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Influence of Breed, Age, and Feeding Regimes on Meat Quality, Amino Acid Profile, and Sensory Attributes of Different Sheep Breed

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ABSTRACT

This study analyzed the effect of breed, age and feeding regimes on the meat quality, carcass traits, amino acid profiles and sensory attributes of Waziristan sheep. Three breeds (Waziri, Balkhi and Mazai) were evaluated under four different feeding regimes (grazing, and grazing with different amount of concentrate (150, 350 and 700g). in both hogget and adult age groups. It was observed that the Waziri breed evidently surpassed the other breeds. The highest quantities of crude protein (31.40 ± 0.11%) and lean meat (67.48 ± 0.67%) with a significant level of essential aminos and lysines, methionine and phenylalanine particularly were attained in grazing +350 g concentrate feeding regime, especially for the Waziri hoggets. Sensory evaluation results indicated better scoring for tenderness (7.80 ± 0.09), juiciness (7.60 ± 0.60), and flavor (7.50 ± 0.80) of meat from grazing +350 g concentrate fed shanks. On the contrary, the Mazai breed had the least encouraging results with lower sensory scores with less amino acid profiles and less crude protein content. Fat content was highest in Balkhi adults under grazing +700 g concentrate feeding regime (16.90 ± 0.41%), while Waziri hoggets maintained balanced fat levels. In overall terms, these results emphasize genetic potential of the Waziri breed particularly the hoggets under grazing +350 g concentrate feeding regime for production of premium mutton. These findings underscore the importance of tailored feeding strategies to optimize meat quality in indigenous sheep breeds.

INTRODUCTION

In developing countries, livestock farming plays a vital role in rural areas, providing essential sources of income, food, and social security (Kumar *et al*., 2021). Among livestock species, sheep hold particular importance due to their adaptability to various environmental conditions, especially in dry sub-humid and semi-arid regions where agriculture faces challenges from climate change. North Waziristan, an arid and mountainous area, is home to several indigenous sheep breeds that are crucial to local communities. These breeds exhibit unique physical, productive, and reproductive traits shaped by specific farming practices and distinct agro-ecological zones.

Several factors influence the production performance of local sheep breeds, including vegetation, temperature, and annual rainfall (Ahmad *et al*., 2023). The farming systems in this region can be categorized into extensive, semi-intensive, and intensive systems, each with its own advantages and limitations. Extensive systems primarily rely on grazing, while intensive systems involve controlled feeding. Semi-intensive systems combine grazing with supplementary feeding. Understanding how these systems function across different agro-ecological zones is crucial for improving sheep production (Ullah *et al*., 2019). The key sheep breeds in North Waziristan include Waziri, Mazai, and Balkhi, each characterized by unique phenotypic and genotypic traits that ensure their survival in harsh environments (Khan *et al*., 2022). This study aims to compare the carcass traits, amino acid profiles, proximate composition, and sensory attributes of mutton from these

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breeds, which has not been previously reported. The findings are expected to facilitate the development of age-specific interventions for sustainable farming practices and enhance the market value of mutton, thereby contributing to the economic well-being of local communities.

MATERIALS AND METHODS

This study was conducted in north waiziristan, khyber pukhtunkhwa, Pakistan (20° 30′20″ S, 54° 37′06″ W) according to the institutional committee on animal use (case number 12/FAHVS/2021).

Species and breed selection

A total of 96 sheep belonging to Balkhi, Waziri and Mazai sheep were selected and managed under unified feeding and farming regime. They were further divided into four feeding groups and subcatergerized into two groups based on age (one group consisted of hogget male lambed age 6-8 months and another group contained adult male rams age between 1-2 years). The feeding system comprised of four types: grazing of 8-10h on daily basis with no concentrate; grazing (8-10h) with Light Supplementation (150g; grazing (8-10h) with moderate supplementation (350g); grazing (8-10h) with high supplementation (700g). The concentrate was consisted of 16% crude protein and 11.2 MJ/kg of metabolizable energy (ME). The feeding period consisted of three months (excluding 14 days of adaptation period) to assess the effect of breed, age and nutritional composition on meat quality characteristics as follow:

Physical parameters

After the conclusion of the feeding system, the sheep were safely transported to the local slaughterhouse, where animals were allowed a resting period of 24 h. During this time, they were provided with green fodder and had free access to drinking water.

Antemortem inspection and empty stomach weight

With the help of a government veterinary officer antemortem inspections was conducted to ensure the health of all sheep. Following inspection, the sheep were subjected to a 12-h fasting period. Empty stomach weights (ESW) of the sheep were recorded individually using a Mars digital electronic balance with an accuracy of ±1.00 g. The sheep were thoroughly washed to remove dirt, debris, and excess hair before slaughter.

Slaughtering and postmortem examination

Post-slaughter, carcasses were inspected to detect any signs of disease, tissue abnormalities, or lymphatic swelling. After clearance, the hot carcass weights were recorded individually. The carcasses were then transferred to cold storage at 0 °C for further analysis. Skin was removed 10 min post-slaughter and weighed. The dressing percentage was determined using the formula: (hot carcass weight ÷ live weight) × 100.

Determination of bone lean meat and fat percentages

Bones were separated, weighed digitally, and calculated as:

Bone percentage = (bone weight ÷ carcass weight) × 100

Lean meat yield was determined by the following formula

Lean meat weight= (lean meat % ÷ 100) × carcass weight

The fat percentage from the sheep carcass was determined by weighing the separated fat deposits (subcutaneous, intermuscular, and abdominal) and expressing it as a percentage of the total carcass weight.

Amino acids analysis via gas chromatography

Mutton from three sheep breeds under four diets in Waziristan was analyzed for amino acids via GC-MS. Samples were iced during transport to PCSIR Karachi. Extraction with 0.1 MHCl used stomacher and mixer mill methods. Extracts were deproteinized, dried under nitrogen, derivatized with MTBSTFA at 100°C, and analyzed within 24 h using GCMS-QP2010 SE with an HP-5 column (170–325 °C over 55.75 min). Amino acids were identified by retention time and m/z ions, quantified via calibration (R^2 = 0.9999), and reported as µg/100 g dry weight.

Nutritive profile of meat

The proximate analysis of mutton, conducted using AOAC (2005) methods, evaluates its nutritional value by determining moisture content, crude protein, fat, and ash. Moisture indicates water content, crude protein reflects nutritional quality, fat contributes to energy and flavor, and ash represents mineral content. This analysis ensures quality and dietary compliance.

Sensory evaluation

A total of 720 mutton samples from three sheep breeds (hogget and adult) under four feeding treatments were evaluated. Ten trained panelists (aged 30–50) from The University of Agriculture Peshawar assessed 72 grilled samples each using a 9-point hedonic scale. Sessions were conducted individually at 10:30 am in a controlled environment. Panelists cleansed their palate between samples with water, apple juice, and crackers, ensuring unbiased, reliable sensory data.

Statistical analysis

The following general linear model (GLM) was used to analyze the sensory attributes (tenderness, juiciness, flavor, aroma, color, and overall liking) of mutton:

$Y_{ijkm} = \mu + B_i + T_j + A_k + (B \times T)_{ij} + (B \times A)_{ik} + (T \times A)_{jk} + (B \times T \times A)_{ijk} + \varepsilon_{ijkm}$

Where; Y_{ijkm} is observed value of the sensory attribute for the m-th replicate within the i-th breed (B), j-th treatment (T), and k-th age group (A); μ is overall mean of the sensory attribute; B_i is fixed effect of the i-th breed (i = Balkhi, Mazai, Waziri); T_j is fixed effect of the j-th treatment (j = grazing, grazing + 150 g concentrate, grazing + 350 g concentrate, grazing + 700 g concentrate); A_k is fixed effect of the k-th age group (k = hogget, adult); $(B \times T)_{ij}$ is interaction effect between breed and treatment; $(B \times A)_{ik}$ is interaction effect between breed and age; $(T \times A)_{jk}$ is interaction effect between treatment and age; $(B \times T \times A)_{ijk}$ is three-way interaction effect between breed, treatment, and age, and ε_{ijkm} is random error term, assumed to be independently and identically distributed, with $\varepsilon_{ijkm} \sim N(0, \sigma^2)$.

The response variable (Y_{ijkm}) follows a normal distribution. Homogeneity of variance was tested using Levene's test and confirmed before applying the model. Independence of observations was assumed, ensuring that replicates within treatments were randomized to minimize bias. The experimental unit for treatment allocation was an individual animal, as sensory evaluation was performed separately for each animal. The GLM was fitted using the statistical software SPSS (Version 17) or SAS (Version 3.5). ANOVA was used to determine the significance of the fixed effects (B_i, T_j, A_k) and their interactions. Post-hoc pairwise comparisons (e.g., Tukey's HSD) were performed to identify significant differences between levels of fixed factors. Residual diagnostics, including normality and homoscedasticity checks, were conducted to validate the model's assumptions. Results are presented as least squares means (LSMeans) with their corresponding standard errors (SE).

RESULTS

The results of the study (Table I) show significant variations in essential amino acid profiles of mutton across breeds, ages, and feeding regimes. Among the breeds, Waziri sheep exhibited the highest total amino acid content in both hogget (33.65±0.32) and adult (31.75±0.50) groups, particularly under grazing+350g concentrate feeding regime, with notable levels of arginine, leucine, and valine ($P < 0.02$). Balkhi sheep, although lower in total amino acids than Waziri, also demonstrated favorable amino acid profiles under grazing +350 g concentrate feeding regime, especially in Hogget mutton (31.21±0.56).

Mazai sheep had the lowest amino acid concentrations, with total amino acid content ranging from 20.00±0.65 to 25.22±1.98, depending on the treatment. Hogget mutton consistently showed higher amino acid values than Adult mutton across all treatments and breeds ($P < 0.03$). Treatments influenced specific amino acids significantly, with grazing+350 g concentrate feeding regime, yielding the highest concentrations of essential amino acids such as lysine, methionine, and phenylalanine across all breeds.

Age also significantly affected certain amino acids, such as arginine and leucine ($P < 0.03$), with hogget mutton generally outperforming adult mutton. Interactions between breed, age, and treatment were significant for some parameters, highlighting the combined influence of genetic and environmental factors on mutton quality.

The analysis of the non-essential amino acid profile of mutton revealed significant variations influenced by breed, age, and feeding regime (Table II). Among the amino acids analyzed, serine, glycine, and cysteine showed significant treatment effects ($P < 0.02$), whereas alanine, aspartic acid, glutamine, and proline concentrations were not significantly affected ($P > 0.05$). Breed-wise differences were significant ($P < 0.05$) for cysteine, alanine, aspartic acid, glutamine, glycine, and serine across all feeding regimes, with Waziri sheep generally demonstrating higher levels of these amino acids compared to Balkhi and Mazai breeds. Proline, however, showed no significant breed-specific variations ($P > 0.05$). Age-specific trends indicated that hoggets consistently had higher total non-essential amino acid concentrations compared to adults across all breeds and treatments. Among feeding regimes, grazing +350 g concentrate feeding regime yielded the highest amino acid concentrations for all breeds, particularly in hoggets. In Balkhi sheep, the highest total non-essential amino acid content (18.48±0.43 g/100g) was observed in hoggets under the grazing+350 g concentrate feeding regime regime, while the lowest (13.41±0.37 g/100g) was recorded in adults under grazing+700 g concentrate feeding regime. Similarly, Mazai sheep exhibited elevated amino acid profiles in hoggets fed on grazing+350 g concentrate feeding regime (16.93±0.21 g/100g), with lower levels observed in adults under grazing+700 g concentrate feeding regime. Waziri sheep demonstrated the best amino acid profile overall, with hoggets in grazing+350 g concentrate feeding regime recording the highest total amino acid content (18.70±0.53 g/100g), followed by adults in T3 (17.10±0.40 g/100g).

Serine, glycine, and cysteine were particularly responsive to dietary treatments, showing significantly higher levels under grazing+350 g concentrate feeding

Table I. Effect of breed, age and different feeding regime on essential amino acids of mutton.

Breed/ Amino acids	Hogget				Adult				P1 value feeding	P2 value breed	P3 value age
	Grazing	Grazing + Concentrate			Grazing	Grazing + Concentrate					
		150 g	350g	700g		150 g	350g	700g			
Balkhi											
Arg	$4.50^{b}\pm0.21$	$4.49^{bc}\pm0.32$	$4.70^{ab}\pm0.24$	$4.30^{c}\pm0.11$	$4.40^{bc}\pm0.23$	$4.32^{c}\pm0.36$	$4.40^{bc}\pm0.21$	$4.00^{d}\pm0.17$	P<0.03	P<0.02	P<0.03
Leucine	$5.40^{bc}\pm0.27$	$5.40^{bc}\pm0.12$	$5.70^{ab}\pm0.19$	$5.40^{bc}\pm1.23$	$5.30^{c}\pm0.21$	$5.20^{cd}\pm0.10$	$5.50^{b}\pm0.12$	$5.40^{bc}\pm1.21$	P<0.03	P<0.02	P<0.03
Ile	$2.90^{bc}\pm0.12$	$3.10^{ab}\pm0.15$	$3.20^{a}\pm0.76$	$3.00^{b}\pm0.87$	$2.70^{c}\pm0.11$	$2.90^{bc}\pm0.13$	$3.10^{ab}\pm0.74$	$3.00^{b}\pm0.81$	NS	NS	P<0.05
Thr	$2.10^{cd}\pm0.32$	$2.20^{c}\pm0.45$	$2.80^{a}\pm1.32$	$1.90^{d}\pm1.54$	$2.00^{cd}\pm0.12$	$2.10^{cd}\pm0.35$	$2.30^{bc}\pm1.12$	$1.80^{d}\pm1.44$	NS	NS	NS
Met	$2.30^{cd}\pm0.23$	$2.20^{d}\pm0.00$	$2.50^{bc}\pm0.56$	$2.00^{e}\pm0.87$	$2.20^{d}\pm0.21$	$2.20^{d}\pm0.02$	$2.30^{cd}\pm0.53$	$2.00^{e}\pm0.81$	NS	P<0.02	NS
Lys	$3.91^{c}\pm 0.43$	$4.11^{bc}\pm1.33$	$4.31^{b}\pm1.54$	$4.01^{bc}\pm1.93$	$3.81^{cd}\pm 0.43$	$3.71^{cd}\pm1.31$	$4.00^{bc}\pm1.53$	$3.91^{c}\pm1.90$	P<0.04	P<0.02	P<0.04
His	$2.10^{cd}\pm0.84$	$2.00^{d}\pm0.81$	$2.30^{bc}\pm0.43$	$2.00^{d}\pm0.44$	$2.10^{cd}\pm0.82$	$2.10^{cd}\pm0.82$	$2.20^{c}\pm0.45$	$2.00^{d}\pm0.40$	NS	P<0.03	NS
Val	$3.30^{cd}\pm1.32$	$3.30^{cd}\pm0.33$	$3.60^{b}\pm0.55$	$3.00^{e}\pm1.32$	$3.20^{d}\pm1.32$	$3.20^{d}\pm0.33$	$3.40^{c}\pm0.55$	$3.00^{e}\pm1.32$	NS	NS	P<0.03
Phe	$2.90^{bc}\pm1.10$	$3.00^{b}\pm0.32$	$3.50^{a}\pm0.43$	$3.00^{b}\pm0.54$	$2.60^{cd}\pm1.11$	$2.80^{bc}\pm0.31$	$3.00^{b}\pm0.41$	$3.00^{b}\pm0.52$	NS	P<0.02	P<0.02
Total	$29.31^{c}\pm0.21$	$29.50^{c}\pm1.33$	$31.21^{b}\pm0.56$	$28.41^{cd}\pm1.00$	$28.31^{cd}\pm0.21$	$28.53^{cd}\pm1.33$	$30.21^{bc}\pm0.60$	$28.11^{d}\pm1.00$			
Mazai											
Arg	$1.30^{hi}\pm0.21$	$1.21^{i}\pm0.11$	$1.60^{g}\pm0.76$	$1.50^{gh}\pm0.66$	$1.33^{hi}\pm0.26$	$1.42^{h}\pm0.12$	$1.50^{gh}\pm0.70$	$1.00^{j}\pm0.63$	P<0.05	P<0.02	P<0.03
Leu	$4.50^{de}\pm1.02$	$4.50^{de}\pm0.24$	$4.60^{d}\pm0.34$	$4.30^{ef}\pm1.09$	$4.40^{e}\pm1.01$	$4.40^{e}\pm0.24$	$4.50^{de}\pm0.21$	$4.30^{ef}\pm1.05$	P<0.03	P<0.02	P<0.03
Ile	$2.50^{d}\pm0.83$	$2.40^{de}\pm0.44$	$2.60^{cd}\pm0.46$	$2.30^{e}\pm1.05$	$2.40^{de}\pm0.82$	$2.40^{de}\pm0.42$	$2.50^{d}\pm0.42$	$2.00^{f}\pm1.00$	NS	NS	P<0.05
Thr	$1.90^{d}\pm1.92$	$2.10^{cd}\pm1.93$	$2.40^{bc}\pm0.32$	$1.80^{d}\pm1.76$	$1.90^{d}\pm1.90$	$2.00^{cd}\pm1.91$	$2.30^{bc}\pm0.31$	$1.70^{dc}\pm1.72$	NS	NS	NS
Met	$2.10^{de}\pm0.44$	$1.90^{ef}\pm0.54$	$2.30^{cd}\pm0.93$	$1.70^{f}\pm0.43$	$2.00^{e}\pm0.41$	$1.90^{ef}\pm0.52$	$2.20^{d}\pm0.91$	$1.60^{fg}\pm0.43$	NS	P<0.02	NS
Lys	$3.41^{de}\pm0.33$	$3.51^{d}\pm0.54$	$3.90^{c}\pm0.34$	$3.00^{e}\pm1.03$	$3.31^{de}\pm0.30$	$3.41^{de}\pm0.51$	$3.80^{cd}\pm0.30$	$3.00^{e}\pm1.00$	P<0.04	P<0.02	P<0.04
His	$1.60^{f}\pm0.65$	$1.80^{e}\pm0.45$	$2.00^{d}\pm0.77$	$1.60^{f}\pm0.54$	$1.60^{f}\pm0.54$	$1.70^{ef}\pm0.33$	$1.90^{de}\pm0.72$	$1.60^{f}\pm0.50$	NS	P<0.03	NS
Val	$3.00^{e}\pm0.04$	$3.10^{de}\pm0.45$	$3.50^{bc}\pm0.43$	$3.00^{e}\pm0.54$	$3.00^{e}\pm0.04$	3.00 ± 0.45	$3.30^{cd}\pm0.43$	$3.00^{e}\pm0.54$	NS	NS	P<0.03
Phe	$2.80^{bc}\pm0.54$	$2.90^{bc}\pm0.67$	$3.30^{ab}\pm0.56$	$2.70^{c}\pm0.77$	$2.70^{c}\pm0.53$	$2.80^{bc}\pm0.62$	$3.00^{b}\pm0.54$	$2.60^{cd}\pm0.74$	NS	P<0.02	P<0.02
Total	$23.01^{f}\pm0.76$	$23.22^{f}\pm0.98$	$25.22^{e}\pm1.98$	$20.00^{g}\pm0.65$	$22.54^{fg}\pm0.76$	$23.02^{f}\pm0.98$	$25.90^{e}\pm1.90$	$20.80^{g}\pm0.65$			
Waziri											
Arg	$4.00^{d}\pm0.43$	$4.31^{c}\pm0.23$	$4.85^{a}\pm0.43$	$3.33^{e}\pm0.91$	$4.11^{cd}\pm0.25$	$4.21^{cd}\pm0.27$	$4.50^{b}\pm0.30$	$3.03^{f}\pm0.71$	P<0.01	P<0.02	P<0.03
Leu	$5.80^{a}\pm0.23$	$5.60^{ab}\pm0.90$	$5.80^{a}\pm0.23$	$5.30^{cd}\pm0.43$	$5.30^{c}\pm0.84$	$5.50^{b}\pm0.30$	$5.60^{ab}\pm0.13$	$5.30^{cd}\pm0.23$	P<0.02	P<0.02	P<0.03
Ile	$3.30^{a}\pm0.22$	$3.10^{ab}\pm0.33$	$3.30^{a}\pm0.22$	$3.10^{ab}\pm0.36$	$3.00^{b}\pm0.32$	$3.10^{ab}\pm0.31$	$3.20^{ab}\pm0.21$	$3.00^{b}\pm0.31$	NS	NS	P<0.05
Thr	$2.50^{b}\pm0.32$	$2.20^{c}\pm0.93$	$2.50^{b}\pm0.32$	$2.00^{cd}\pm0.23$	$2.20^{c}\pm0.90$	$2.10^{cd}\pm0.91$	$2.30^{bc}\pm0.31$	$2.20^{c}\pm0.20$	NS	NS	NS
Met	$2.80^{a}\pm0.87$	$2.40^{c}\pm1.00$	$2.80^{a}\pm0.87$	$2.10^{de}\pm0.66$	$2.30^{cd}\pm0.31$	$2.30^{cd}\pm1.01$	$2.60^{b}\pm0.83$	$2.10^{de}\pm0.61$	NS	P<0.02	NS
Lys	$4.90^{a}\pm0.34$	$4.30^{b}\pm1.11$	$4.90^{a}\pm0.34$	$4.00^{bc}\pm0.45$	$4.00^{bc}\pm1.06$	$4.20^{bc}\pm1.11$	$4.30^{b}\pm0.32$	$4.00^{bc}\pm0.40$	P<0.01	P<0.02	P<0.04
His	$2.60^{a}\pm0.65$	$2.30^{bc}\pm0.56$	$2.60^{a}\pm0.65$	$2.00^{d}\pm0.56$	$2.30^{bc}\pm0.53$	$2.10^{cd}\pm0.51$	$2.40^{b}\pm0.60$	$2.00^{d}\pm0.50$	NS	P<0.03	NS
Val	$3.80^{a}\pm0.76$	$3.50^{bc}\pm0.66$	$3.80^{a}\pm0.76$	$3.10^{de}\pm0.54$	$3.40^{c}\pm0.54$	$3.50^{bc}\pm0.66$	$3.60^{b}\pm0.76$	$3.10^{de}\pm0.54$	NS	NS	P<0.03
Phe	$3.50^{a}\pm0.54$	$3.20^{ab}\pm0.44$	$3.50^{a}\pm0.54$	$3.00^{b}\pm0.56$	$3.00^{b}\pm0.54$	$3.10^{ab}\pm0.44$	$3.20^{ab}\pm0.51$	$2.90^{bc}\pm0.52$	NS	P<0.02	P<0.02
Total	$33.65^{a}\pm0.32$	$30.51^{bc}\pm0.56$	$33.65^{a}\pm0.32$	$27.93^{d}\pm0.31$	$29.61^{c}\pm0.32$	$30.11^{bc}\pm0.56$	$31.75^{b}\pm0.50$	$27.63^{d}\pm0.31$			

The first P1-value show treatment effect on essential amino acid profile which was significant *** for Arginine (Arg), Leucine (Len) and Lysine (Lys) in all feeding systems for all sheep breed. While non-significant P>0.05. Isoleucine (Ile), Threonine (Thr), Methionine (Met), Histidine (His), Valine (Val) and Phenylalanine (Phe) in all feeding systems, 2nd P value showed the effect of breed which was significant *** for Arginine (Arg), Leucine, Lysine (Lys), Methionine (Met), Histidine (His) and Phe in all feeding regime while non-significant P>0.05 for Isoleucine (Ile), Thr and Val in all feeding system. 3rd P-value show age effect which was significant *** for Arg, Leu, Lys, Met, His and Phe in all feeding regime while non-significant P>0.05 for Ile, Val and Thr. [a,b,c,d] Means within rows with different superscripts are significantly different.

Table II. Effect of breed, age and different feeding regime on non-essential amino acid of mutton.

Breed/ Amino acids	Hogget				Adult				P1-value feed-ing	P2-value breed	P3 value age
	Grazing	Grazing + Concentrate			Grazing	Grazing + Concentrate					
		150 g	350g	700g		150 g	350g	700g			
Balkhi											
Ala	4.30^{c}±0.32	4.32^{c}±0.40	4.40^{bc}±0.21	4.00^{d}±0.33	4.00^{d}±0.11	4.11^{cd}±0.21	4.32^{c}±0.33	3.87^{de}±0.10	NS	P<0.05	P<0.03
Asn	1.81^{bc}±0.21	1.88^{bc}±0.23	1.90^{b}±0.11	1.13^{gh}±1.11	1.70^{de}±0.31	1.74^{cd}±0.03	1.80^{bc}±0.21	1.12^{gh}±1.41	NS	P<0.05	P<0.03
Gla	2.30^{bc}±1.21	2.41^{bc}±0.23	2.60^{ab}±0.55	2.00^{cd}±0.37	2.00^{cd}±1.10	2.11^{c}±0.13	2.30^{bc}±0.50	2.00^{cd}±0.30	NS	P<0.05	P<0.05
Gly	1.90^{cd}±1.22	2.00^{cd}±0.65	2.20^{ab}±0.34	1.30^{ef}±0.28	1.80^{cd}±1.11	2.00^{cd}±0.15	2.10^{b}±0.14	1.20^{f}±0.11	P<0.04	P<0.05	NS
Pro	0.70^{b}±0.21	0.81^{ab}±0.31	0.85^{ab}±0.65	0.10^{e}±0.32	0.60^{bc}±0.11	0.68^{bc}±0.11	0.70^{b}±0.45	0.10^{e}±0.31	NS	NS	NS
Cys	0.41^{cd}±0.23	0.47^{bc}±0.55	0.57^{ab}±0.86	0.16^{e}±0.45	0.40^{cd}±0.13	0.43^{c}±0.15	0.54^{ab}±0.80	0.15^{ef}±0.05	P<0.05	P<0.01	P<0.04
Ser	1.72^{d}±0.22	1.79^{bc}±0.88	1.80^{bc}±1.44	1.31^{gh}±0.55	1.70^{de}±0.52	1.75^{cd}±0.28	1.79^{bc}±1.34	1.32^{gh}±0.50	P<0.02	P<0.05	NS
Total	16.76^{c}±0.32	16.93^{bc}±0.54	18.48^{ab}±0.43	13.41^{ef}±0.37	11.84^{h}±0.98	12.82^{fg}±0.64	13.55^{ef}±0.32	9.69^{j}±0.20			
Mazai											
Ala	4.10^{cd}±0.31	4.20^{cd}±0.10	4.28^{cd}±0.11	3.70^{de}±0.30	4.00^{d}±0.11	4.10^{cd}±0.13	4.20^{cd}±0.31	3.50^{e}±0.10	NS	P<0.05	P<0.03
Asn	1.71^{de}±0.22	1.72^{d}±0.20	1.81^{ab}±0.11	1.78^{c}±1.10	1.68^{e}±0.12	1.70^{de}±0.10	1.75^{cd}±0.13	1.76^{cd}±1.12	NS	P<0.05	P<0.03
Gla	2.20^{c}±0.23	2.30^{bc}±0.13	2.40^{bc}±0.05	1.70^{d}±0.17	2.00^{cd}±0.73	2.20^{c}±0.12	2.31^{bc}±0.01	1.65^{de}±0.16	NS	P<0.05	P<0.05
Gly	1.70^{d}±0.20	1.80^{cd}±0.61	2.00^{b}±0.30	1.50^{e}±0.20	1.65^{de}±0.10	1.70^{d}±0.31	1.90^{cd}±0.30	1.40^{ef}±0.20	P<0.04	P<0.05	NS
Pro	0.60^{bc}±0.11	0.61^{bc}±0.38	0.75^{ab}±0.44	0.44^{d}±0.31	0.50^{cd}±0.12	0.55^{c}±0.31	0.60^{bc}±0.42	0.40^{de}±0.30	NS	NS	NS
Cys	0.38^{d}±0.13	0.40^{cd}±0.05	0.49^{b}±0.81	0.10^{g}±0.41	0.38^{d}±0.13	0.40^{cd}±0.05	0.49^{b}±0.81	0.10^{g}±0.41	P<0.05	P<0.01	P<0.04
Ser	1.50^{f}±0.34	1.59^{ef}±0.28	1.60^{e}±1.04	1.21^{hi}±0.51	1.45^{fg}±0.30	1.50^{f}±0.22	1.55^{ef}±1.01	1.25^{h}±0.50	P<0.04	P<0.05	NS
Total	13.72^{e}±0.65	14.37^{de}±0.97	16.93±0.21	13.43^{ef}±0.71	11.66^{hi}±0.27	12.15^{g}±0.42	12.8^{fg}±0.65	10.06^{ij}±0.97			
Waziri											
Ala	4.40^{bc}±0.12	4.58^{bc}±0.10	4.60^{b}±0.30	4.00^{d}±0.32	4.00^{d}±0.11	4.50^{bc}±0.21	4.83^{a}±0.31	3.80^{de} ±0.21	NS	P<0.05	P<0.03
Asn	1.84^{bc}±0.33	1.89^{ab}±0.18	2.10^{a}±0.77	1.00^{h}±0.35	1.30^{g}±0.15	1.53^{f}±0.15	2.00^{ab}±0.21	1.20^{gh}±0.30	NS	P<0.05	P<0.03
Gla	2.40^{bc}±1.11	2.75^{ab} ±0.23	2.80^{a}±0.15	2.10^{c}±0.30	2.00^{cd}±1.86	2.43^{bc} ±0.20	2.59^{b}±0.11	2.00^{cd}±0.10	NS	P<0.05	P<0.05
Gly	2.00^{b}±1.02	2.20^{ab}±0.61	2.37^{a}±0.04	1.70^{d}±0.21	1.90^{cd}±1.02	2.00^{cd}±0.51	2.20^{ab}±0.14	1.60^{e}±0.20	P<0.04	P<0.05	NS
Pro	0.70^{b}±0.27	0.96^{ab}±0.30	0.97^{a}±0.11	0.10^{e}±1.00	0.60^{bc}±0.20	0.70^{b}±0.11	0.80^{ab}±0.10	0.17^{de}±0.00	NS	NS	NS
Cys	0.49^{b}±0.21	0.53^{ab}±0.51	0.59^{a}±0.81	0.13^{f}±0.15	0.38^{d}±0.11	0.40^{cd}±0.11	0.47^{bc}±0.85	0.13^{f}±0.10	P<0.05	P<0.01	P<0.04
Ser	1.82^{bc}±0.12	1.93^{ab}±0.18	1.95^{a}±1.14	1.21^{hi}±0.51	1.70^{de}±0.13	1.77^{c}±0.21	1.83^{b}±0.04	1.40^{g}±0.51	P<0.02	P<0.05	NS
Total	16.83^{bc}±0.46	17.10^{b}±0.40	18.70^{a}±0.53	13.05^{f}±0.99	11.88^{h}±0.34	13.33^{ef}±0.62	14.69^{d}±0.23	10.30^{i}±0.12			

The first P1-value show the treatment effect on the non-essential amino acid profile, which was significant P<0.02 for Ser, Gly, and Cys in all feeding systems for all sheep breeds. However, non-significant differences (P>0.05) were observed for Ala, Aspartic acid (Asp), Glutamine (Gln) and Proline (Pro). While the 2nd P value showed the effect of breed which was significant P<0.05 for Cys, Ala, Asp, Gln, Gly and Ser in all feeding regime while non-significant P>0.05 for Prol.

regime in all breeds. Conversely, grazing +700 g concentrate feeding regime-fed sheep consistently exhibited the lowest amino acid concentrations, irrespective of age or breed. Overall, Waziri hoggets under the grazing+350 g concentrate feeding regime feeding regime displayed the most favorable amino acid profile, indicating a strong influence of breed, age, and diet on the nutritional quality of mutton. The findings underscore the importance of optimizing feeding strategies to enhance the amino acid composition of meat, particularly in high-performing breeds like Waziri.

The carcass quality traits of sheep has been presented in Table III. Waziri sheep consistently exhibited superior dressing percentages and lean meat content compared to Balkhi and Mazai breeds. The highest dressing percentage (60.37±0.76%) and lean meat percentage (67.48 ± 0.67%) were observed in Waziri hoggets under the grazing +350 g concentrate feeding regime feeding regime. Conversely, Balkhi sheep demonstrated greater fat percentages, particularly under grazing+700 g concentrate feeding regime, where adults recorded 20.00±0.43%. Bone percentages were highest in Balkhi sheep (34.62±0.14%) under grazing feeding regime treatments.

Table III. Effect of breed, age and feeding regime on carcass quality of sheep breeds in Waziristan.

Breed/ Parameters	Hogget				Adult				P1-value feeding	P2-value breed	P3 value age
	Grazing	Grazing + Concentrate			Grazing	Grazing + Concentrate					
		150 g	350g	700g		150 g	350g	700g			
Balkhi											
Empty stomach wt	36.00± 0.12	48.00^{cd}± 0.41	45.00^{d}± 0.11	50.00^{c}± 0.42	60.00^{a}± 0.22	58.00^{ab}± 0.42	55.00^{b}± 0.18	60.00^{a}± 0.21	P < 0.05 (T1)	P < 0.01	P < 0.01
Hot carcass weight	16.00± 0.14	22.50^{c}± 0.33	25.00^{bc}± 0.31	24.00^{bc}± 0.21	26.00^{b}± 0.21	26.00^{b}± 0.52	29.00^{ab}± 0.13	30.00^{a}± 0.11	P < 0.05 (T2)	P < 0.01	P < 0.01
Dressing (%)	44.44^{e}± 0.65	46.88^{de}± 0.32	55.56^{b}± 0.10	48.00^{d}± 0.18	43.33^{ef}± 0.32	44.83^{e}± 0.30	52.73^{c}± 0.43	50.00^{cd}± 0.11	P < 0.01 (T3)	P < 0.01	P < 0.01
Lean meat (%)	56.25^{cd}± 0.34	53.33^{de}± 0.30	60.00^{bc}± 0.13	50.00^{e}± 0.10	47.69^{ef}± 0.32	46.15^{f}± 0.10	51.72^{de}± 0.12	46.67^{f}± 0.88	P < 0.05 (T1)	P < 0.05	P < 0.01
Bone (%)	28.13^{bc}± 0.32	31.11^{ab}± 0.11	28.00^{bc}± 0.14	29.17^{bc}± 0.54	32.69^{ab}± 0.32	34.62^{a}± 0.14	31.03^{ab}± 0.56	32.67^{ab}± 0.67	NS	P < 0.02	P < 0.02
Fat (%)	10.00^{de}± 0.23	11.00^{d}± 0.21	10.00^{de}± 0.43	20.00^{a}± 0.64	18.00^{ab}± 0.41	18.00^{ab}± 0.10	16.00^{b}± 0.87	20.00^{a}± 0.43	P < 0.01	P < 0.01	P < 0.01
Mazai											
Empty stomach wt	27.00^{fg}± 0.45	29.00^{fg}± 0.56	28.00^{fg}± 0.53	30.00^{f}± 0.11	33.00^{e}± 0.32	31.00^{ef}± 0.63	32.00^{ef}± 0.32	33.00^{e}± 0.19	P < 0.05 (T1)	P < 0.01	P < 0.01
Hot carcass weight	11.80^{ef}± 0.53	13.50^{e}± 0.30	14.00^{de}± 0.32	12.50^{ef}± 0.12	13.50^{e}± 0.33	14.30^{de}± 0.12	15.30^{de}± 0.14	16.00^{d}± 0.56	P < 0.05 (T2)	P < 0.01	P < 0.01
Dressing (%)	43.70^{ef}± 0.11	46.55^{de}± 0.11	50.00^{cd}± 0.74	41.67^{ef}± 0.43	40.91^{f}± 0.56	46.13^{de}± 0.98	47.81^{de}± 0.85	48.48^{d}± 0.03	P < 0.01 (T3)	P < 0.01	P < 0.01
Lean meat (%)	56.78^{cd}± 0.05	57.78^{cd}± 0.57	58.57^{c}± 0.64	48.00^{ef}± 0.67	48.15^{ef}± 0.76	52.45^{de}± 0.75	52.29^{de}± 0.76	53.13^{de}± 0.43	P < 0.05 (T1)	P < 0.05	P < 0.01
Bone (%)	30.51^{b}± 0.56	29.63^{b}± 0.06	28.57^{bc}± 0.23	30.40^{b}± 0.56	33.33^{ab}± 0.45	27.97^{bc}± 0.73	28.10^{bc}± 0.42	25.00^{c}± 0.42	NS	P < 0.02	P < 0.02
Fat (%)	12.00^{cd}± 0.32	12.00^{cd}± 0.34	13.00^{cd}± 0.75	20.00^{a}± 0.21	17.00^{ab}± 0.11	17.50^{ab}± 0.56	19.00^{ab}± 0.64	20.00^{a}± 0.54	P < 0.01	P < 0.01	P < 0.01
Waziri											
Empty stomach wt	21.00^{h}± 0.04	20.00^{hi}± 0.54	27.00^{fg}± 0.05	26.00^{g}± 0.67	30.00^{f}± 0.76	29.00^{fg}± 0.67	31.00^{ef}± 0.55	30.00^{f}± 0.31	P < 0.05 (T1)	P < 0.01	P < 0.01
Hot carcass weight	10.00^{f}± 0.76	10.00^{f}± 0.33	16.30^{d}± 0.43	13.50^{e}± 0.73	14.00^{de}± 0.11	14.00^{de}± 0.56	16.00^{d}± 0.01	14.50^{de}± 0.42	P < 0.05 (T2)	P < 0.01	P < 0.01
Dressing (%)	47.62^{de}± 0.65	50.00^{bc}± 0.43	60.37^{a}± 0.76	51.92^{cd}± 0.65	46.67^{de}± 0.87	48.28^{d}± 0.89	51.61^{cd}± 0.43	48.33^{d}± 0.43	P < 0.01 (T3)	P < 0.01	P < 0.01
Lean meat (%)	55.00^{d}± 0.45	60.00 ^{bc}± 0.56	67.48^{a}± 0.67	62.96^{b}± 0.76	50.00^{e}± 0.04	57.14^{cd}± 0.58	56.25^{cd}± 0.96	53.79^{de}± 0.99	P < 0.05 (T1)	P < 0.05	P < 0.01
Bone (%)	30.00^{b}± 0.57	25.00^{c}± 0.68	20.86^{e}± 0.98	22.22^{d}± 0.89	28.57^{bc}± 0.54	28.57^{bc}± 0.90	28.13^{bc}± 0.45	31.72^{ab}± 0.76	NS	P < 0.02	P < 0.02
Fat (%)	12.00^{cd}± 0.07	11.00^{d}± 0.56	11.00^{d}± 0.76	14.50^{bc}± 0.37	13.00^{c}± 0.22	12.50^{cd}± 0.32	13.00^{c}± 0.67	14.00^{bc}± 0.43	P < 0.01	P < 0.01	P < 0.01

P1 value show the treatment effect, which was significant in T1 for empty stomach weight, and hot carcass weight was significant in T2, T3, and T4. Dressing %, Lean Meat % and Fat % was effected significantly in T2, T3 and T4 while bone % was non-significant. 2nd P value showed age effect in which all the carcass parameter effected significantly 3rd P value show Breed effect which was significant P<0.01 ^{a,b,c,d} Means within columns with different superscripts are significantly different.

Table IV. Effect of breed, age and feeding regime on the mutton nutritive value of Waziristan sheep.

Breed/ Parameters	Hogget Grazing	Hogget Grazing + Concentrate 150 g	Hogget Grazing + Concentrate 350g	Hogget Grazing + Concentrate 700g	Adult Grazing	Adult Grazing + Concentrate 150 g	Adult Grazing + Concentrate 350g	Adult Grazing + Concentrate 700g	P1-value feeding	P2-value breed	P3 value age
Balkhi											
Empty stomach wt	36.00 ± 0.12	$48.00^{cd}\pm0.41$	$45.00^{d}\pm0.11$	$50.00^{c}\pm0.42$	$60.00^{a}\pm0.22$	$58.00^{ab}\pm0.42$	$55.00^{b}\pm0.18$	$60.00^{a}\pm0.21$	$P < 0.05$ (T1)	$P < 0.01$	$P < 0.01$
Hot carcass weight	16.00 ± 0.14	$22.50^{c}\pm0.33$	$25.00^{bc}\pm0.31$	$24.00^{bc}\pm0.21$	$26.00^{b}\pm0.21$	$26.00^{b}\pm0.52$	$29.00^{ab}\pm0.13$	$30.00^{a}\pm0.11$	$P < 0.05$ (T2)	$P < 0.01$	$P < 0.01$
Dressing (%)	$44.44^{e}\pm0.65$	$46.88^{de}\pm0.32$	$55.56^{b}\pm0.10$	$48.00^{d}\pm0.18$	$43.33^{ef}\pm0.32$	$44.83^{e}\pm0.30$	$52.73^{c}\pm0.43$	$50.00^{cd}\pm0.11$	$P < 0.01$ (T3)	$P < 0.01$	$P < 0.01$
Lean meat (%)	$56.25^{cd}\pm0.34$	$53.33^{de}\pm0.30$	$60.00^{bc}\pm0.13$	$50.00^{e}\pm0.10$	$47.69^{ef}\pm0.32$	$46.15^{f}\pm0.10$	$51.72^{de}\pm0.12$	$46.67^{f}\pm0.88$	$P < 0.05$ (T1)	$P < 0.05$	$P < 0.01$
Bone (%)	$28.13^{bc}\pm0.32$	$31.11^{ab}\pm0.11$	$28.00^{bc}\pm0.14$	$29.17^{bc}\pm0.54$	$32.69^{ab}\pm0.32$	$34.62^{a}\pm0.14$	$31.03^{ab}\pm0.56$	$32.67^{ab}\pm0.67$	NS	$P < 0.02$	$P < 0.02$
Fat (%)	$10.00^{de}\pm0.23$	$11.00^{d}\pm0.21$	$10.00^{de}\pm0.43$	$20.00^{a}\pm0.64$	$18.00^{ab}\pm0.41$	$18.00^{ab}\pm0.10$	$16.00^{b}\pm0.87$	$20.00^{a}\pm0.43$	$P < 0.01$	$P < 0.01$	$P < 0.01$
Mazai											
Empty stomach wt	$27.00^{fg}\pm0.45$	$29.00^{fg}\pm0.56$	$28.00^{fg}\pm0.53$	$30.00^{f}\pm0.11$	$33.00^{e}\pm0.32$	$31.00^{ef}\pm0.63$	$32.00^{ef}\pm0.32$	$33.00^{e}\pm0.19$	$P < 0.05$ (T1)	$P < 0.01$	$P < 0.01$
Hot carcass weight	$11.80^{ef}\pm0.53$	$13.50^{e}\pm0.30$	$14.00^{de}\pm0.32$	$12.50^{ef}\pm0.12$	$13.50^{e}\pm0.33$	$14.30^{de}\pm0.12$	$15.30^{de}\pm0.14$	$16.00^{d}\pm0.56$	$P < 0.05$ (T2)	$P < 0.01$	$P < 0.01$
Dressing (%)	$43.70^{ef}\pm0.11$	$46.55^{de}\pm0.11$	$50.00^{cd}\pm0.74$	$41.67^{ef}\pm0.43$	$40.91^{f}\pm0.56$	$46.13^{de}\pm0.98$	$47.81^{de}\pm0.85$	$48.48^{d}\pm0.03$	$P < 0.01$ (T3)	$P < 0.01$	$P < 0.01$
Lean meat (%)	$56.78^{cd}\pm0.05$	$57.78^{cd}\pm0.57$	$58.57^{c}\pm0.64$	$48.00^{ef}\pm0.67$	$48.15^{ef}\pm0.76$	$52.45^{de}\pm0.75$	$52.29^{de}\pm0.76$	$53.13^{de}\pm0.43$	$P < 0.05$ (T1)	$P < 0.05$	$P < 0.01$
Bone (%)	$30.51^{b}\pm0.56$	$29.63^{b}\pm0.06$	$28.57^{bc}\pm0.23$	$30.40^{b}\pm0.56$	$33.33^{ab}\pm0.45$	$27.97^{bc}\pm0.73$	$28.10^{bc}\pm0.42$	$25.00^{c}\pm0.42$	NS	$P < 0.02$	$P < 0.02$
Fat (%)	$12.00^{cd}\pm0.32$	$12.00^{cd}\pm0.34$	$13.00^{cd}\pm0.75$	$20.00^{a}\pm0.21$	$17.00^{ab}\pm0.11$	$17.50^{ab}\pm0.56$	$19.00^{ab}\pm0.64$	$20.00^{a}\pm0.54$	$P < 0.01$	$P < 0.01$	$P < 0.01$
Waziri											
Empty stomach wt	$21.00^{h}\pm0.04$	$20.00^{hi}\pm0.54$	$27.00^{fg}\pm0.05$	$26.00^{g}\pm0.67$	$30.00^{f}\pm0.76$	$29.00^{fg}\pm0.67$	$31.00^{ef}\pm0.55$	$30.00^{f}\pm0.31$	$P < 0.05$ (T1)	$P < 0.01$	$P < 0.01$
Hot carcass weight	$10.00^{f}\pm0.76$	$10.00^{f}\pm0.33$	$16.30^{d}\pm0.43$	$13.50^{e}\pm0.73$	$14.00^{de}\pm0.11$	$14.00^{de}\pm0.56$	$16.00^{d}\pm0.01$	$14.50^{de}\pm0.42$	$P < 0.05$ (T2)	$P < 0.01$	$P < 0.01$
Dressing (%)	$47.62^{de}\pm0.65$	$50.00^{bc}\pm0.43$	$60.37^{a}\pm0.76$	$51.92^{cd}\pm0.65$	$46.67^{de}\pm0.87$	$48.28^{d}\pm0.89$	$51.61^{cd}\pm0.43$	$48.33^{d}\pm0.43$	$P < 0.01$ (T3)	$P < 0.01$	$P < 0.01$
Lean meat (%)	$55.00^{d}\pm0.45$	$60.00^{bc}\pm0.56$	$67.48^{a}\pm0.67$	$62.96^{b}\pm0.76$	$50.00^{e}\pm0.04$	$57.14^{cd}\pm0.58$	$56.25^{cd}\pm0.96$	$53.79^{de}\pm0.99$	$P < 0.05$ (T1)	$P < 0.05$	$P < 0.01$
Bone (%)	$30.00^{b}\pm0.57$	$25.00^{c}\pm0.68$	$20.86^{e}\pm0.98$	$22.22^{d}\pm0.89$	$28.57^{bc}\pm0.54$	$28.57^{bc}\pm0.90$	$28.13^{bc}\pm0.45$	$31.72^{ab}\pm0.76$	NS	$P < 0.02$	$P < 0.02$
Fat (%)	$12.00^{cd}\pm0.07$	$11.00^{d}\pm0.56$	$11.00^{d}\pm0.76$	$14.50^{bc}\pm0.37$	$13.00^{c}\pm0.22$	$12.50^{cd}\pm0.32$	$13.00^{c}\pm0.67$	$14.00^{bc}\pm0.43$	$P < 0.01$	$P < 0.01$	$P < 0.01$

Its P-Value show breed effect which was significant for moisture %, ash%, CP% and Fat%. 2nd P-value show treatment effect which was significant. 3rd P-value show age effect which was also significant

Hoggets across all breeds generally produced higher dressing percentages and lean meat content than adults. For instance, Waziri hoggets under grazing+350 g concentrate feeding regime exhibited the best carcass quality, with significantly higher dressing percentages ($P < 0.01$) and lean meat yields ($P < 0.01$). Adults, on the other hand, had higher fat content, particularly in Balkhi and Mazai breeds, where fat percentages reached 20.00±0.43%

and 20.00±0.54%, respectively, under grazing+700 g concentrate feeding regime.

The grazing+350 g concentrate feeding regime feeding regime yielded the highest hot carcass weights, dressing percentages, and lean meat percentages across all breeds and age groups. Waziri hoggets fed on grazing+350 g concentrate feeding regime recorded the highest hot carcass weight (16.30±0.43 kg), while Balkhi adults under grazing+700 g concentrate feeding regime had the heaviest empty stomach weight (60.00±0.21 kg). In contrast, grazing+700 g concentrate feeding regime -fed animals exhibited lower dressing percentages and lean meat yields, with increased fat content, highlighting the adverse effects of this feeding regime on carcass quality.

The nutritive value of mutton from Waziristan sheep are given in Table IV. The Waziri breed consistently exhibited higher crude protein content compared to the Balkhi and Mazai breeds, with the highest CP value of 31.40±0.11% observed in Waziri hoggets under the grazing+700 g concentrate feeding regime feeding regime. Balkhi and Mazai breeds showed moderate CP levels, while the lowest values were recorded in Mazai sheep, with adults under grazing only system producing only 22.00±0.33%. The fat content was notably higher in Balkhi sheep, particularly in adults under grazing+700 g concentrate feeding regime (16.90±0.41%), compared to lower fat percentages in Waziri sheep, especially hoggets under grazing regime (7.50±0.56%).

Hoggets generally displayed higher moisture and CP percentages compared to adults, with significant differences observed ($P < 0.02$). For instance, Waziri hoggets under grazing+350 g concentrate feeding regime had the highest CP (31.40±0.11%) and moisture (72.50±0.23%), while adults of the same breed and treatment exhibited lower moisture (71.80±0.11%) and CP levels (28.30±0.16%). Adults, however, had higher fat percentages across all breeds and feeding regimes, with Balkhi adults under grazing+700 g concentrate feeding regime achieving the maximum fat content of 16.90±0.41%.

The grazing+350 g concentrate feeding regime feeding regime was particularly effective in enhancing the CP content across all breeds, with Waziri hoggets showing the highest CP levels (31.40±0.11%). Fat content, however, was increased under grazing+700 g concentrate feeding regime, particularly in Balkhi sheep, where hoggets recorded 13.50±0.41%, and adults peaked at 16.90±0.41%. Ash content varied significantly across treatments, with the lowest values recorded in Waziri hoggets under grazing+700 g concentrate feeding regime (0.71±0.65%) and the highest in Mazai adults under grazing regime (1.83±0.43%).

The sensory attributes of Waziristan sheep mutton have been presented in Table V. The Waziri breed demonstrated superior sensory qualities compared to the Balkhi and Mazai breeds. Waziri hoggets under grazing+350 g concentrate feeding regime recorded the highest tenderness (7.80±0.09), flavor (7.50±0.80), and overall liking (7.20±0.62). In contrast, Mazai sheep had lower sensory scores, with adults under grazing regime achieving the lowest tenderness (5.70±0.54) and overall liking (6.00±0.70). Cooked color was also most favorable in Waziri sheep, particularly hoggets under grazing+350 g concentrate feeding regime (6.70±0.64), compared to lower scores in the Mazai breed. Notably, aroma did not show significant breed differences ($P > 0.05$).

Hoggets consistently outperformed adults in most sensory attributes, with significant differences ($P < 0.01$). For instance, Waziri hoggets under grazing+350 g concentrate feeding regime had higher juiciness (7.60±0.60) and tenderness (7.80±0.09) than their adult counterparts (7.40±0.32 for juiciness and 6.96±0.41 for tenderness). Across all breeds, hoggets showed better overall liking, flavor, and juiciness compared to adults. Feeding regimes had a pronounced effect on sensory properties, with grazing+350 g concentrate feeding regime producing the most favorable outcomes. Waziri hoggets under grazing+350 g concentrate feeding regime displayed the highest scores for juiciness (7.60±0.60), flavor (7.50±0.80), and aroma (7.60±0.90). Tenderness was highest under grazing +700 g concentrate feeding regime for Waziri hoggets (7.79±0.54), though grazing+350 g concentrate feeding regime still produced comparably high scores. Across breeds, grazing feeding regime tended to yield lower scores for sensory attributes compared to other treatments.

DISCUSSION

Variations in mutton amino acid profiles underscore the combined influence of genetics and environment on meat quality. Waziri sheep, particularly under the grazing +350 g concentrate feeding regime, demonstrated superior amino acid profiles, suggesting a genetic predisposition for enhanced synthesis or retention, consistent with the findings of Knapik *et al.* (2017). Hogget mutton consistently exhibited higher total amino acid content compared to adult mutton, attributable to the metabolic and structural advantages of younger animals. Age-related declines in amino acid levels are associated with increased connective tissue and reduced protein turnover in older animals (Costa *et al*., 2023). The grazing +350 g concentrate feeding regimen significantly enhanced essential amino acids such as lysine, methionine, and phenylalanine, highlighting the critical role of

Table V. Effect of breed, age and feeding regime on scenery properties of Waziristan sheep mutton.

Age group/ Parameters	Hogget				Adult				P1-value feeding	P2-value breed	P3 value age
	Grazing + Concentrate				Grazing + Concentrate						
	8-10 h+0 g	4-6h+150 g	2-4 h+350g	0 h +700g	8-10 h+0 g	4-6h+150g	2-4 h+350g	0 h+700g			
Balkhi											
Tenderness	7.00^{ab}±1.02	7.10^{ab}±0.11	7.30^{ab}±0.62	7.29^{ab}±0.86	6.50^{cd}±0.04	6.70^{cd}±0.33	6.86^{c}±0.42	6.80^{c}±0.63	P<0.01	P<0.01	P<0.01
Juiciness	7.10^{b}±1.00	7.20^{b}±0.10	7.50^{a}±0.67	7.10^{bc}±0.82	6.70^{bc}±0.01	6.90^{bc}±0.37	7.30^{ab}±0.41	6.90^{bc}±0.60	P<0.05	P<0.05	P<0.01
Flavor	6.50^{d}±0.76	6.70^{cd}±0.51	7.10^{bc}±0.90	6.80^{cd}±048	6.90^{c}±0.85	7.00^{bc}±0.21	7.30^{b}±0.89	7.00^{bc}±0.74	P<0.01	P<0.01	P<0.01
Aroma	6.80^{cd}±0.75	7.00^{c}±0.56	7.50^{ab}±0.91	7.60^{ab}±0.61	7.00^{c}±0.80	7.30^{bc}±0.33	7.60^{ab}±0.21	7.69^{a}±0.03	P<0.05	NS	P<0.01
Color	6.30^{b}±0.74	6.40^{ab}±0.95	6.50^{ab}±0.67	6.40^{ab}±0.42	6.10^{c}±0.53	6.20^{bc}±0.41	6.30^{b}±0.78	6.30^{b}±0.23	P<0.05	P<0.01	P<0.01
Overall liking	6.30^{c}±0.70	6.50^{bc}±0.90	6.80^{b}±0.62	6.40^{bc}±0.43	6.20^{cd}±0.51	6.30^{c}±0.41	6.50^{bc}±0.70	6.30^{b}±0.21	P<0.05	P<0.01	P<0.01
Mazai											
Tenderness	6.20^{cd}±0.06	6.40^{cd}±0.84	6.60^{cd}±0.12	6.69^{c}±0.32	5.70^{de}±0.54	5.80^{d}±0.16	5.96^{d}±0.54	5.86^{d}±0.21	P<0.01	P<0.01	P<0.01
Juiciness	6.40^{cd}±1.01	6.30^{cd}±0.14	6.50^{c}±0.62	6.30^{cd}±0.21	6.20^{d}±0.11	6.20^{d}±0.30	6.30^{cd}±0.43	6.20^{cd}±0.11	P<0.05)	P<0.05	P<0.01
Flavor	6.10^{e}±0.70	6.40^{de}±0.52	6.80^{cd}±0.11	6.90^{c}±0.43	6.40^{de}±0.80	6.60^{d}±0.20	7.20^{b}±0.80	7.00^{bc}±0.70	P<0.01	P<0.01	P<0.01
Aroma	6.30^{de}±0.70	6.60^{cd}±0.50	7.00^{c}±0.90	7.30^{bc}±0.67	6.40^{d}±0.84	6.80^{cd}±0.34	7.20^{bc}±0.25	7.40^{ab}±0.04	P<0.05	NS	P<0.01
Color	6.00^{cd}±0.74	6.10^{c}±0.90	6.30^{bc}±0.44	6.30^{b}±0.40	5.80^{d}±0.50	6.20^{bc}±0.61	6.10^{c}±0.75	6.10^{c}±0.26	P<0.05	P<0.01	P<0.01
Overall liking	6.00^{d}±0.70	6.20^{cd}±0.90	6.20^{cd}±0.60	6.20^{cd}±0.43	6.10^{cd}±0.51	6.10^{cd}±0.62	6.10^{cd}±0.70	6.10^{cd}±0.26	P<0.05	P<0.01	P<0.01
Waziri											
Tenderness	7.40^{ab}±1.10	7.50^{ab}±0.10	7.80^{a}±0.09	7.79^{a}±0.54	6.50^{cd}±0.01	6.70^{bc}±0.35	6.96^{b}±0.41	6.90^{b}±0.43	P<0.01	P<0.01	P<0.01
Juiciness	7.30^{ab}±1.86	7.30^{ab}±0.11	7.60^{a}±0.60	7.40^{ab}±0.80	6.80^{bc}±0.02	6.90^{bc}±0.01	7.40^{ab}±0.32	7.20^{b}±0.27	P<0.05)	P<0.05	P<0.01
Flavor	6.90^{c}±0.76	7.20^{b}±0.53	7.50^{ab}±0.80	7.50^{ab}±0.40	7.00^{bc}±0.88	7.30^{b}±0.10	7.70^{a}±0.11	7.60^{a}±0.19	P<0.01	P<0.01	P<0.01
Aroma	7.00^{c}±0.70	7.30^{bc}±0.52	7.60^{ab}±0.90	7.60^{ab}±0.65	7.20^{bc}±0.81	7.40^{b}±0.22	7.70^{a}±0.27	7.69^{a}±0.04	P<0.05	NS	P<0.01
Color	6.40^{ab}±0.75	6.50^{ab}±0.88	6.70^{a}±0.64	6.40^{ab}±0.43	6.10^{c}±0.52	6.30^{b}±0.40	6.40^{ab}±0.71	6.30^{b}±0.29	P<0.05	P<0.01	P<0.01
Overall liking	6.60^{bc}±0.70	6.80^{b}±0.90	7.20^{a}±0.62	6.50^{bc}±0.43	6.30^{c}±0.51	6.60^{bc}±0.41	6.80^{b}±0.70	6.30^{c}±0.21	P<0.05	P<0.01	P<0.01

Its P-Value show breed effect which was significant for tenderness, Juiciness, flavor, cooked color and overall acceptances of mutton and non- significant for aroma 2md p-value show treatment effect were statically significant P<0.01 tenderness, Juiciness, flavor, aroma, cooked color and overall acceptances of mutton were statically significant P<0.01. the 3rd p-value show age effect which show significant tenderness, Juiciness, flavor, aroma, cooked color and overall acceptances of mutton were statically significant P<0.01

balanced nutrition in promoting muscle protein synthesis (Chacko *et al*., 2024). The study revealed that the interplay of breed, age, and feeding regimen favors the genetic potential of Waziri sheep for a healthier amino acid profile. Conversely, the Mazai breed exhibited the lowest amino acid concentrations, although an improved feeding system could potentially mitigate this, as observed in low-performing breeds by Khan *et al*. (2022).

The study revealed that NEAA levels under the grazing+350g concentrate feeding treatment were consistent with the findings of Costa *et al*. (2023). The NEAA profile of hoggets displayed a superior amino acid composition, likely due to enhanced protein synthesis and reduced connective tissue deposition. These observations align with Chacko *et al*. (2024), who attributed such differences to reduced protein turnover and physiological changes in muscle with age. The grazing+350g concentrate feeding system notably increased NEAA concentrations, particularly cysteine, glycine, and serine, which are crucial for collagen synthesis and antioxidative functions, thereby improving meat tenderness. This is in agreement with Zhao *et al*. (2020). Conversely, the lower NEAA concentrations observed in the grazing+700 g concentrate feeding system suggest suboptimal nutritional availability (Knapik *et al*., 2017). Waziri sheep outperformed the Balkhi and Mazai breeds, consistent with Khan *et al*. (2022), who reported that higher-performing breeds tend to exhibit superior meat quality and amino acid retention.

In the present study, Waziri sheep demonstrated superior carcass characteristics compared to the Balkhi and Mazai breeds. These findings align with Knapik *et al*. (2017), who noted that carcass traits are closely associated with the muscle-to-fat ratio and nutrient efficiency. The enhanced carcass quality and lean meat content in hoggets were linked to increased muscle deposition and reduced fat accumulation. Regarding feeding systems, the grazing+350g concentrate feeding regimen resulted in higher carcass quality, likely due to balanced nutrition that supported optimal muscle development (Costa *et al*., 2023). In contrast, the grazing+350 g concentrate feeding system led to increased fat deposition and reduced carcass quality, suggesting an imbalance in the energy-to-protein ratio (Zhao *et al*., 2020). The elevated fat deposition in Balkhi and Mazai sheep under the grazing+700 g concentrate feeding regime regimen and the superior carcass quality of Waziri sheep under the grazing+350 g concentrate feeding regime regimen underscore the critical roles of age, breed selection, and feeding strategies in optimizing carcass traits.

The superior proximate composition of Waziri sheep meat compared to the Mazai breed highlights its genetic potential for lean meat production (Ali *et al*., 2022). Conversely, hoggets outperformed adults in moisture and crude protein (CP) levels due to the age-dependent prioritization of muscle growth over fat deposition in younger animals. The lower moisture and CP levels, coupled with a higher fat percentage in adults, reflect the age-related shift toward adipogenesis (Zhao *et al*., 2020). The grazing+350g concentrate feeding regime feeding system enhanced protein content across breeds by promoting amino acid synthesis and absorption (Costa *et al*., 2023). In contrast, the grazing+700g concentrate feeding regime feeding system favored fat deposition, particularly in Balkhi adults, by prioritizing energy storage over protein accretion. These findings emphasize the critical roles of feeding system specificity and breed selection in improving mutton production. This aligns with Knapik *et al*. (2017), who highlighted the influence of genetic predisposition on fat deposition in certain breeds. Variations in ash content across breeds and treatments were also noteworthy. Higher ash content in Mazai adults under the grazing feeding regime feeding system may be attributed to differences in mineral retention or bone density.

In sensory evaluation, Waziri sheep exhibited a superior sensory profile, particularly under the grazing +350 g concentrate feeding regimen, which notably enhanced tenderness and flavor. These findings align with Ding *et al*. (2024), who linked nutrient-rich diets to improved muscle structure and marbling. The superior tenderness, juiciness, and flavor observed in hoggets are likely due to finer muscle fibers and optimized intramuscular fat deposition (Sañudo *et al*., 2020; Hopkins and Geesink, 2022). The balanced nutrient profile of amino acids and fatty acid deposition in the grazing+350g concentrate feeding regime feeding regimen contributed to enhanced sensory attributes, consistent with the findings of Costa *et al*. (2023). The higher aroma scores in Waziri hoggets under the grazing+350g concentrate feeding regime system underscore the role of tailored diets in enhancing flavor compounds. Conversely, the lower scores observed in Mazai sheep under the grazing feeding regime regimen highlight the interaction between genetic potential and suboptimal nutrition. These findings emphasize the importance of breed selection, optimized feeding strategies, and focusing on the hogget stage to achieve superior mutton sensory attributes.

CONCLUSION

The results of the present study indicate that the Waziri breed particularly hoggets under the grazing +350 g concentrate feeding regime feeding system demonstrated better carcass and mutton attributes, emphasizing the critical role of breed, age and optimized feeding strategies for better mutton quality.

DECLARATIONS

Ethics statement

The study was approved by the Ethical Committee of Faculty of Animal Husbandry & Veterinary Sciences, The University of Agriculture, Peshawar, Pakistan (Approval No. 12/FAH&VS/2021).

Data availability statement

The relevant data are provided in the paper. The data of the current experiment can be obtained from corresponding author when needed.

Statement of conflict of interest

The authors have declared no conflict of interest.

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