https://doi.org/10.17221/53/2025-CJAS

Carcass traits and meat quality in Balkan goats: A multivariate evaluation of crossbreeding and slaughter weight effects

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Citation: Stanišić N., Cekić B., Maksimović N., Petričević M., Delić N., Stajić S., Keškić T. (2025): Carcass traits and meat quality in Balkan goats: A multivariate evaluation of crossbreeding and slaughter weight effects. Czech J. Anim. Sci, 70: 438–449.

Abstract: This study investigated the effects of slaughter weight and breed on carcass characteristics, meat quality, and technological properties in purebred Balkan and F1 crossbred (Balkan × Saanen) male goats. A total of 48 animals, divided into four slaughter weight groups (10, 15, 18, and 22 kg), were analysed for carcass composition, muscle traits, and fat distribution. ANOVA and multivariate analyses (PCA and HCA) revealed significant effects of weight and breed on key carcass and meat quality parameters. Heavier animals exhibited higher intramuscular fat and primal cut yields with superior water-holding capacity (WHC), while lighter goats had leaner carcasses with less muscle pigment. Crossbred F1 goats demonstrated a more balanced muscle-to-fat ratio, whereas pure Balkan goats tended to accumulate fat more rapidly at higher weights. These findings indicate that optimal slaughter weight selection should align with market demands, such as producing leaner meat in lighter Balkan goats, or achieving increased marbling and better economic returns in heavier crossbred animals. Future research should explore genetic effects on muscle and fat deposition and assess consumer preferences to refine breeding and production strategies.

Keywords: autochthonous goat; carcass metrics; hierarchical cluster analysis (HCA); muscle composition; principal component analysis (PCA)

As of 2023, the global goat population exceeds one billion, playing a crucial role in agricultural systems worldwide due to the species' adaptability and the high nutritional value of its meat (FAO 2023). Goat meat consumption has been increasing steadily, particularly in Asia and Africa, which together

Financed by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia – SRO (No. 451-03-136/2025-03/200022).

https://doi.org/10.17221/53/2025-CJAS

account for over 80% of the world's goat population. In Europe, while goat meat remains a traditional product in the countries like Spain, Greece, and France, the overall consumption is lower than that of other meats. Spain, for instance, recorded the household consumption of 39 million kilograms in 2023 (Guzman et al. 2019; FAO 2023).

Goat meat consumption is influenced by cultural and geographical factors (Sacca et al. 2019). In Serbia, goat farming is primarily based on smallholder systems (Zujovic et al. 2009). In spite of growing interest, goat meat remains a niche product in both the EU and Serbia due to established consumer preferences for other meats and limited retail availability (Stanisic et al. 2012). However, indigenous goat breeds play a vital role in sustainable livestock production, contributing to biodiversity and supporting local economies. These breeds are well-adapted to their environments and exhibit desirable meat characteristics, making them valuable for regional meat production.

The Balkan goat, a native breed to the Western Balkans, is primarily raised in extensive systems and it is known for its resilience and ability to utilise low-quality forage efficiently. It is a dairy-type breed, typically characterised by a well-developed forequarter, a robust constitution, and high disease resistance, requiring minimal nutritional and management inputs (Zujovic et al. 2009; Stanisic et al. 2012). The Balkan goat has been underutilised in structured meat production despite its adaptability. Crossbreeding with improved dairy breeds, such as Saanen, has been explored as a strategy to enhance growth performance and meat yield. However, studies evaluating the impact of slaughter weight on these crossbred goats remain scarce. While dairy breeds like the Saanen typically exhibit lower muscle development compared to specialised meat breeds such as the Boer goat (Marques et al. 2013), Saanen goats are commonly used in Serbia for crossbreeding to improve the characteristics of local autochthonous breeds (Stanisic et al. 2012).

Carcass characteristics and meat quality in goats are influenced by multiple factors, including genotype (Dhanda et al. 1999; Oman et al. 2000), sex (Hogg et al. 1992; Todaro et al. 2004), diet and production system (Johnson and McGowan 1998; Marinova et al. 2001), and slaughter weight (Marichal et al. 2003). Carcass composition and slaughter weight are critical factors affecting meat quality, yield, and economic viability. Previous studies suggest that higher slaughter weights improve muscle deposition, conformation, and physicochemical properties such as intramuscular fat content and reduced cooking losses (Kadim and Mahgoub 2011). Optimal slaughter weights, which generally range between 15 and 25 kg for kids, balance muscle growth and fat deposition, ensuring desirable meat quality while avoiding excessive fat accumulation (Dhanda et al. 2003). However, ideal slaughter weight thresholds vary depending on breed and production system. While heavier animals yield more meat, excessive fat deposition may negatively impact consumer acceptance and economic efficiency. Previous research on indigenous goat breeds and their crossbreds indicates that selecting appropriate slaughter weights is crucial for optimising both meat quality and production efficiency (Marichal et al. 2003).

Although there is extensive research on commercial goat breeds, studies examining carcass composition and meat quality in Balkan goats and their crossbreds under controlled slaughter weight conditions are limited. Moreover, the relationships between carcass traits, meat quality parameters, and technological properties have not been fully elucidated. Addressing these knowledge gaps is essential for enhancing the marketability of indigenous goat meat and developing more efficient production strategies.

This study aims to evaluate the carcass composition and meat quality of Balkan goats and their F1 crossbreds with Saanen goats at different slaughter weights. By applying multivariate analysis techniques, this research aims to identify key factors influencing meat quality and categorise similar traits to provide better-informed breeding and management decisions in goat production systems.

MATERIAL AND METHODS

The experiment complied with the principles outlined in the Serbian Law 41/2009 on animal welfare and Rulebook 39/10 for the handling and protection of animals used for experimental purposes, as well as the EU Council Directives 98/58/EC and 2010/63/EU regarding the protection of farmed and experimental animals. The study was designed to minimise animal distress and suffering, and all procedures were performed in accordance with internationally recognised ethical standards for animal research.

https://doi.org/10.17221/53/2025-CJAS

This study was conducted on male goat kids raised on a commercial farm in Western Serbia (44°12'16.2''N 21°30'40.3''E). The animals belonged to two genetic groups: purebred Balkan (B) and F1 crossbred Balkan × Saanen (B × S). A total of 48 kids (n = 6 per weight group), all born as twins, were reared under identical management and feeding conditions to ensure uniformity. The experiment included four target slaughter weights: 10 kg, 15 kg, 18 kg and 22 kg. After weaning, the kids were placed in group housing systems with a space of around 0.4 m^2 indoors and 2–4 m^2 outdoors per animal. At the same time, the dairy goat flock was managed by feeding adapted to milk yield (e.g. 16–18% CP starter and hay *ad libitum* for kids; forage plus ~0.4 kg concentrate per litre of milk for dams), twice daily milking under hygienic conditions and reproduction programmes aiming at a 12-month birth interval to ensure welfare and sustainable productivity. All animals were weaned at approximately eight weeks of age and fed a standardised diet consisting of high-quality forage (lucerne hay) and a commercial concentrate mix formulated to meet their nutritional requirements. The concentrate contained 16.0% crude protein, 13.5% moisture, 8.0% fibre, 8.0% ash, 1.0% calcium, 0.5% phosphorus, 0.3% sodium, and added vitamins and minerals. Feeding was *ad libitum* and conducted in groups until slaughter.

Following the standard commercial practices, all animals were transported and slaughtered at a commercial abattoir upon reaching their designated target weights. Feed was withdrawn 12 h prior to slaughter, but water remained available. Before slaughter, animals were weighed to determine slaughter live weight (SLW). They were then electrically stunned and slaughtered following the standard commercial procedures. After skinning, evisceration, and removal of the head and legs, hot carcass weight (HCW) and the weights of offal (heart, lungs, liver, kidneys, spleen, rumen, rennet, small and large intestines), skin, head, and legs were recorded. Empty body weight (EBW) was calculated by deducting the weight of digesta. After 24 h of chilling at 4 °C, the cold carcass weight (CCW) and the weight of fat deposits (pelvic, abomasum and kidney fat) were measured. Chill loss was subsequently calculated.

After 24 h of chilling, the left half of each carcass was dissected to assess the proportions of primal cuts, including the leg, shoulder, chest with forearm, loin, neck, back, and thigh. A detailed analysis of the 9^{th} to 11^{th} rib section was performed to determine the distribution of muscle, fat, bone, and connective tissue. The shares of first-category (leg and loin), second-category (shoulder, neck, and back), and third-category (chest with forearm and thigh) cuts were calculated.

For all carcasses, the *longissimus thoracis et lumborum* (LTL) muscle was removed from the left 9^{th} to 11^{th} rib region for further analysis. Water-holding capacity (WHC) was determined following the method described by Grau et al. (1953). The pH value of meat at 24 h postmortem (pH24) was measured using a portable pH meter with a combined electrode (HI 83141; Hanna Instruments, Woonsocket, USA). Cooked meat samples (100 °C for 10 min) were used to assess the firmness, expressed as shear force, using a texture analyser (TA. XT Plus; Stable Micro System, Ltd., Godalming, UK). The texture analyses were carried out according to Hopkins et al. (2010), with slight modifications. After cooling to room temperature, meat samples were cut into 1 × 1 cm pieces along the muscle fibre direction. Each sample underwent a double compression test to 50% of its original height using a 25 mm compression platen (P/25) and a 5 kg load cell. The pre-test, test, and post-test speeds were 60 mm/min and 300 mm/min, respectively. Higher values indicated greater shear force and meat firmness.

The remaining lean LTL muscle samples were vacuum-packed and stored at –18 °C for chemical analysis, including moisture, protein, fat, and ash content, according to AOAC (2005) methods. The collagen content in muscle samples was determined spectrophotometrically by measuring hydroxyproline content and multiplying by a factor of 7.25 (Hill 1966). The total pigment content was assessed using the Hornsey method (Bunning and Hamm 1970). Additionally, muscle fibre thickness was measured using a specialised microscope equipped with a calibrated eyepiece graticule. For each muscle sample, at least 30 fibres were randomly selected and measured to obtain an average fibre diameter. This manual method aligns with established histological techniques for assessing the muscle fibre morphology, as described by Khan et al. (1981).

All statistical analyses were performed using SPSS v22 (IBM Corp., Armonk, NY, USA). Data were tested for normality and homogeneity of vari-

https://doi.org/10.17221/53/2025-CJAS

ance before analysis. A two-way analysis of variance (ANOVA) was conducted to examine the effects of slaughter weight and genotype, as well as their interaction, on carcass traits, meat composition, and technological properties. When significant differences ($P < 0.05$) were detected, post-hoc comparisons were performed using Tukey's HSD test. To explore multivariate relationships among carcass and meat quality traits, principal component analysis (PCA) was conducted. A PCA biplot was generated in SPSS v22 and adjusted in Microsoft Excel to visualise clustering patterns based on key traits such as carcass fat, muscle composition, intramuscular fat, protein content, and technological properties. Additionally, hierarchical cluster analysis (HCA) was used to group traits based on similarity within each genotype. Clustering was performed using Ward's method with squared Euclidean distance as the similarity measure. Statistical significance was set at $P < 0.05$, with highly significant effects noted at $P < 0.01$.

RESULTS

Slaughter weight significantly influenced key carcass traits (Table 1). As expected, increasing weight was associated with older slaughter age and higher empty body weight (EBW), hot carcass weight (HCW), and cold carcass weight (CCW) in both pure Balkan (B) and Balkan × Saanen (B × S) groups ($P < 0.01$). Despite these increases, HCW/EBW and CCW/EBW ratios remained stable across weight categories and breeds, suggesting a consistent carcass component distribution. Chill loss decreased with slaughter weight ($P < 0.01$) and was lower in B × S than in B kids at all weights ($P < 0.01$). Body component proportions shifted with weight: head and legs decreased ($P < 0.01$), while fat depot shares increased ($P < 0.05$). The proportions of rennet, lungs, heart, and kidneys also declined with increasing weight ($P < 0.01$), whereas the large and small intestines, rumen, stomach, liver, and spleen remained unaffected by weight or breed.

The proportions of the main half carcass parts and tissue composition of the 9–11th rib cut are shown in Table 2. The leg proportion in the half carcass increased with slaughter weight in both groups ($P < 0.01$), with the lowest values in the 10 kg group. Shoulder and chest proportions remained stable across weights. The loin share differed only in pure Balkan goats, where kids slaughtered at 18 kg had a significantly higher loin share than those slaughtered at 10 kg ($P < 0.05$). The neck proportion declined with weight in the Balkan group ($P < 0.05$). The back ($P < 0.05$) and thigh ($P < 0.01$) proportions decreased with increasing weight, particularly when comparing the 10 and 15 kg groups with those of 18 and 22 kg. A weight × breed interaction ($P < 0.01$) affected the thigh share, suggesting different trends between genotypes. First-category parts (comprising leg and loin) increased with weight in both groups ($P < 0.01$), with a significant breed × weight interaction ($P < 0.05$). Second- and third-category parts remained unchanged.

Dissection of the three-rib cut revealed that muscle and connective tissue proportions declined with weight while the fat proportion increased ($P < 0.05$). A weight × breed interaction ($P < 0.05$) indicated that the muscle proportion decreased at different rates between breeds. The fat proportion increased in both groups ($P < 0.01$), whereas the connective tissue proportion declined ($P < 0.01$). The bone proportion was not significantly affected by weight or breed.

The chemical and technological properties of the *longissimus thoracis et lumborum* (LTL) muscle (Table 3) showed that water content decreased and protein content increased with slaughter weight ($P < 0.01$), particularly between the 10 kg group and heavier weights. Fat content also increased with weight ($P < 0.01$), with B kids having a higher protein content ($P < 0.05$) and B × S kids showing a higher fat content ($P < 0.01$), alongside a significant weight × breed interaction. Pigment content increased with weight ($P < 0.01$), suggesting higher myoglobin levels in older animals. Breed significantly influenced pH24 values, with B kids having lower values than B × S ($P < 0.01$). The WHC values decreased with weight ($P < 0.01$), while B × S meat was firmer than B meat ($P < 0.05$). Muscle fibre thickness increased with weight ($P < 0.01$) but it was not breed-dependent.

The PCA biplot (Figure 1) illustrates relationships between carcass traits (EBW, carcass fat, first-category parts, fat and muscle proportions in the three-rib cut), chemical composition (intramuscular fat, protein and collagen content), and technological properties (fibre thickness, pH and WHC) of the LTL muscle. PC1 (42.92% of variance) separates heavier, fatter animals (high intramuscular fat, carcass fat, EBW) from those with higher collagen content and WHC. Traits such as intramuscular fat,

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Table 1. Age, carcass traits, and proportions of offal, skin, head, and legs in Balkan (B) and Balkan × Saanen (B × S) kids at different slaughter weights (*n* = 6 animals per breed × weight group)

Breed/weight group	B				B × S				SEM	Significance level		
	10	15	18	22	10	15	18	22		weight	breed	W × B
Carcass traits												
Age (days)	61.0[a]	82.2[b]	106[c]	138[d]	63.8[a]	78.7[b]	103[c]	129[d]	4.08	***	ns	ns
EBW (kg)	8.25[a]	12.0[b]	14.4[c]	16.6[d]	8.43[a]	12.5[b]	14.5[c]	16.5[d]	0.47	ns	ns	ns
HCW (kg)	5.13[a]	7.38[b]	8.98[c]	10.2[d]	5.09[a]	7.92[b]	8.96[c]	10.2[d]	0.30	ns	ns	ns
HCW/EBW (%)	62.0	61.6	62.3	61.6	60.6	63.1	62.0	61.7	0.36	ns	ns	ns
CCW (kg)	4.84[a]	6.99[b]	8.54[c]	9.80[d]	4.82[a]	7.61[b]	8.58[c]	9.78[d]	0.29	ns	ns	ns
CCW/EBW (%)	58.5	58.3	59.2	58.9	56.3	60.6	59.3	59.3	0.36	ns	ns	ns
Chill loss (%)	5.71[c]	5.35[bc]	4.87[ab]	4.34[a]	5.24[b]	3.93[a]	4.29[a]	3.92[a]	0.11	***	***	*
Head (% of EBW)	6.96[c]	5.93[b]	5.26[a]	5.28[a]	6.43[b]	5.84[a]	5.63[a]	5.30[a]	0.10	***	ns	ns
Legs (% of EBW)	4.93[b]	4.44[ab]	3.98[a]	3.91[a]	5.19[b]	4.19[a]	3.75[a]	3.68[a]	0.10	***	ns	ns
Skin (% of EBW)	10.4	9.87	10.2	10.2	7.86	7.53	9.80	9.51	0.29	ns	*	ns
Depot fat (% of EBW)												
Pelvic fat	0.46	0.71	0.74	0.89	0.34[a]	0.89[b]	0.48[ab]	0.96[b]	0.06	*	ns	ns
Abomasum fat	1.04	1.03	1.27	1.26	1.06[a]	1.23[a]	1.23[a]	1.55[b]	0.06	**	ns	ns
Kidney fat	0.45	0.62	0.78	0.59	0.51	0.69	0.34	0.50	0.05	ns	ns	ns
Total carcass fat	1.94	2.35	2.79	2.74	1.64[a]	2.81[b]	2.05[ab]	3.00[b]	0.12	*	ns	ns
Offal (% of EBW)												
Large intestine	2.46	2.12	2.31	2.49	2.22	2.01	2.09	2.42	0.06	ns	ns	ns
Rumen	3.20	2.79	3.07	3.14	2.84	2.85	3.12	3.02	0.08	ns	ns	ns
Small intestine	3.59	3.64	3.37	3.69	3.88	3.67	3.58	3.69	0.09	ns	ns	ns
Rennet	1.01[b]	0.86[ab]	0.72[a]	0.77[a]	1.02[b]	0.81[a]	0.82[a]	0.74[a]	0.02	**	ns	ns
Stomach	10.3	9.11	9.47	10.1	9.65	8.79	9.50	9.97	0.17	ns	ns	ns
Liver	2.82	2.92	2.70	2.78	2.84	2.92	3.06	2.79	0.05	ns	ns	ns
Lungs	2.72[b]	2.58[ab]	1.88[a]	2.08[a]	2.20[a]	2.61[b]	2.18[a]	2.18[a]	0.06	**	ns	ns
Heart	0.66[b]	0.55[a]	0.49[a]	0.50[a]	0.59[b]	0.61[b]	0.67[b]	0.52[a]	0.01	**	*	**
Spleen	0.34	0.34	0.26	0.24	0.31	0.31	0.33	0.30	0.01	ns	ns	ns
Kidneys	0.68[b]	0.59[ab]	0.55[a]	0.49[a]	0.60[b]	0.64[b]	0.56[ab]	0.47[a]	0.01	***	ns	ns

[a–d]Within a breed, the mean values in rows with different letters differ significantly at $P < 0.05$; *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

CCW = cold carcass weight; EBW = empty body weight; HCW = hot carcass weight; ns = not significant; SEM = standard error of the mean

fibre thickness, first-category parts, protein content, and EBW strongly correlate along PC1, while collagen and WHC show an inverse relationship. PC2 (11.99% of variance) differentiates animals based on pH, collagen, muscle tissue proportion (negatively correlated), and carcass traits like fat and protein content (positively correlated). Heavier B × S kids cluster toward the right, associated with greater fat and protein content, while lighter B kids are positioned toward the left, linked to higher collagen and WHC values.

Hierarchical cluster analysis (Figure 2) reveals breed-specific relationships between carcass composition and meat quality traits. In the pure Balkan group (Figure 2A), two primary clusters emerge: one linking fat-related traits (carcass fat, fat content, collagen) with slaughter weight, and the other grouping meat quality parameters (LTL muscle tissue, WHC, fibre thickness), suggesting the absence of relationship between fat deposition and meat quality. In B × S goats (Figure 2B), fat-related traits cluster closely with first-category

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Table 2. Proportions of main half carcass parts and tissue composition of the three-rib cut in Balkan (B) and Balkan × Saanen (B × S) kids at different slaughter weights (n = 6 animals per breed × weight group)

Breed/weight group	B				B × S				SEM	Significance level		
	10	15	18	22	10	15	18	22		weight	breed	W × B
Leg	23.3^{a}	26.1^{b}	27.3^{b}	27.4^{b}	24.8^{a}	29.1^{b}	27.3^{b}	27.3^{b}	0.34	**	ns	ns
Loin	9.03^{a}	9.55^{ab}	11.0^{b}	10.1^{ab}	9.08	9.80	10.1	9.76	0.17	*	ns	ns
Shoulder	18.2	20.3	20.0	20.9	20.4	19.4	22.2	21.2	0.29	ns	ns	ns
Back	10.0^{b}	9.91^{b}	8.26^{a}	8.03^{a}	9.81^{b}	9.41^{b}	7.61^{a}	7.73^{a}	0.28	*	ns	ns
Neck	10.2^{b}	7.80^{a}	7.87^{a}	9.02^{ab}	8.62	7.97	8.42	8.79	0.19	*	ns	ns
Chest with forethigh	19.6	18.2	19.5	18.6	18.2	17.1	18.7	18.2	0.29	ns	ns	ns
Second thigh	8.49^{c}	7.37^{b}	5.58^{a}	5.59^{a}	8.26^{b}	6.26^{a}	6.11^{a}	6.49^{a}	0.17	***	ns	**
By categories (%)												
First	32.4^{a}	35.7^{b}	38.3^{c}	37.5^{bc}	34.0^{a}	39.1^{b}	37.4^{b}	36.9^{b}	0.33	***	ns	*
Second	38.4	38.0	36.1	38.0	38.8	36.8	38.4	37.7	0.31	ns	ns	ns
Third	28.0	25.6	25.1	24.5	26.4	23.4	21.4	24.7	0.50	ns	ns	ns
9–11th three-rib cut												
Muscle (%)	59.2^{b}	59.8^{b}	55.2^{a}	55.2^{a}	62.2^{a}	57.6^{b}	58.1^{b}	57.1^{b}	0.87	*	ns	*
Fat (%)	7.79^{a}	11.7^{b}	16.0^{c}	16.4^{c}	5.53^{a}	11.1^{b}	11.8^{b}	16.6^{c}	0.77	**	ns	ns
Connective (%)	4.41^{c}	3.18^{b}	2.12^{a}	1.97^{a}	3.63^{b}	2.71^{ab}	2.81^{ab}	2.19^{a}	0.15	ns	ns	ns
Bones (%)	27.2	24.5	25.9	26.2	26.6	26.2	26.0	24.3	0.67	ns	ns	ns

$^{a-c}$Within a breed, the mean values in rows with different letters differ significantly at P < 0.05; *P < 0.05, **P < 0.01, ***P < 0.001

Categories: First = leg + loin; Second = shoulder + back + neck; Third = chest with forearm + thigh

ns = not significant; SEM = standard error of the mean

Table 3. Chemical and technological properties of the *longissimus thoracis et lumborum* (LTL) muscle in Balkan (B) and Balkan × Saanen (B × S) kids at different slaughter weights (n = 6 animals per breed × weight group)

Breed/weight group	B				B × S				SEM	Significance level		
	10	15	18	22	10	15	18	22		weight	breed	W × B
Chemical composition												
Water (%)	77.7^{b}	76.6^{a}	76.1^{a}	75.7^{a}	77.8^{c}	76.6^{b}	76.3^{ab}	75.3^{a}	0.16	***	ns	ns
Fat (%)	1.52^{a}	1.94^{ab}	1.78^{ab}	2.09^{b}	1.37^{a}	1.97^{a}	2.52^{b}	3.12^{b}	0.09	***	*	*
Protein (%)	19.6^{a}	20.3^{b}	21.0^{c}	21.1^{c}	19.6^{a}	20.5^{b}	20.1^{b}	20.5^{b}	0.10	***	*	*
Ash (%)	1.16	1.11	1.09	1.09	1.17	1.13	1.10	1.11	0.02	ns	ns	ns
Collagen (%)	0.40	0.39	0.36	0.35	0.40	0.40	0.34	0.37	0.01	ns	ns	ns
Pigment content (ppm)	74.3^{a}	78.1^{a}	85.9^{ab}	91.8^{b}	68.9^{a}	82.7^{b}	88.8^{bc}	95.1^{c}	1.69	***	ns	ns
Technological properties												
pH 24	5.69	5.72	5.62	5.62	5.72	5.72	5.72	5.74	0.01	ns	**	ns
WHC (cm^{2})	114^{c}	110^{bc}	102^{ab}	98.4^{a}	118^{c}	104^{b}	100^{ab}	96.5^{a}	1.25	**	ns	ns
Firmness (kg)	14.1	16.9	15.2	17.8	17.9	17.7	20.4	19.5	0.63	ns	*	ns
Fibre thickness (μm)	25.5^{a}	29.6^{a}	33.4^{b}	38.0^{b}	27.8^{a}	30.5^{b}	33.0^{b}	33.7^{b}	0.77	***	ns	ns

$^{a-c}$Within a breed, the mean values in rows with different letters differ significantly at P < 0.05; *P < 0.05, **P < 0.01, ***P < 0.001

ns = not significant; SEM = standard error of the mean; WHC = water-holding capacity

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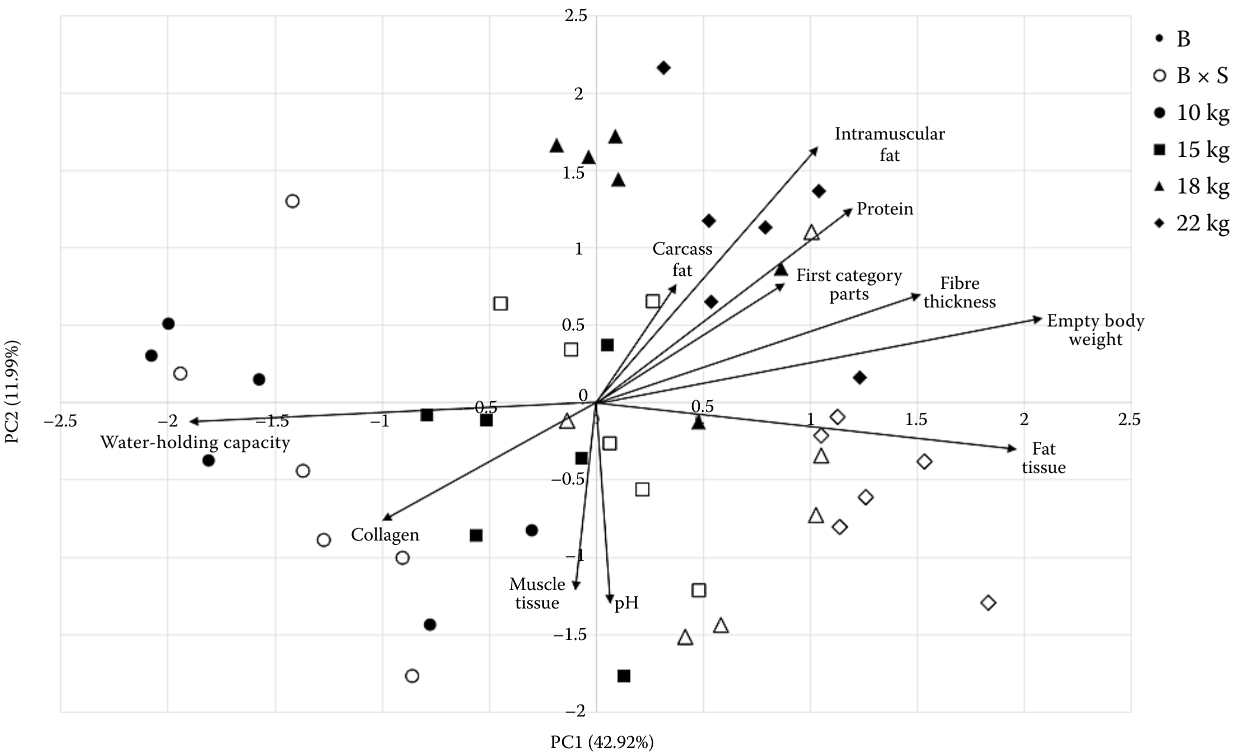

Figure 1. Principal component analysis (PCA) biplot of carcass traits, chemical composition, and technological properties of the *longissimus thoracis et lumborum* (LTL) muscle in Balkan (B) and Balkan × Saanen (B × S) kids at different slaughter weights

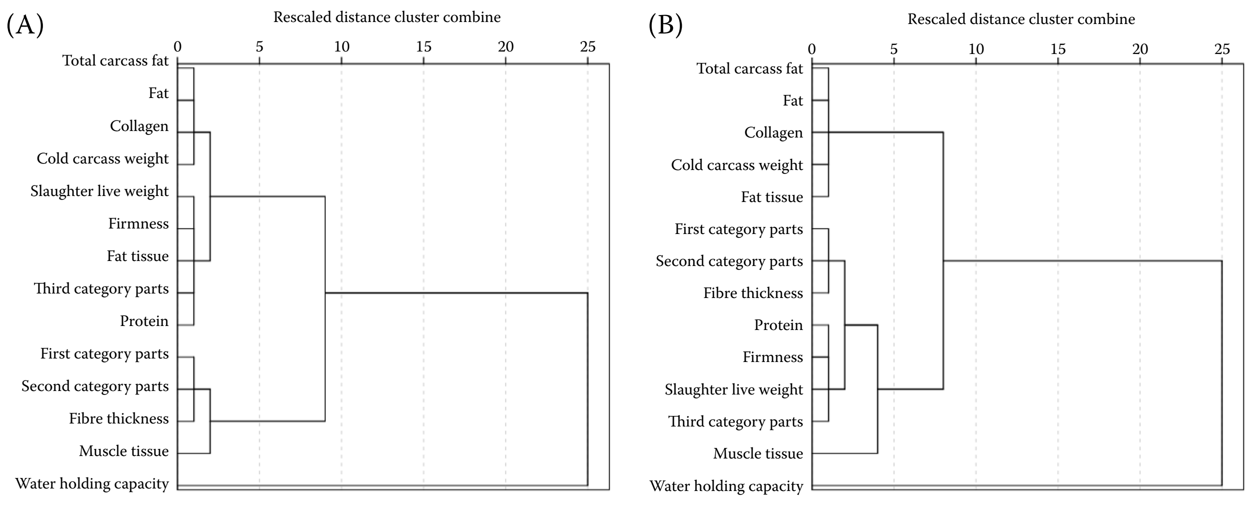

Figure 2. Hierarchical cluster analysis dendrogram of carcass and meat quality traits
(A) In pure Balkan (B) kids and (B) Balkan × Saanen (B × S) kids

parts, indicating a stronger link between carcass fat and economically valuable cuts. Protein and fibre thickness cluster separately, suggesting weaker associations with fat accumulation in crossbreds. SLW and third-category parts form a distinct cluster, highlighting differences in growth and carcass composition trends between breeds.

DISCUSSION

Finding the optimal slaughter weight is a clue to balancing meat quality and economic efficiency. Since goat kids are typically priced by hot carcass weight, dressing percentage is crucial in determining saleable yield. Studies suggest that slaughter

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weights between 15 and 25 kg are common in goat meat production, with heavier weights improving tenderness and increasing fat deposition (Kadim and Mahgoub 2011). More recently, Guerrero et al. (2018) emphasised the need to balance fat accumulation and lean tissue growth for optimal meat quality.

Our findings confirm that increasing slaughter weight significantly enhances meat yield in both genetic groups (Table 1), consistent with previous research showing a direct correlation between weight and carcass yield (Dhanda et al. 2003; Kadim and Mahgoub 2011; Stanisic et al. 2012). Notably, the HCW/EBW and CCW/EBW ratios remained stable across weight categories, indicating that the muscle distribution remains consistent regardless of the growth stage. Additionally, heavier animals showed a higher muscle proportion, supporting Marichal et al. (2003), while Balkan kids had less skin than B × S crossbreds, contradicting Dhanda et al. (2003). Increased slaughter weight was also linked to higher subcutaneous fat deposition, as reported by Kaic et al. (2012).

The interaction between breed and weight affected the chill loss significantly, which decreased as weight increased and remained lower in crossbreds (Table 1). This aligns with Guerrero et al. (2018), suggesting that crossbreeding reduces post-slaughter losses and enhances carcass quality. Since the chill loss is linked to muscle water content, its reduction can improve the cut yield (da Silva et al. 2022). However, previous studies have reported varied results, with some findings that higher slaughter weights improve primal cut yields and physicochemical properties (Mioc et al. 2001; Tshabalala et al. 2003).

Table 2 shows that increasing slaughter weight significantly alters the carcass part distribution in both Balkan and Balkan × Saanen kids. The proportion of legs increased beyond 10 kg in both groups, suggesting that heavier animals allocate more growth to this high-value cut. Conversely, back and neck percentages declined with weight, possibly reflecting a shift toward more economically valuable sections. Notably, the shoulder proportion remained stable, indicating a minimum influence from overall weight gain. The thigh percentage decreased with weight, with a significant weight × breed interaction highlighting genetic differences in muscle and fat deposition. Additionally, the increase in first-category cuts (leg and loin) varied between genotypes, suggesting the potential for genetic selection to enhance the primal cut yield (Santos et al. 2015; Teixeira et al. 2024).

The 9–11th rib section is widely used in cattle to estimate the carcass composition due to its ease of acquisition and predictive accuracy (Paulino et al. 2005; Fernandes et al. 2008). Though primarily applied in bovines, it has also been validated for assessing the overall body composition in small ruminants (Teixeira et al. 2024). Tissue analysis of the three-rib cut revealed that muscle and connective tissue proportions declined with increasing slaughter weight while fat increased in both groups (Table 2). A significant interaction for the muscle proportion suggests a breed-specific difference in muscle decline rates. This trend aligns with studies showing that heavier animals accumulate fat at the expense of lean tissue (Dhanda et al. 2003; Kadim and Mahgoub 2011). However, the absence of breed effect contradicts findings by Sen et al. (2004) and Kadim and Mahgoub (2011), who reported enhanced muscle growth efficiency in crossbreds.

The observed changes in the *longissimus thoracis et lumborum* (LTL) muscle highlight the effects of growth and crossbreeding on meat quality (Table 3). As slaughter weight increased, water and protein content decreased, while fat content rose, which is consistent with previous findings in small ruminants, where maturation leads to intramuscular fat deposition and muscle composition shifts (Dhanda et al. 2003; Kadim and Mahgoub 2011; Santos et al. 2015; Janos et al. 2023). The higher protein content in pure Balkan kids suggests a genetic predisposition to lean muscle growth, whereas the elevated fat in crossbreds reflects dairy genetics favouring the fat deposition (Ekiz et al. 2012). This aligns with studies reporting improved sensory attributes, including juiciness and flavour, in the meat from crossbreds due to higher intramuscular fat content (Atti et al. 2004). Greater fat marbling, often linked to improved sensory attributes, was more prominent in crossbreds (Brzostowski et al. 2008). Previous studies also reported that crossing local goats with commercial or dairy breeds enhances growth and tenderness but leads to higher fat deposition (Atti et al. 2004). The significant weight × breed interactions indicate that the genetic background modulates the impact of growth on the LTL muscle composition, reinforcing the role of selective breeding in optimising meat traits.

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Maturity-related increases in pigment content and muscle fibre thickness (Table 3) indicate greater myoglobin accumulation, leading to a darker meat colour and potentially affecting the overall meat quality. In contrast, lighter-weight goats have the lower total pigment content, resulting in a paler, more pinkish appearance of meat, which is often preferred by consumers (Mancini and Hunt 2005). Additionally, the decline in WHC values with weight has practical implications, as the reduced moisture retention can affect juiciness and processing yield. WHC is a key determinant of meat quality in goat kids (Marichal et al. 2003), with muscle fibre structure playing a significant role (Hoffman et al. 2003).

Tenderness is a major factor in consumer preference, and the perceived toughness of goat meat often limits its appeal (Webb et al. 2005). The meat from crossbreds was firmer in this study, likely due to differences in the LTL muscle fibre composition and connective tissue properties. Despite the well-known influence of collagen on firmness (Starkey 2017), its content remained unchanged across weight and breed groups (Table 3), likely due to the animals' young age, as collagen crosslinking increases with maturity (Therkildsen et al. 2002).

Principal component analysis (PCA) results highlight carcass weight and fat deposition as primary determinants of meat quality, aligning with prior studies on goat meat variability (Dhanda et al. 2003; Webb et al. 2005). The biplot (Figure 1) illustrates distinct trait patterns, complementing ANOVA findings and providing practical insights for breeding and production strategies. PC1, explaining the largest variance, separates leaner animals (lower scores, left side) from those with higher fat and LTL muscle fibre thickness (higher scores, right side). Lighter goats, particularly those slaughtered at 10 kg, exhibit a greater muscle proportion, collagen content, and lower water-holding capacity (higher WHC values), aligning with findings that younger animals have leaner carcasses (Kadim and Mahgoub 2011).

In contrast, heavier goats, particularly crossbreds, display higher slaughter weight, carcass fat, intramuscular fat, protein, and primal cuts (leg and loin), consistent with studies reporting the increased fat accumulation at higher slaughter weights (Marichal et al. 2003). This clustering underscores the trade-off between fat deposition and technological properties such as WHC, which affects meat processing and juiciness (Therkildsen et al. 2002; Paulino et al. 2005). PC2, which explains additional 11.99% of the variance, differentiates animals by pH and the balance between muscle and fat deposition. Notably, 18 kg and 22 kg goats shift positions depending on breed: Balkan goats cluster leftward at 18 kg, while at 22 kg, they shift right, opposite to F1 crossbreds. This pattern reflects a breed-dependent response to growth, consistent with ANOVA results showing interaction effects on protein and fat content (Table 3) and previous research on indigenous and hybrid goats (Stanisic et al. 2012).

The cluster analysis (Figure 2) further supports these patterns, revealing breed-specific differences in carcass composition and meat quality. In purebred Balkan goats, total carcass fat, collagen, and cold carcass weight (CCW) form a strong cluster, suggesting a close correlation between fat accumulation and carcass weight (Webb et al. 2005). The clustering of protein, fibre thickness, muscle tissue, and WHC in a separate group highlights the breed's tendency of leaner growth (Kadim and Mahgoub 2011; Stanisic et al. 2012). In F1 crossbreds, carcass fat and collagen remain linked but they are more closely associated with CCW and primal cuts (leg and loin), indicating a stronger relationship between fat distribution and valuable meat portions. The clustering of protein and fibre thickness separately from fat-related traits suggests that the crossbreds maintain a more balanced distribution of muscle and fat, consistent with studies on hybrid goats (Atti et al. 2004; Kadim and Mahgoub 2011).

Overall, the ANOVA, PCA and HCA results in this study underscore the importance of optimising slaughter weight and breed selection to achieve desirable carcass composition and meat quality. Heavier animals, particularly F1 crossbreds, yield more intramuscular fat and primal cuts, such as the leg and loin, making them suitable for markets that prioritise marbling and tenderness. However, this comes at the cost of accumulating more carcass fat, which may affect processing efficiency (Dhanda et al. 2003; Kadim and Mahgoub 2011). In contrast, purebred Balkan goats produce leaner carcasses with higher WHC values, complying with consumer preferences for low-fat, high-protein meat. The significant interaction between weight and breed highlights the role of the genetic background in tissue development. Balkan goats tend to increase fat deposition at higher weights, whereas F1 cross-

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breds exhibit a more balanced muscle-fat distribution. The reduction in non-carcass components, such as the head and legs, with increasing slaughter weight enhances economic returns by maximising the edible meat yield (Marques et al. 2013).

These insights suggest that producers targeting high-quality lean meat should prioritise lighter Balkan goats. At the same time, those seeking higher yields and improved fat distribution may benefit from crossbreeding with Saanen goats. Future research should explore the physiological mechanisms driving these differences, assess long-term crossbreeding benefits, and evaluate consumer preferences for various carcass traits in various production systems to refine breeding and management strategies.

CONCLUSION

This study provides valuable insights into how slaughter weight and breed influence carcass composition and meat quality in indigenous goats. The results indicate that heavier animals, particularly F1 crossbreds, yield higher intramuscular fat and primal cuts like the leg and loin. In contrast, lighter Balkan goats produce leaner carcasses, providing consumers with a high-protein, low-fat diet. Additionally, their meat has the lower total pigment content, resulting in a paler, more pinkish appearance, which consumers often prefer. However, their reduced water-holding capacity could underscore the processing characteristics, potentially affecting texture and yield during meat processing.

The observed differences between breeds suggest that crossbreeding of Balkan goats can enhance carcass yield and fat distribution, but careful weight management is necessary to maintain desirable meat quality traits. The observed weight × breed interactions highlight the need for strategic breeding and slaughter weight management to balance yield, quality, and consumer preference – whether for leaner meat or higher marbling and economic returns.

Future research should focus on the underlying physiological mechanisms driving these variations and explore long-term crossbreeding effects under different production systems and feeding strategies to optimise meat quality. Additionally, consumer preference studies could help refine production strategies to align with market trends and demand.

Conflict of interest

The authors declare no conflict of interest.

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Received: April 15, 2025
Accepted: September 16, 2025
Published online: October 29, 2025