykorea.go.kr/foodcode/01_03.jsp?idx=319. Accessed 1 May 2025

15. Charrondière UR, Rittenschober D, Nowak V, Wijesinha-Bettoni R, Stadlmayr B, Haytowitz D, et al. FAO/INFOODS Guidelines for converting units, denominators and expressions. Version 1.0. Rome: Food and Agriculture Organization of the United Nations; 2012.

16. Joo SH, Jeong WC, Lee JG, Joo ST. Amino acids and mineral composition of the four major muscles from Korean native black goat. Ann. Anim. Resour. Sci. 2017;28:187–93. https://doi.org/10.12718/aars.2017.28.4.187

17. Tomović VM, Jokanović MR, Švarc-Gajić JV, Vasiljević IM, Šojić BV, Škaljac SB, et al. Physical characteristics and proximate and mineral composition of Saanen goat male kids meat from Vojvodina (Northern Serbia) as influenced by muscle. Small Rumin Res. 2016;145:44–52. https://doi.org/10.1016/j.smallrumres.2016.10.019

18. Kitagawa T, Funaba M, Matsui T. Relationships between mineral concentrations and physicochemical characteristics in the *Longissimus thoracis* muscle of Japanese Black cattle. Anim. Sci. J. 2018;89:211–8. https://doi.org/10.1111/asj.12919

19. Whyte H, Cama-Moncunill R, Dunne PG, McElhinney C, Monahan FJ, Schmidt O, et al. The potential of the mineral composition to discriminate between beef from different cattle diets and between individual muscles. Food Control. 2024;163:110539. https://doi.org/10.1016/j.foodcont.2024.110539

20. Ahmad T, Kumar Y, Singh JN. Effect of frozen storage of goat meat on quality parameters stored in the form of chunk and mince in two packaging materials. Indian J. Anim. Res. 2018;52:780–5. https://doi.org/10.18805/ijar.b-3273

21. Gawat M, Kaur L, Singh J, Boland M. Physicochemical and quality characteristics of New Zealand goat meat and its ultrastructural features. Food Res. Int. 2022;161:111736. https://doi.org/10.1016/j.foodres.2022.111736

22. Pophiwa P, Webb EC, Frylinck L. A review of factors affecting goat meat quality and mitigating strategies. Small Rumin Res. 2020;183:106035. https://doi.org/10.1016/j.smallrumres.2019.106035

23. Lamri M, della Malva A, Djenane D, López-Pedrouso M, Franco D, Albenzio M, et al. Towards the discovery of goat meat quality biomarkers using label-free proteomics. J Proteomics. 2023;278:104868. https://doi.org/10.1016/j.jprot.2023.104868

672 24. Choi DM, Kang KM, Kang SM, Kim HY, Choi DM, Kang KM, et al. Physicochemical
673 properties of black Korean goat meat with various slaughter ages. Animals. 2023;13:692.
674 https://doi.org/10.3390/ani13040692

675 25. Apata ES. Effects of post-motem processings and freezing on water holding capacity, warner
676 bratzler value and chemical composition of chevon. Am. J. Res. Commun. 2014;2:100–13.

677 26. Xiao Y, Fu S, Jiao Y, Zhang R, Liu Y. Study on the changes of goat meat quality and the
678 expression of 17 quality-related genes within 48 h of postmortem aging. Food Res Int.
679 2022;158:111506. https://doi.org/10.1016/j.foodres.2022.111506

680 27. Purslow PP. The structure and role of intramuscular connective tissue in muscle function.
681 Front Physiol. 2020;11:495. https://doi.org/10.3389/fphys.2020.00495

682 28. Swatland HJ. Stratification of connective tissue toughness in beef roasts assessed by
683 simultaneous fluorometry and penetrometry. Food Res Int. 2006;39:1106–9.
684 https://doi.org/10.1016/j.foodres.2006.03.004

685 29. Roseland JM, Nguyen QV, Douglass LW, Patterson KY, Howe JC, Williams JR, et al. Fatty
686 acid, cholesterol, vitamin, and mineral content of cooked beef cuts from a national study. J
687 Food Compos Anal. 2018;66:55-64. https://doi.org/10.1016/j.jfca.2017.12.003

688 30. Sieck GC, Ferreira LF, Reid MB, Mantilla CB. Mechanical properties of respiratory muscles.
689 Compr Physiol. 2013;3:1553–67. https://doi.org/10.1002/cphy.c130003

690 31. Nishimura T. The role of intramuscular connective tissue in meat texture. Anim Sci J.
691 2010;81:21–7. https://doi.org/10.1111/j.1740-0929.2009.00696.x

692 32. Cañizares GI, Chávari ACT, Marques RO, Gomes HFB, Brito EP, Lourençon RV, et al.
693 Muscle fiber area, collagen and fatty acid profile of goat meat. Sci Electron Arch.
694 2022;15(6):32-41. https://doi.org/10.36560/15620221552

695 33. Ryan SM, Unruh JA, Corrigan ME, Drouillard JS, Seyfert M. Effects of concentrate level on
696 carcass traits of Boer crossbred goats. Small Rumin Res. 2007;73:67–76.
697 https://doi.org/10.1016/j.smallrumres.2006.11.004

698 34. Bakhsh A, Hwang YH, Joo ST. Effect of slaughter age on muscle fiber composition,
699 intramuscular connective tissue, and tenderness of goat meat during post-mortem time. Foods.
700 2019;8:571. https://doi.org/10.3390/foods8110571

701 35. Kim HJ, Kim HJ, Kim KW, Lee J, Lee SH, Lee SS, et al. Effect of feeding alfalfa and
702 concentrate on meat quality and bioactive compounds in Korean native black goat loin during
703 storage at 4℃. Food Sci. Anim. Resour. 2022;42:517–35.
704 https://doi.org/10.5851/kosfa.2022.e21

705 36. Purchas RW, Rutherfurd SM, Pearce PD, Vather R, Wilkinson BHP. Concentrations in beef
706 and lamb of taurine, carnosine, coenzyme Q10, and creatine. Meat Sci. 2004;66:629–37.
707 https://doi.org/10.1016/S0309-1740(03)00181-5

37. Jacobson C, Pethick D. Nutrient composition of Australian goatmeat. Meat & Livestock Australia Limited; 2013. Report No.: B.GOA.0037.

38. Smeti S, Yagoubi Y, Srihi H, Lobón S, Bertolín JR, Mahouachi M, et al. Effects of using rosemary residues as a cereal substitute in concentrate on vitamin E, antioxidant activity, color, lipid oxidation, and fatty acid profile of Barbarine lamb meat. Animals. 2021;11:2100. https://doi.org/10.3390/ani11072100

39. Moon S-H, Kim NY, Seong H-J, Chung SU, Tang Y, Oh M, et al. Comparative analysis of proximate composition, amino acid and fatty acid content, and antioxidant activities in fresh cuts of Korean native goat (*Capra hircus coreanae*) meat. Korean J Food Preserv. 2021;28:303–12. https://doi.org/10.11002/kjfp.2021.28.3.303

40. Lopes LS, Martins SR, Chizzotti ML, Busato KC, Oliveira IM, Machado Neto OR, et al. Meat quality and fatty acid profile of Brazilian goats subjected to different nutritional treatments. Meat Sci. 2014;97:602–8. https://doi.org/10.1016/j.meatsci.2014.03.005

41. Machado BAS, Gomes IS, Nunes C da SO, Andrade G de Q, Nery TBR, Reis JH de O, et al. Lipid content and fatty acids compositions in commercial cuts of young goat meat. Cienc Rural. 2019;49. https://doi.org/10.1590/0103-8478cr20180587

42. Tikk M, Tikk K, Tørngren MA, Meinert L, Aaslyng MD, Karlsson AH, et al. Development of inosine monophosphate and its degradation products during aging of pork of different qualities in relation to basic taste and retronasal flavor perception of the meat. J. Agric. Food Chem. 2006;54:7769–77. https://doi.org/10.1021/jf060145a

43. Kalbe C, Metzger K, Gariépy C, Palin M-F. Effect of muscle fibre types and carnosine levels on the expression of carnosine-related genes in pig skeletal muscle. Histochem. Cell Biol. 2023;160:63–77. https://doi.org/10.1007/s00418-023-02193-6

44. Wang J, Song Y, Zhao L, Yang P, Huang F, Wu Y, et al. Characterization and discrimination of lamb with different breeds and muscle types using precursors and volatile compounds. Food Chem X. 2024;22:101437. https://doi.org/10.1016/j.fochx.2024.101437

45. Ivanović S, Pavlović M, Pavlović I, Tasić A, Janjić J, Baltić MŽ. Influence of breed on selected quality parameters of fresh goat meat. Arch. Anim. Breed. 2020;63:219–29. https://doi.org/10.5194/aab-63-219-2020

46. Ripoll G, Córdoba M de G, Alcalde MJ, Martín A, Argüello A, Casquete R, et al. Volatile organic compounds and consumer preference for meat from suckling goat kids raised with natural or replacers milk. Ital J Anim Sci. 2019;18:1259–70. https://doi.org/10.1080/1828051X.2019.1646107

47. He S, Zhang B, Dong X, Wei Y, Li H, Tang B. Differentiation of goat meat freshness using gas chromatography with ion mobility spectrometry. Molecules. 2023;28:3874. https://doi.org/10.3390/molecules28093874

744 48. Ercolini D, Russo F, Nasi A, Ferranti P, Villani F. Mesophilic and psychrotrophic bacteria
745 from meat and their spoilage potential in vitro and in beef. Appl. Environ. Microbiol.
746 2009;75:1990-2001. https://doi.org/10.1128/AEM.02762-08

747 49. Yoder LE, Rehm JG, Smith HR, Tigue DA, Wilborn B, Morey A, et al. Evaluation of
748 simulated shelf-life conditions for food service applications on chicken tenderloins. Animals.
749 2021;11:2028. https://doi.org/10.3390/ani11072028

750

Tables and figures

Table 1. Proximate (%) compositions of different meat cuts and sexes from imported goats

Traits	Male			Female			SEM	*P*-value		
	Shoulder	Rib	Loin	Shoulder	Rib	Loin		*P* (S)	*P* (C)	*P* (S×C)
Moisture	76.4^{a}	73.4^{ab}	74.3^{ab}	76.0^{a}	68.8^{c}	72.4^{b}	0.78	0.033	<0.001	0.006
Crude protein	20.2^{ab}	19.4^{b}	20.6^{a}	20.0^{ab}	17.9^{c}	19.8^{ab}	0.24	0.01	<0.001	0.015
Crude fat	2.5^{d}	6.4^{bc}	3.9^{bcd}	3.0^{cd}	12.4^{a}	6.8^{b}	0.81	0.005	<0.001	0.004
Crude ash	1.07	1.02	1.05	1.11	0.91	1.02	0.05	0.378	0.148	0.449

$^{a–d}$ Different letters within the same row indicate significant differences ($p<0.05$).
S, Sex. C, Cuts. S×C, The interaction between sex and cuts.

Table 2. Mineral contents (mg/100g) of different meat cuts and sexes from imported goats

Traits	Male			Female			SEM	*P*-value		
	Shoulder	Rib	Loin	Shoulder	Rib	Loin		*P* (S)	*P* (C)	*P* (S×C)
K	313.9^{ab}	280.6^{bc}	311.3^{ab}	322.1^{a}	273.8^{c}	316.3^{a}	7.62	0.764	<0.001	0.556
P	183.9^{ab}	163.2^{bc}	183.5^{abc}	188.4^{a}	163.1^{bc}	186.4^{a}	4.73	0.665	<0.001	0.779
Na	62.5^{b}	72.9^{a}	63.4^{b}	70.3^{ab}	74.3^{a}	68.4^{ab}	2.10	0.077	<0.001	0.178
Mg	21.9^{a}	18.7^{bc}	20.9^{abc}	21.0^{ab}	18.1^{c}	20.7^{abc}	0.65	0.342	<0.001	0.831
Ca	5.7	6.0	5.6	5.4	7.2	6.6	0.53	0.291	0.08	0.187
Zn	4.9	5.5	5.0	5.9	5.6	4.5	0.38	0.558	0.05	0.124
Fe	3.2	3.0	3.0	2.6	2.0	2.2	0.27	0.05	0.114	0.624
Cu	0.10	0.10	0.12	0.11	0.10	0.10	0.01	0.723	0.176	0.296
Mn	0.03	0.03	0.03	0.03	0.02	0.03	0.01	0.724	0.828	0.291

$^{a–c}$ Different letters within the same row indicate significant differences ($p<0.05$).
Fe, Iron; Ca, Calcium; P, Phosphorus; K, Potassium; Na, Sodium; Mn, Manganese; Zn, Zinc; Mg, Magnesium; Cu, Copper.
S, Sex. C, Cuts. S×C, The interaction between sex and cuts.

Table 3. Physicochemical properties, cholesterol, and collagen content of different meat cuts and sexes from imported goats

Traits	Male			Female			SEM	*P*-value		
	Shoulder	Rib	Loin	Shoulder	Rib	Loin		*P* (S)	*P* (C)	*P* (S×C)
pH	6.5	6.5	6.2	6.5	6.5	6.3	0.10	0.762	<0.001	0.18
WHC (%)	52.0	53.8	53.8	51.6	57.7	54.4	2.42	0.624	0.123	0.482
Cooking loss (%)	35.3^{c}	40.6^{a}	32.9^{cd}	35.7^{bc}	39.5^{ab}	31.5^{d}	0.85	0.450	<0.001	0.365
Shear force (N)	39.6	38.1	39.9	32.6	32.9	34.9	2.66	0.124	0.445	0.768
Cholesterol (mg/100g)	53.1^{ab}	56.1^{ab}	55.0^{ab}	52.0^{b}	64.1^{a}	61.0^{ab}	2.72	0.119	0.025	0.202
Collagen (g/100g)	0.7^{c}	1.2^{a}	0.9^{b}	0.7^{c}	1.1^{a}	0.8^{bc}	0.04	0.204	<0.001	0.243

$^{a–d}$ Different letters within the same row indicate significant differences ($p<0.05$).
S, Sex. C, Cuts. S×C, The interaction between sex and cuts.

Table 4. Instrumental color value of different meat cuts and sexes from imported goats

Traits	Male			Female			SEM	*P*-value		
	Shoulder	Rib	Loin	Shoulder	Rib	Loin		*P* (S)	*P* (C)	*P* (S×C)
CIE *L**	36.3^{ab}	39.8^{a}	33.5^{b}	36.3^{ab}	38.5^{ab}	37.7^{ab}	1.13	0.530	<0.001	0.002
CIE *a**	19.3^{abc}	20.8^{ab}	16.9^{c}	21.1^{ab}	21.6^{a}	18.6^{bc}	0.58	0.006	<0.001	0.703
CIE *b**	9.8	9.0	8.2	9.6	9.5	9.5	0.50	0.085	0.323	0.416

$^{a–c}$ Different letters within the same row indicate significant differences (p<0.05).
S, Sex. C, Cuts. S×C, The interaction between sex and cuts.

775 **Table 5. Bioactive compounds of different meat cuts and sexes from imported goats**

Traits	Male			Female			SEM	*P*-value		
	Shoulder	Rib	Loin	Shoulder	Rib	Loin		*P* (S)	*P* (C)	*P* (S×C)
L-Carnitine (μmol/g)	3.1	2.8	3.3	3.5	3.3	3.6	0.23	0.241	0.001	0.665
CoQ_{10} (mg/100g)	2.7^{ab}	2.1^{b}	2.4^{ab}	3.2^{a}	2.1^{b}	2.3^{ab}	0.24	0.551	<0.001	0.175
Carnosine (mg/100g)	120.5^{cd}	106.1^{d}	307.6^{a}	119.6^{d}	173.2^{bc}	189.2^{b}	12.07	0.236	<0.001	<0.001
Anserine (mg/100g)	134.8^{cd}	107.3^{d}	325.2^{a}	148.0^{cd}	191.4^{bc}	257.8^{ab}	16.49	0.604	<0.001	<0.001
α-tocopherol (μg/100g)	33.8^{c}	40.6^{c}	56.0^{bc}	79.7^{a}	48.2^{c}	73.0^{ab}	5.16	<0.001	0.004	0.005

776
777
778 $^{a–d}$ Different letters within the same row indicate significant differences (p<0.05).
779 S, Sex. C, Cuts. S×C, The interaction between sex and cuts.
780

Table 6. Fatty acid (mg/100g) content of different meat cuts and sexes from imported goats

Fatty acids	Male			Female			SEM	*P*-value		
	Shoulder	Rib	Loin	Shoulder	Rib	Loin		*P* (S)	*P* (C)	*P* (S×C)
C14:0	50.49^{b}	156.68^{b}	105.29^{b}	49.42^{b}	305.35^{a}	150.81^{b}	25.30	0.034	<0.001	0.010
C16:0	532.65^{d}	1482.12^{bc}	916.37^{bcd}	602.72^{cd}	2874.05^{a}	1569.24^{b}	211.53	0.012	<0.001	0.006
C16:1n7	34.59^{c}	89.13^{bc}	54.02^{bc}	51.02^{bc}	187.69^{a}	113.27^{ab}	17.37	0.017	<0.001	0.022
C18:0	518.76^{c}	1463.56^{b}	858.68^{b}	515.26^{c}	2705.40^{a}	1248.98^{b}	164.18	0.005	<0.001	0.004
C18:1n9	845.33^{c}	2107.89^{bc}	1294.23^{bc}	1158.33^{c}	4320.26^{a}	2563.53^{b}	294.01	0.003	<0.001	0.005
C18:1n7	52.60^{c}	134.36^{bc}	83.95^{bc}	71.18^{bc}	356.09^{a}	160.44^{b}	23.49	0.002	<0.001	<0.001
C18:2n6	116.91^{b}	163.00^{ab}	110.57^{b}	127.07^{b}	247.50^{a}	151.29^{b}	21.11	0.110	<0.001	0.005
C18:3n6	9.57^{c}	22.72^{b}	13.69^{bc}	9.20^{c}	38.98^{a}	16.40^{bc}	2.40	0.023	<0.001	0.004
C18:3n3	26.38^{b}	44.22^{b}	30.00^{b}	31.54^{b}	82.89^{a}	49.19^{b}	7.17	0.036	<0.001	0.014
C20:1n9	10.40^{c}	23.47^{bc}	16.11^{bc}	16.11^{bc}	66.86^{a}	34.55^{b}	4.44	0.002	<0.001	<0.001
C20:3n6	5.87^{c}	9.72^{ab}	6.65^{bc}	7.27^{cb}	11.71^{a}	7.25^{bc}	0.76	0.055	<0.001	0.678
C20:4n6	49.25	52.94	42.15	52.21	55.42	49.61	4.23	0.383	0.063	0.704
C20:5n3	14.54^{ab}	15.50^{ab}	12.65^{b}	19.48^{ab}	22.62^{a}	19.32^{ab}	2.12	0.042	0.095	0.698
C22:4n6	5.76^{c}	15.12^{ab}	9.40^{bc}	5.99^{c}	18.76^{a}	9.42^{bc}	1.85	0.523	<0.001	0.429
C22:5n3	26.76^{b}	42.38^{ab}	26.10^{b}	31.18^{ab}	52.50^{a}	38.25^{ab}	4.92	0.124	<0.001	0.617
C22:6n3	4.35^{b}	8.28^{b}	5.00^{b}	6.33^{b}	15.99^{a}	8.57^{b}	1.13	0.003	<0.001	0.042
SFA	1101.89^{c}	3102.36^{b}	1880.34^{bc}	1167.40^{c}	5884.79^{a}	2969.04^{b}	388.08	0.008	<0.001	0.004
UFA	1202.31^{c}	2728.71^{bc}	1704.52^{bc}	1586.92^{c}	5477.27^{a}	3221.11^{b}	367.79	0.004	<0.001	0.004
MUFA	942.92^{c}	2354.85^{bc}	1448.30^{bc}	1296.64^{c}	4930.91^{a}	2871.79^{b}	334.32	0.003	<0.001	0.004
PUFA	259.38^{b}	373.87^{ab}	256.21^{b}	290.27^{b}	546.36^{a}	349.31^{b}	40.53	0.061	<0.001	0.096
MUFA/SFA	0.85^{bc}	0.77^{c}	0.77^{c}	1.11^{a}	0.84^{bc}	0.98^{ab}	0.04	0.006	<0.001	0.002
PUFA/SFA	0.25^{a}	0.13^{b}	0.14^{b}	0.25^{a}	0.09^{b}	0.12^{b}	0.02	0.264	<0.001	0.587

$^{a–d}$ Different letters within the same row indicate significant differences (p<0.05).

C14:0 (myristic acid), C16:0 (palmitic acid), C16:1n7 (palmitoleic acid), C18:0 (stearic acid), C18:1n9 (oleic acid), C18:1n7 (vaccenic acid), C18:2n6 (linoleic acid), C18:3n6 (γ-linolenic acid), C18:3n3 (α-linolenic acid), C20:1n9 (eicosenoic acid), C20:3n6 (dihomo-γ-linolenic acid; DGLA), C20:4n6 (arachidonic acid), C20:5n3 (eicosapentaenoic acid; EPA), C22:4n6 (adrenic acid), C22:5n3 (docosapentaenoic acid; DPA), and C22:6n3 (docosahexaenoic acid; DHA).

S, Sex. C, Cuts. S×C, The interaction between sex and cuts.

Table 7. Nucleotide metabolite (mg/100g) of different meat cuts and sexes from imported goats

Traits	Male			Female			SEM	*P*-value		
	Shoulder	Rib	Loin	Shoulder	Rib	Loin		*P* (S)	*P* (C)	*P* (S×C)
Adenosine triphosphate	4.8^{ab}	3.2^{b}	5.9^{a}	6.0^{a}	5.1^{ab}	6.2^{a}	0.46	0.005	0.005	0.332
Guanosine monophosphate	2.1^{ab}	1.9^{ab}	2.6^{ab}	1.7^{b}	1.9^{ab}	2.8^{a}	0.23	0.794	0.001	0.383
Inosine monophosphate	63.9^{b}	70.0^{b}	117.0^{a}	63.7^{b}	70.2^{b}	102.9^{a}	6.69	0.597	<0.001	0.091
Adenosine diphosphate	20.3	20.5	16.1	20.1	18.2	16.0	1.13	0.397	0.004	0.548
Hypoxanthine	3.2	3.1	2.0	3.6	3.1	2.2	0.36	0.696	<0.001	0.693
Adenosine monophosphate	6.4^{ab}	6.1^{b}	8.3^{a}	7.6^{ab}	7.8^{ab}	7.3^{ab}	0.48	0.202	0.123	0.017
Inosine	92.8^{ab}	81.2^{ab}	75.8^{b}	105.5^{a}	100.2^{ab}	76.2^{ab}	6.80	0.233	<0.001	0.105

$^{a–b}$ Different letters within the same row indicate significant differences (p<0.05).
S, Sex. C, Cuts. S×C, The interaction between sex and cuts.

Table 8. Sensory evaluation of different meat cuts and sexes from imported goats

Attribute	Male			Female			SEM	*P*-value		
	Shoulder	Rib	Loin	Shoulder	Rib	Loin		*P* (S)	*P* (C)	*P* (S×C)
Appearance	5.8	5.9	5.3	6.0	5.7	5.8	0.22	0.259	0.093	0.139
Aroma	4.1^{b}	5.4^{a}	5.0^{ab}	4.9^{ab}	5.6^{a}	5.4^{a}	0.24	0.036	0.550	0.165
Juiciness	5.0^{ab}	5.1^{a}	4.0^{b}	5.0^{a}	5.3^{a}	5.0^{ab}	0.24	0.031	0.004	0.081
Peculiar odor	5.2^{a}	4.7^{ab}	5.0^{ab}	4.2^{ab}	4.3^{ab}	3.9^{b}	0.28	<0.001	0.534	0.396
Taste	4.4^{b}	5.4^{a}	5.2^{ab}	5.2^{ab}	5.9^{a}	5.6^{a}	0.22	<0.001	<0.001	0.523
Tenderness	5.2^{ab}	4.7^{bc}	4.2^{c}	5.6^{ab}	6.2^{a}	5.5^{ab}	0.24	<0.001	0.035	0.049
Overall acceptability	4.7^{c}	5.5^{abc}	5.2^{bc}	5.2^{bc}	6.2^{a}	5.9^{ab}	0.21	<0.001	<0.001	0.754

$^{a–c}$ Different letters within the same row indicate significant differences ($p<0.05$).
S, Sex. C, Cuts. S×C, The interaction between sex and cuts.

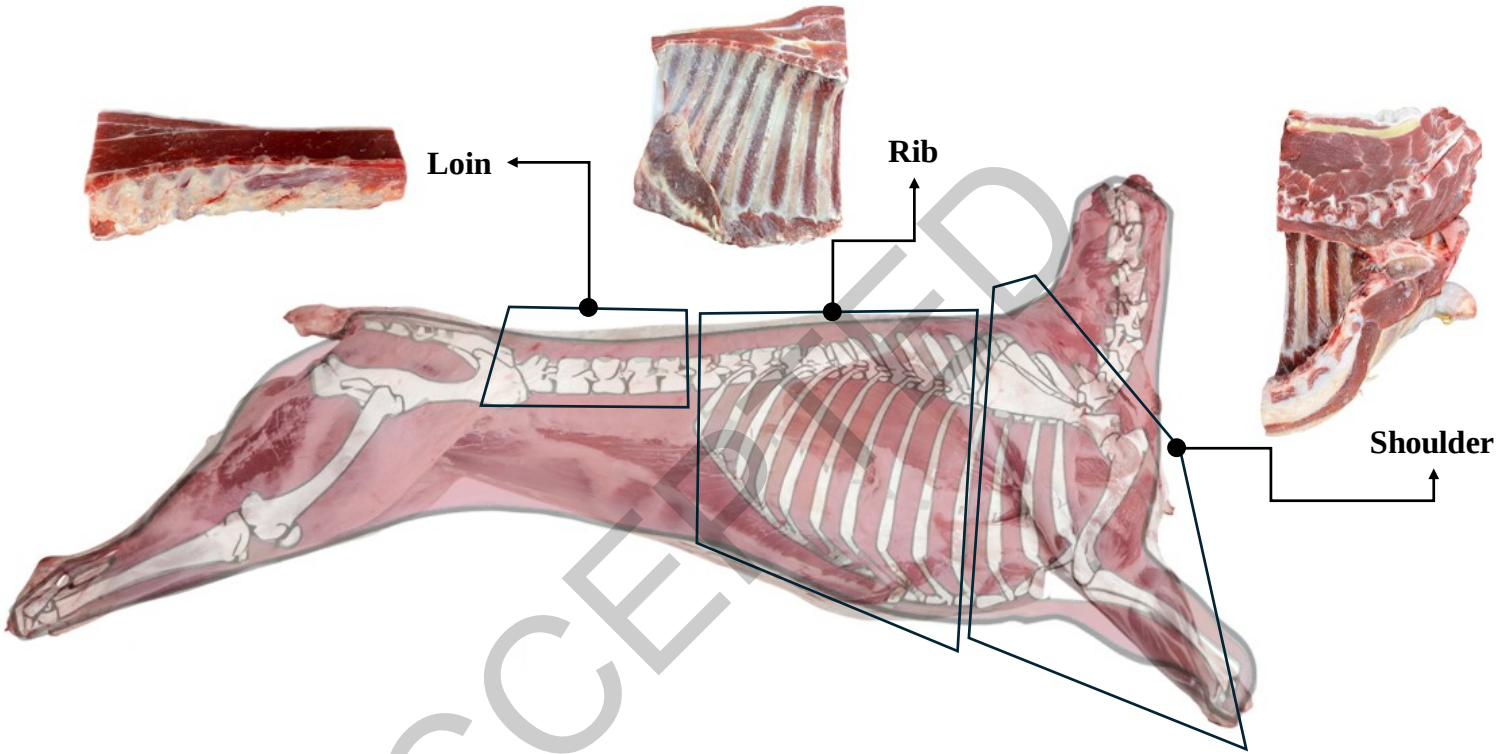


Fig. 1. Primal cuts of goat meat illustrate cutting locations for the shoulder, rib, and loin

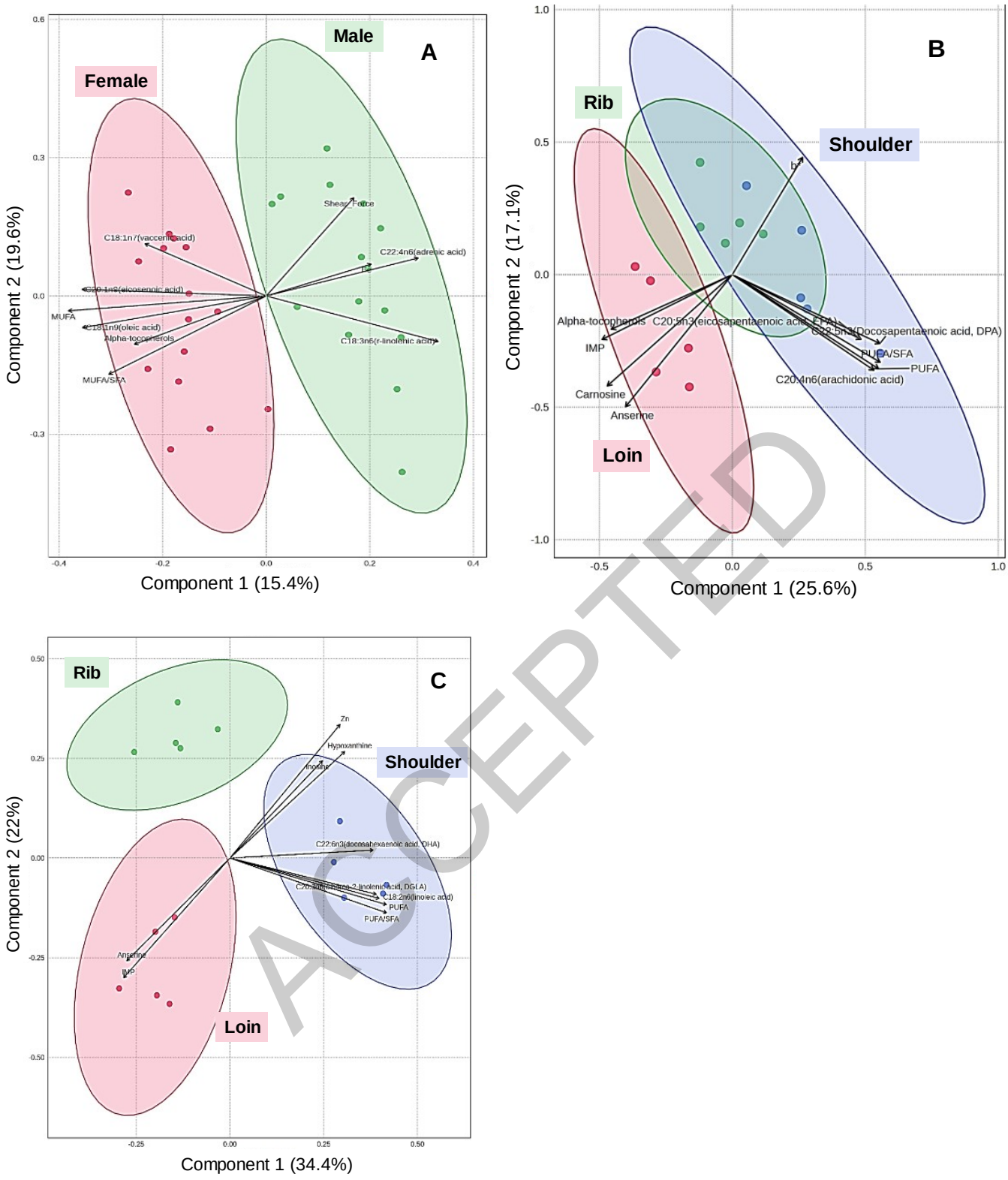


Fig. 2. Partial least squares-discriminant analysis (PLS-DA) biplots showing multivariate distribution in imported frozen Boer goat meat: (A) by sex, (B) by cuts in males, and (C) by cuts in females. Points represent samples; vectors indicate variable contributions.

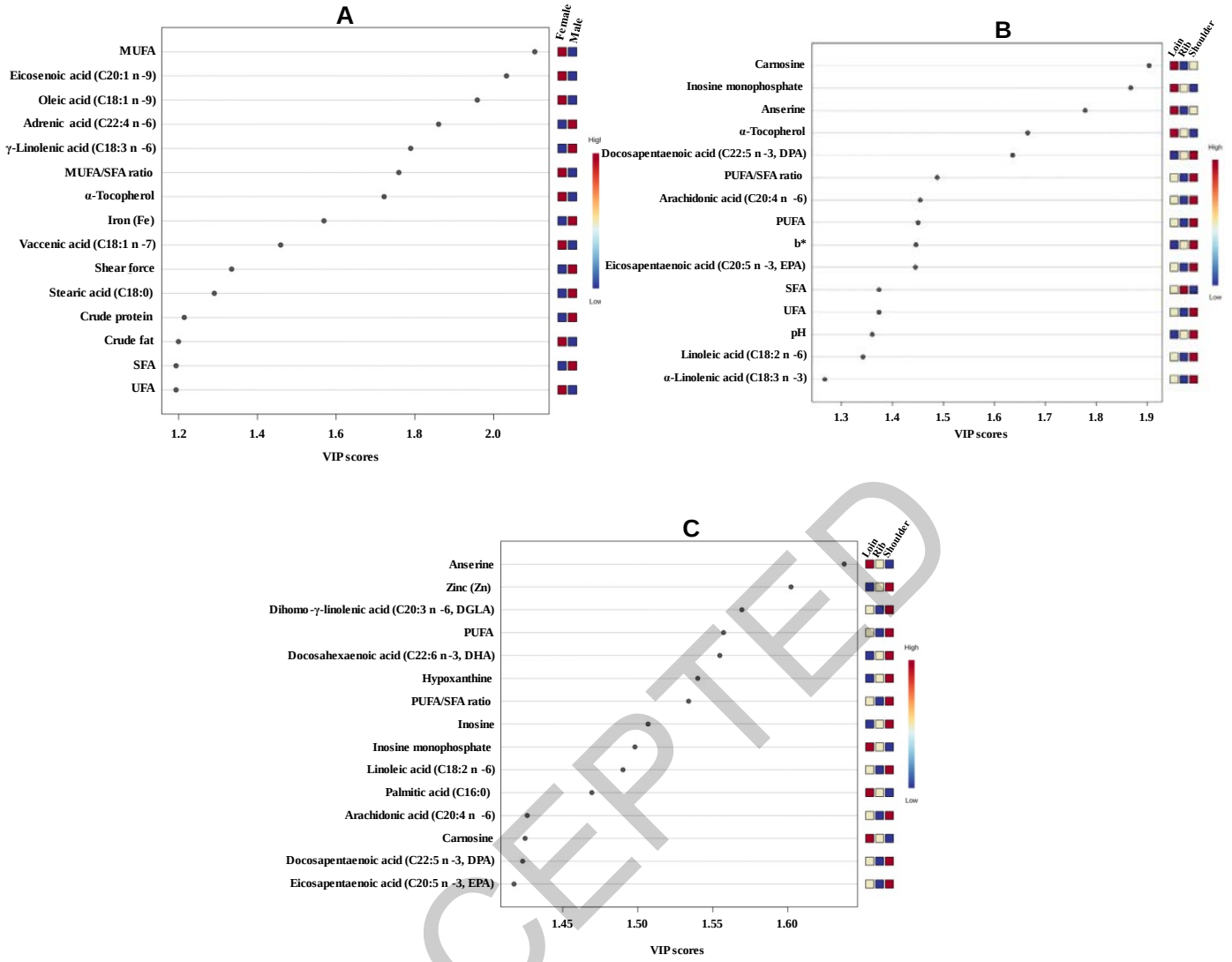


Fig. 3. Partial least squares-discriminant analysis (PLS-DA) variable importance in projection (VIP) scores and heatmaps of quality traits in imported frozen Boer goat meat: (A) sex-based comparison; (B) key variables across cuts in males; (C) in females. Variables with VIP>1.0 are most influential; heatmap colors show relative levels per group.

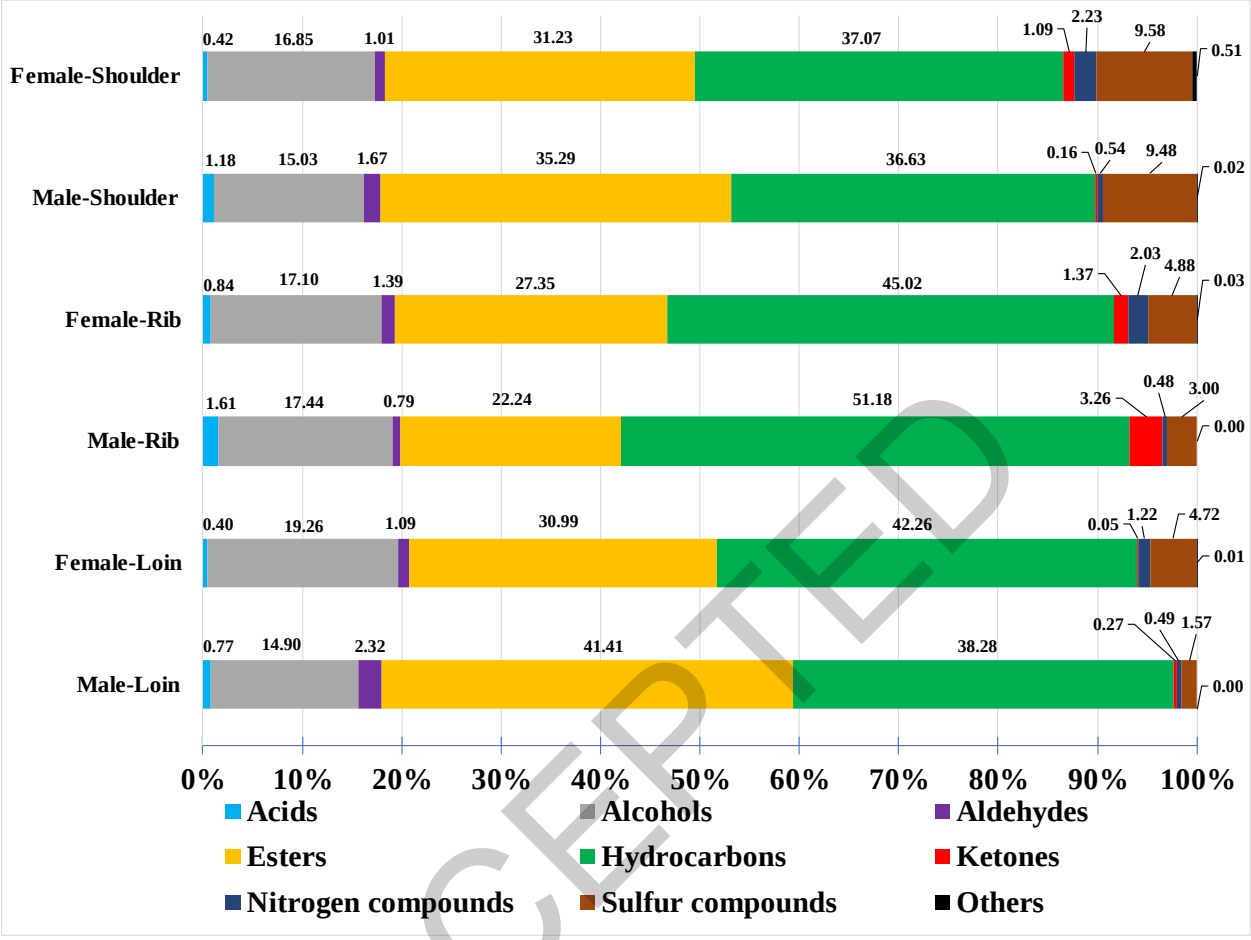
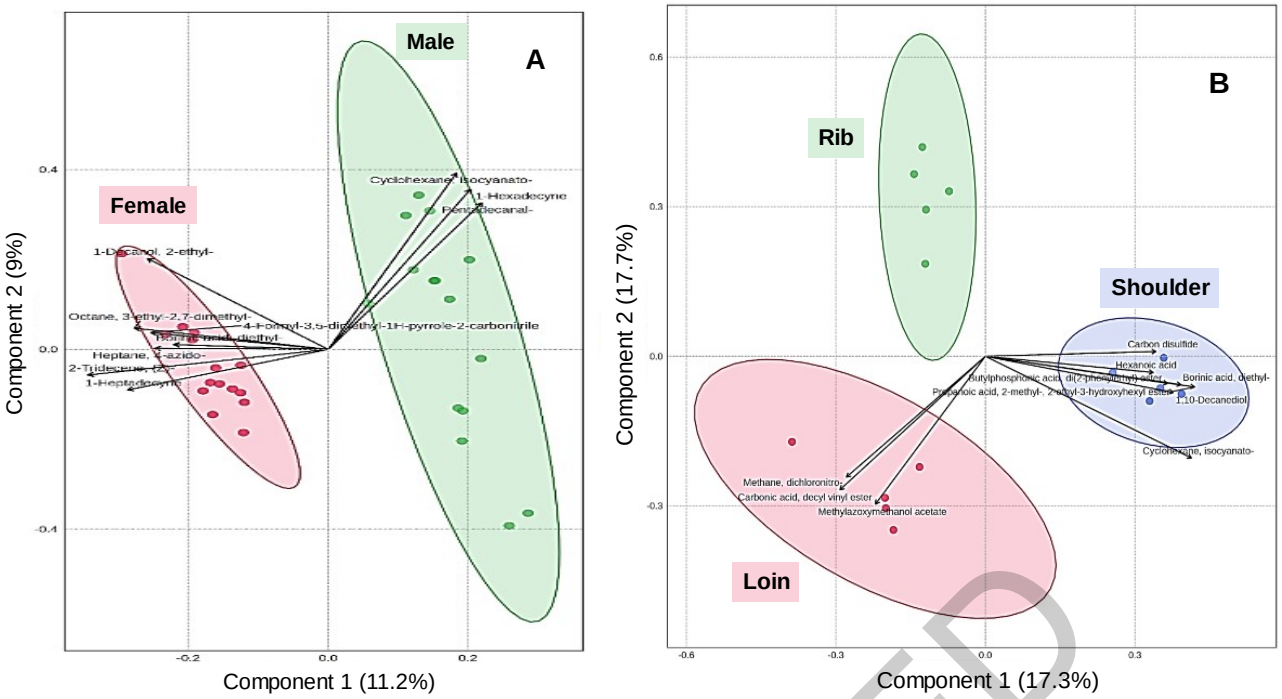
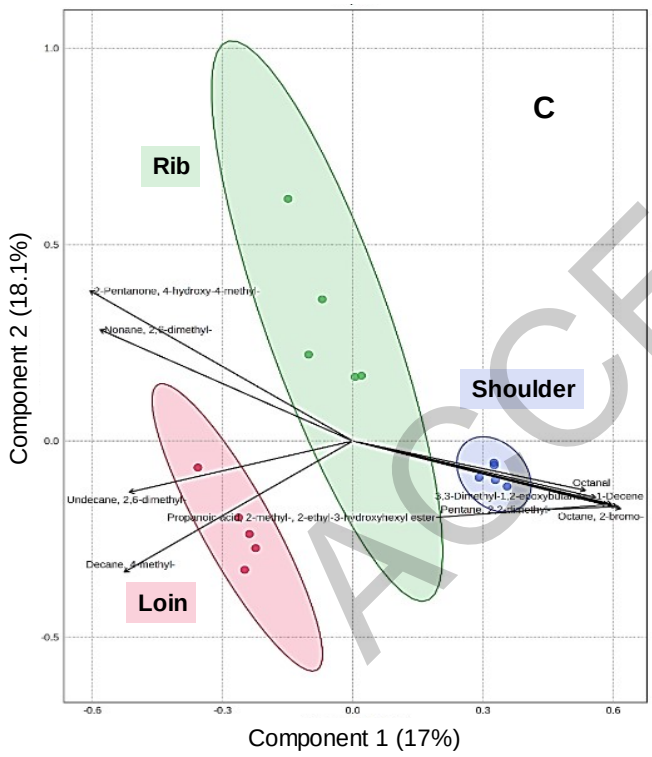


Fig. 4. Relative (%) composition of volatile organic-compound (VOCs) families in imported Boer goat meat by sex and cut (shoulder, rib, loin). Colors indicate chemical families. Values reflect each family's proportion of total VOC peak area.



822



823

824 **Fig. 5. Partial least-squares discriminant analysis (PLS-DA) biplots of volatile organic compound (VOCs)**
825 **profiles in imported frozen Boer goat meat: (A) by sex, (B) by cuts in males, (C) by cuts in females. Markers**
826 **represent samples; vectors show each VOC's contribution to separation.**
827

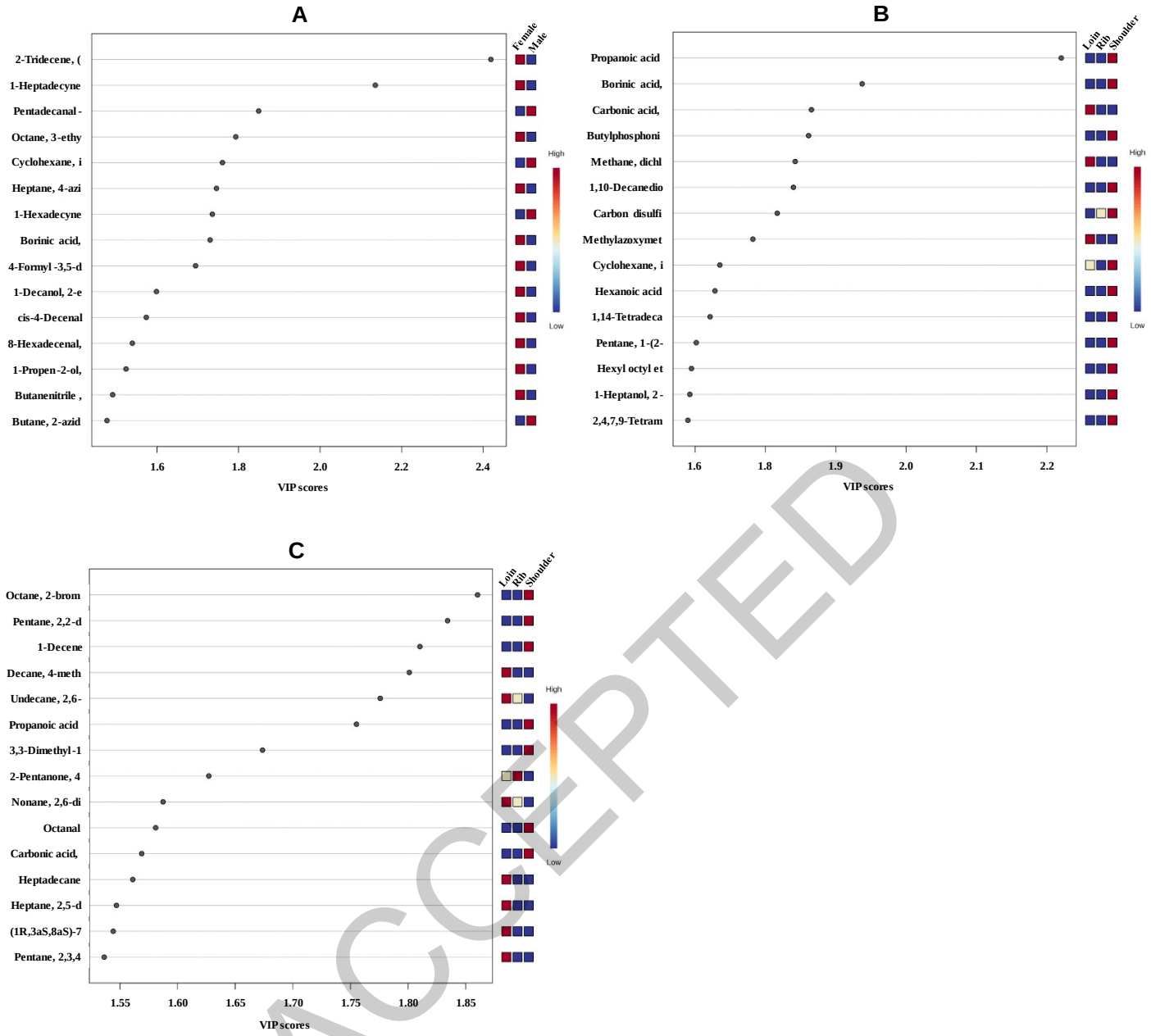


Fig. 6. Partial least squares-discriminant analysis (PLS-DA) variable importance in projection (VIP) scores and heatmaps of volatile organic compounds (VOCs) profiles in imported frozen Boer goat meat: (A) sex-based comparison; (B) key VOCs across cuts in males; (C) in females. Compounds with VIP>1.0 are most influential; heatmap tiles show relative VOCs abundance across groups.