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Morphometric Variation and Production Constraints of Criollo Sheep in the High Andes of Southern Peru

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Abstract

This study aimed to characterize the morphometric traits and production systems of Criollo sheep in the highlands of Caylloma, Arequipa, Peru. A total of 455 sheep were evaluated using a stratified proportional sampling method across the districts of Tisco, San Antonio de Chuca, and Yanque. Morphometric data were collected under standardized conditions, and nine zoometric indices were calculated to assess functional conformation and productive aptitude. Additionally, 52 sheep producers were surveyed to contextualize herd management practices. Results revealed low levels of formal education and limited technical assistance among producers. Sheep farming was primarily sustained by family tradition, with declining flock sizes attributed to pasture scarcity and climatic challenges. Campaign-based sales strategies and rudimentary reproductive management were prevalent. Health practices showed widespread deworming but limited preventive care. Multivariate analysis indicated significant morphometric variation linked to sex, biotype, and dental stage. This integrative approach highlights both the adaptive potential and production constraints of Criollo sheep in high-altitude environments, providing a basis for developing breeding strategies based on morphometric indices.

Keywords: Criollo sheep; morphometric characterization; high Andean livestock; production systems; zoometric indices

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1. Introduction

The high Andean regions of southern Peru, located above 3500 m, impose severe environmental constraints on livestock due to hypoxia, low temperatures, intense solar radiation, and highly seasonal forage availability. Pasture productivity is limited to short rainy seasons, while prolonged dry periods result in recurrent feed shortages and grazing pressure [1]. This vulnerability is exacerbated by increasing climatic variability and land degradation, underscoring the importance of livestock breeds that are both productive and resilient under such marginal conditions [1].

Criollo sheep have become a cornerstone of Andean pastoralism, providing meat, wool, hides, and manure for rural households [2]. These animals, introduced during colonial times and acclimatized over centuries, represent a strategic genetic resource for subsistence economies in the highlands. In Peru alone, Criollo or Criollo-derived sheep comprise over 80% of the national flock [3], reflecting their adaptability and socioeconomic importance. The resilience and multifunctionality of Criollo sheep make them critical for household food security, particularly in areas where technical support is scarce and market integration is limited.

Criollo sheep exhibit numerous adaptive traits, including tolerance to hypoxia, disease resistance, and the ability to thrive on sparse native forages. Studies have shown that they often outperform exotic breeds under harsh conditions, with better survival, reproductive efficiency, and robustness [2,3]. Their genetic makeup may include alleles associated with cold tolerance, metabolic efficiency, and other physiological traits that support survival under high-altitude stressors. Research on other native populations, such as the Chocholteca Creole in Mexico and Colombian sheep breeds, has revealed unique genetic and epigenetic mechanisms that promote adaptation to environmental challenges, including hypoxia, heat, and nutritional scarcity [2,4,5]. These findings highlight the importance of conserving locally adapted sheep populations like the Peruvian Criollo, which may serve as reservoirs of resilience traits essential for breeding programs under increasing climate pressures.

In terms of phenotypic performance, several studies across highland ecosystems have quantitatively demonstrated the relevance of morphometric traits for evaluating body development, productivity, and local adaptation in small ruminants. Ormachea [6] observed progressive increases in body weight (from ~22 to 35 kg), thoracic perimeter, and rump length as Criollo sheep advanced through dental development stages in the Peruvian Altiplano, suggesting a clear ontogenetic trajectory. Similarly, Contreras et al. [3] developed predictive models for live weight estimation based on thoracic perimeter, achieving coefficients of correlation above 0.90 in Huancavelica sheep. In Botswana, Thutwa et al. [7] reported that sex and regional origin significantly influenced traits such as body length and withers height, with males exhibiting up to 20% higher values than females. De la Barra et al. [8] found that zoometric indices, such as thoracic and pelvic indices, accounted for more than 60% of the morphostructural variability in Chilean meat sheep, highlighting their utility in biotype classification. Bernardi et al. [9], working with Dorper lambs, also reported strong correlations ($r > 0.85$) between thoracic perimeter and both live weight and thoracic index, reinforcing the reliability of these measurements in extensive production systems.

Despite this progress, formal research on the productive and morphometric traits of Peruvian Criollo sheep remains limited. Although the history of crossbreeding with commercial breeds, such as Corriedale and Junín, is well documented, no molecular studies have quantified genetic introgression in Peruvian Criollo sheep. However, a recent genome-wide SNP study of Creole goats from northern Peru revealed clear population structure and evidence of genetic admixture, particularly in coastal and Amazonian populations, likely resulting from regional animal movement and uncontrolled breeding [10]. While not directly linked to exotic breed introgression, these findings highlight the potential vulnerability of native livestock to genetic erosion. Similarly, studies in Colombian sheep have documented substantial introgression from non-native breeds using SNP data [2], reinforcing the need to implement molecular monitoring and conservation strategies of Criollo sheep in Peru.

Morphometric evaluations, including linear body measurements and zoometric indices, offer a cost-effective method to assess body conformation, functionality, and potential productive aptitude [6,11]. These indices are particularly useful in regions where genetic testing is inaccessible. Previous studies have shown that Criollo ewes in the highlands tend to exhibit compact bodies, robust thoracic development, and favorable pelvic traits, suggesting suitability for meat production and reproductive efficiency. Moreover, traits like thoracic perimeter correlate strongly with body weight, enabling practical weight estimation models for field use [3]. In contrast, our study represents the first integrated analysis of morphology, production systems, and health management in Criollo sheep from the Caylloma region, encompassing three high-Andean districts with distinct ecological features. This multidisciplinary approach allows for the identification of geographically influenced morphometric variability and structural production constraints, thereby providing a comprehensive baseline for targeted breeding strategies and conservation efforts.

This study seeks to fill the knowledge gap by characterizing the morphometric and productive traits of Criollo sheep in three districts of Caylloma, Arequipa. The research followed a step-by-step process: (1) standardized morphometric measurements were collected from 455 sheep; (2) nine zoometric indices were calculated to evaluate body conformation and functional aptitude; (3) 52 sheep producers were surveyed to gather data on herd management, health practices, and socioeconomic conditions; (4) multivariate and mixed-effects statistical analyses were applied to assess morphometric variation across biological and geographic factors; and (5) results were interpreted to identify adaptive traits and inform breeding priorities. We aim to quantify morphological variations across different regions, sexes, and dental stages, and to assess their associations with production management practices and structural constraints. This integrated approach provides a comprehensive baseline to support both conservation and sustainable use strategies. The findings will also contribute to improving breeding decisions and livestock development policies in the Peruvian Andes by identifying key morphometric traits (such as thoracic perimeter, rump length, and cannon bone circumference) that are strongly associated with body weight and functional body structure. These traits can be used as practical, low-cost selection tools for field-based evaluation and genetic improvement. Additionally, by documenting the regional variation in morphology and management, the study provides actionable insights for designing targeted breeding strategies, community-based training programs, and public policies that enhance the resilience, productivity, and cultural value of Criollo sheep in high-altitude systems.

2. Materials and Methods

2.1. Study Area and Environmental

The research was conducted in the province of Caylloma, located in the Arequipa department, southern Peru (Figure 1). The selected study districts—Tisco, San Antonio de Chuca, and Yanque—are situated in the southern Andean highlands, between 3420 and 4537 m above sea level. These areas belong to a dry puna agroecological zone characterized by low temperatures, limited rainfall, and seasonal climatic variation. This region presents significant environmental challenges for livestock production, such as frost events, irregular precipitation, and extended dry periods. These factors affect forage availability and overall herd health. In recent years, climate change has exacerbated these conditions, impacting the productivity and reproductive efficiency of livestock, particularly small ruminants. Despite these constraints, Criollo sheep have demonstrated considerable adaptability to these high-altitude environments, relying primarily on native pastures and extensive grazing systems.

2.2. Study Design and Sampling Strategy

This research was conducted under a non-experimental, descriptive, and cross-sectional design aimed at characterizing the morphometric and productive aspects of Creole sheep in the southern highlands of Peru. The investigation was carried out in March 2024. The reference population consisted of 33,403 sheep registered in the districts of Tisco, San Antonio de Chuca, and Yanque, according to official livestock production records. To ensure statistical representativeness, a stratified proportional sampling strategy was applied based on the total sheep population per district. The sample size was calculated using the finite population formula, with a 95% confidence level (Z = 1.96), an expected proportion of 50% (p = 0.5), a complementary proportion of 50% (q = 0.5), and a 5% maximum allowable error (e = 0.05), resulting in a total sample of 455 sheep proportionally distributed across the three districts. This sampling design minimized selection bias and allowed for adequate territorial coverage of the phenotypic variability present in the study population. This type of design was deemed appropriate because it enables the observation and description of phenotypic and productive traits under natural, unmanaged field conditions, without introducing experimental manipulation, thus reflecting the real characteristics of local sheep populations.

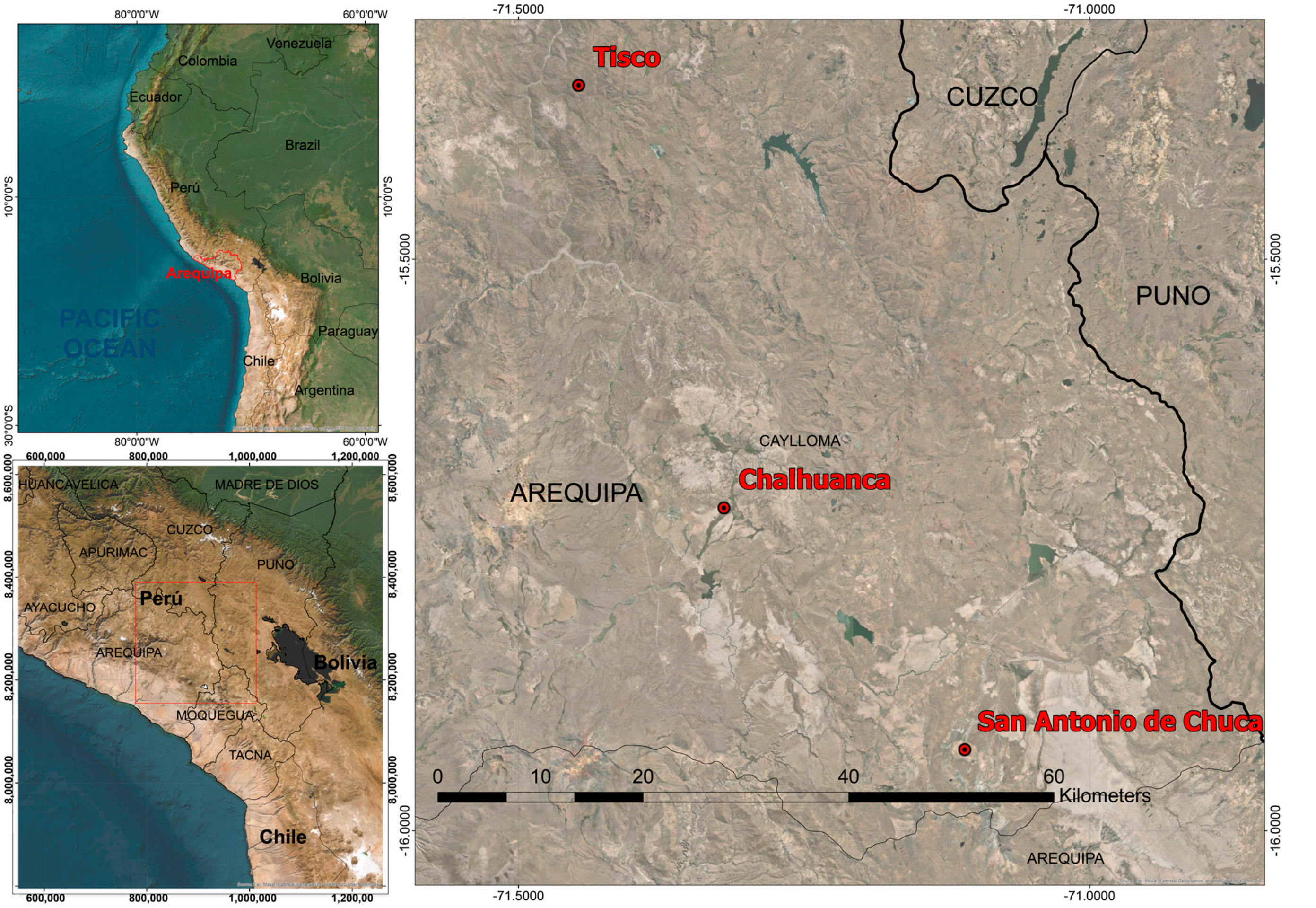

Figure 1. Location of sample collection.

All morphometric measurements were taken by trained personnel using standardized procedures. Each measurement was repeated in cases where visual or instrumental inconsistencies were detected, particularly when values differed by more than 0.5 cm. In such cases, a third measurement was performed to ensure consistency. This approach aimed to minimize measurement error and improve the reliability of the collected data.

2.3. Morphometric Evaluation and Zoometric Indices

Morphometric assessments were performed under standardized conditions between 7:00 and 10:00 a.m., using a calibrated digital scale to estimate body weight and a flexible measuring tape to acquire linear body traits. The recorded variables included Number Birdths (NB), Body contidion score (BC), body weight (WEIGHT), withers height (WH), body length (BL), dorso-sternal diameter (TD), bicostal diameter (TW), rump length (RL), rump width (RW), head length (HL), head width (HW), thoracic perimeter (TP), and cannon bone perimeter (CP). These variables were selected due to their relevance in the functional and productive evaluation of ovine biotypes. From these measurements, nine zoometric indices were calculated to infer body conformation, productive aptitude, and the degree of morphofunctional harmony. These indices were selected based on previous studies in small ruminants that demonstrate their utility in predicting body functionality and adaptation under extensive grazing conditions. The Body Index (BI) evaluates overall body compactness and suitability for meat production. The Thoracic Index (TI) estimates chest depth, which is linked to respiratory capacity and adaptation to hypoxic environments. The Cephalic Index (CI) describes head proportions and has been associated with breed differentiation. The Pelvic Index (PI) relates to pelvic width and is often considered in reproductive aptitude. The Proportionality Index (PRI) assesses the balance between body length and withers height, reflecting body harmony. The Metacarpal–Thoracic Index (MTI) indicates limb sturdiness relative to thoracic size, associated with locomotor efficiency. The Relative Thoracic Depth Index (RDTI) measures vertical chest development in relation to limb length. The Transverse Pelvic Index (TPI) and Longitudinal Pelvic Index (LPI) provide information on the shape and orientation of the pelvis, both of which influence reproductive performance and muscular development. These indices, interpreted together, allow for a comprehensive assessment of morphostructural aptitude in high-altitude sheep populations.

2.4. Questionnaire Design and Characterization of the Production System

To contextualize the morphometric evaluation, a structured questionnaire was developed and applied to characterize the ovine production systems in the study area. The instrument was adapted from the "Ficha de Diagnóstico—Sistemas Productivos" developed by INIA–PROGAN (Arequipa), and was pilot-tested in a representative highland community to ensure clarity, logical flow, and cultural relevance. Based on this pilot, modifications were made to improve language and structure. The final version included seven thematic sections: (1) geographic and general farm information; (2) socioeconomic characteristics; (3) herd management and infrastructure; (4) feeding practices, including feed sources and seasonal availability; (5) animal health and preventive care; (6) reproductive performance; and (7) commercialization strategies and sales channels. The survey was conducted through face-to-face interviews with 16 experienced sheep producers, selected based on flock size and management experience. Responses were recorded manually and later digitized. This methodological approach allowed for a comprehensive characterization of the production system, enabling the analysis of extrinsic factors that influence phenotypic variation and the identification of constraints and opportunities to improve ovine productivity in high-altitude environments.

2.5. Statistical Analysis

Principal Coordinates Analysis (PCoA) based on Bray–Curtis dissimilarity matrices was applied, followed by PERMANOVA using the adonis2 function from the vegan package (v2.6-4) to evaluate multivariate differences among groups. Spearman's rank correlations were performed to explore associations among zoometric variables and morphometric indices. Linear mixed-effects models were then fitted using lme4 (v1.1-35.1) and lmerTest (v3.1-3), specifying sex and dental stage as fixed effects, and modeling district as a random effect to account for geographic variability. Effect plots were generated with sjPlot (v2.8.15), and model outputs were exported to Excel files using openxlsx (v4.2.5) within RStudio (version 2024.12.1+402).

3. Results

3.1. Sociodemographic, Economic, and Productive Characterization of Sheep Producers

A total of 52 sheep producers from the districts of Tisco, San Antonio de Chuca, and Yanque were surveyed. The average age of the producers ranged from 42.43 ± 2.92 years in Yanque to 50.00 ± 2.57 years in San Antonio de Chuca, with a broad age distribution from 18 to 77 years, indicating that sheep farming is primarily carried out by adult members of rural households (Table 1). Male participation predominated in all three districts, particularly in Tisco and San Antonio de Chuca (66.7%), while Yanque reported a slightly lower proportion (56.2%). In terms of education, the most common level attained was incomplete primary schooling, particularly in Yanque (50.0%), indicating a low level of formal education among producers (Table 1).

Table 1. Sociodemographic and economic characterization of sheep producers from Tisco, San Antonio de Chuca, and Yanque.

Variable	Tisco	San Antonio de Chuca	Yanque
Mean age (±SE)	46.89 ± 3.87	50.00 ± 2.57	42.43 ± 2.92
Age (min–max)	18–77	29–71	22–65
% Male/Female	66.7/33.3	66.7/33.3	56.2/43.8
Predominant education level	Incomplete primary (33.3%)	Incomplete primary (38.9%)	Incomplete primary (50.0%)
Years of livestock farming (mean ± SE)	9.00 ± 0.46	9.16 ± 0.45	10.00 ± 0.00
Monthly income (S/.) (mean ± SD)	1107.69 ± 507.7	878.75 ± 304.08	820.00 ± 240.05
Income range (S/.)	150–2000	180–1200	300–1000

Livestock farming experience was relatively homogeneous, with an average ranging from 9.00 ± 0.46 years in Tisco to 10.00 ± 0.00 years in Yanque, indicating a long-standing tradition of animal husbandry in these communities. The monthly income from sheep farming varied, with Tisco reporting the highest average (S/1107.69 ± 507.7) and Yanque reporting the lowest (S/820.00 ± 240.05). This income reflects the central role of livestock in household economies, despite variation in access to markets and prices (Table 1).

Regarding productive practices, campaign-based production—where producers accumulate animals to sell in one or two batches per year—was reported by 16.6% of respondents in Tisco, 50.0% in San Antonio de Chuca, and 37.5% in Yanque. This strategy allows for flexibility in marketing but also reflects irregular cash flow (Table 2).

Sheep farming was identified as the main source of income for most households. However, technical assistance is limited and often focused on alpaca production. While the majority of producers reported receiving some form of support from municipalities or NGOs, especially in Yanque (87.5%), this assistance is not specifically tailored to sheep production (Table 2). Family tradition was the principal motivation for raising sheep across all districts. This reflects intergenerational knowledge transfer in high Andean regions, where children inherit and manage livestock. Over the past five years, 75% of producers reported a decrease in flock size, 15% noted stability, and only 10% observed an increase. The primary cause of this decline was pasture scarcity, compounded by climate variability and competition with alpacas for grazing areas (Table 2).

Table 2. Productive practices and technical support.

Variable	Tisco	San Antonio de Chuca	Yanque
Campaign-based production (%)	16.6 (Yes)/83.4 (No)	50.0 (Yes)/50.0 (No)	37.5 (Yes)/62.5 (No)
Livestock as main income source (%)	Not specified	Not specified	Not specified
Technical assistance (%)	72.2 (Yes)/27.8 (No)	72.2 (Yes)/27.8 (No)	87.5 (Yes)/12.5 (No)
Main reason for raising sheep	Family tradition	Family tradition	Family tradition
Change in sheep population over the last 5 years	75% Decrease/15% Stable/10% Increase	75% Decrease/15% Stable/10% Increase	75% Decrease/15% Stable/10% Increase
Main causes of change in the sheep population	Lack of pasture (18), Market demand (4), Others (4)	Lack of pasture (18), Market demand (4), Others (4)	Lack of pasture (18), Market demand (4), Others (4)

3.2. Health Management and Phenotypic Characterization of Criollo Sheep

The health and reproductive management practices of sheep producers in Tisco, San Antonio de Chuca, and Yanque revealed critical deficiencies. None of the producers used a sanitary calendar, although 92.3% performed deworming, predominantly targeting intestinal nematodes, lice, and ticks. Most deworm their herds once or twice annually. Pneumonia, ectoparasitosis, and gastrointestinal–pulmonary conditions were the most frequent diseases. Regarding treatment, 80.77% relied on veterinary drugs, while 19.23% used medicinal plants. Preventive care like hoof trimming was largely absent (92.31%). Only up to 15% of flocks presented visible symptoms, such as nasal or ocular discharge or coughing. Reproductive management was rudimentary: 100% practiced uncontrolled natural mating without andrological evaluation of rams, whose selection was based mainly on body size or weight. Mortality in 2023 averaged 9%, dropping to 1% in early 2024; primary causes included hypothermia, pneumonia, and accidental injuries (Supplementary Table S1).

The phenotypic evaluation by sex and district revealed consistent morphological patterns among Criollo sheep populations. Males exhibited greater values than females for most linear measurements, particularly in body length, thoracic dimensions, and withers height. In Tisco, males showed higher thoracic perimeter and cannon bone perimeter, while females presented slightly greater dorsal–sternal diameters. San Antonio de Chuca males surpassed females in nearly all traits, especially in rump width and head width. In Yanque, females had higher withers height and rump length, but males showed marginally higher proportional and pelvic indices. Indices such as ITO, IPRO, and IMETO remained elevated in males across districts, suggesting greater body compactness and muscularity (Supplementary Table S2).

3.3. Multivariate Analysis of Morphometric Variation

Principal coordinates analysis (Figure 2A,B) illustrates partial overlap among individuals across dentition stages, and districts. Nevertheless, the PERMANOVA (Table 3) demonstrates significant morphological structuring by dentition ($p < 0.0001$), district ($p < 0.0001$), and sex ($p = 0.0225$). Additionally, significant interaction effects were detected for dentition × district ($p < 0.0001$) and sex × dentition × district ($p = 0.0322$), indicating that morphometric variation is modulated by both biological and geographical factors, consistent with the observed ordination patterns.

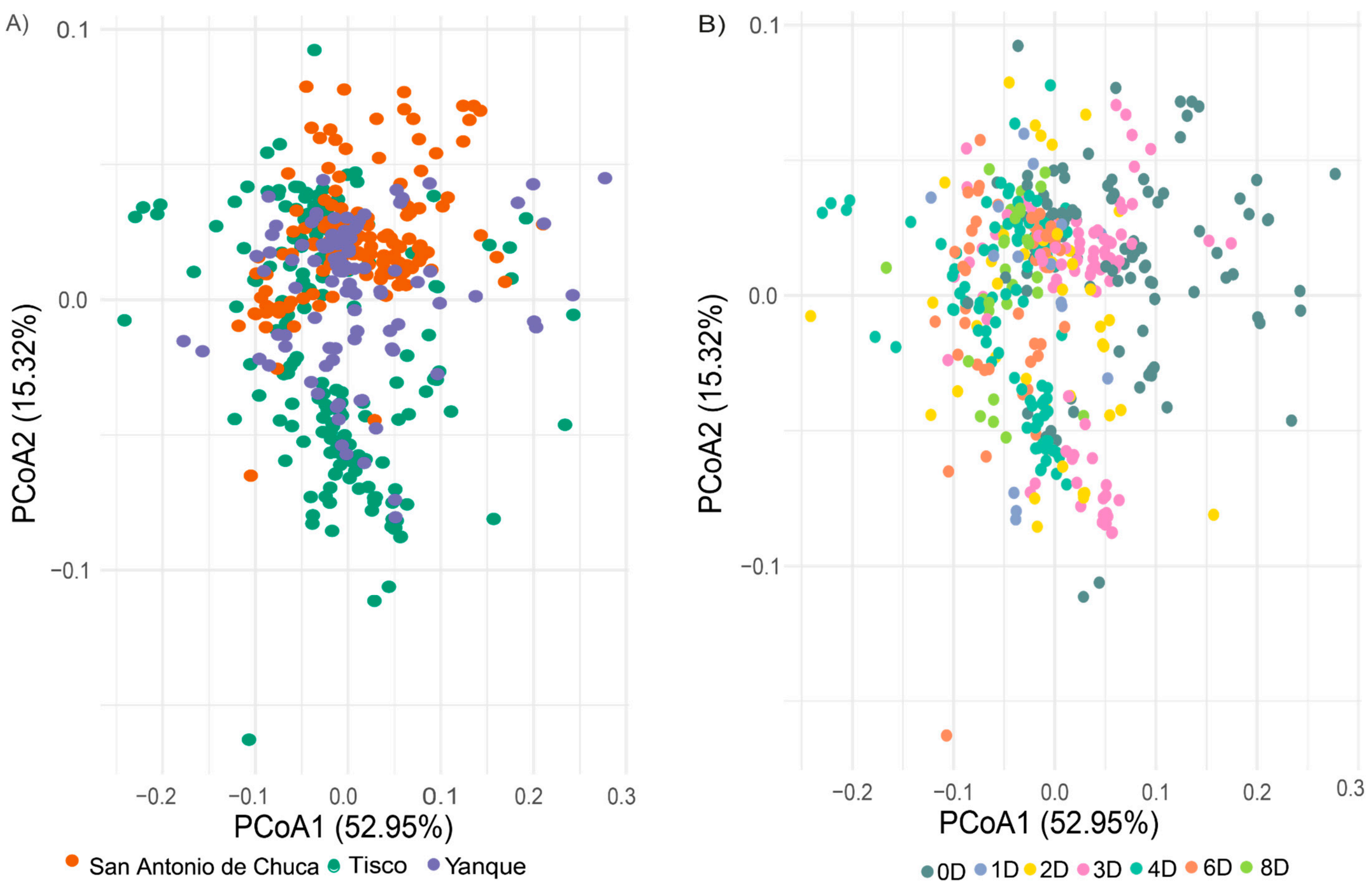

Figure 2. Principal Coordinates Analysis (PCoA) of morphometric traits in Criollo sheep from Tisco, San Antonio de Chuca, and Yanque, Caylloma, Arequipa, stratified by (**A**) dentition and sex, and (**B**) district and sex.

Table 3. PERMANOVA results assessing the effects of sex, dentition stage, district, and their interactions on the morphometric variation of Criollo sheep populations.

Variables	Df	SumOfSqs	R^2	F	*p*-Value
Sex	1	0.02	0.005	3.29	0.0225 *
Teeth	6	1.11	0.255	30.49	0.0001 ***
District	2	0.29	0.066	23.82	0.0001 ***
Sex × Teeth	6	0.06	0.013	1.56	0.0714
Sex × District	2	0.02	0.005	1.96	0.0639
Teeth × District	12	0.24	0.056	3.35	0.0001 ***
Sex × Teeth × District	9	0.09	0.021	1.64	0.0322 *
Residual	416	2.53	0.579		
Total	454	4.37	1		

Notes: Significance codes: * $p < 0.05$; *** $p < 0.001$.

3.4. Spearman Correlations Among Morphometric and Zoometric Traits

A Spearman correlation analysis (Figure 3) revealed significant positive associations between NB and PRI, as well as between weight and WH, BL, RW, HW, TP, and TPI. WH correlated positively with weight; BL with RW, RDTI, and TPI; and TD with RL, HW, TP, RDTI, and TPI. TW showed a positive correlation with RL, while RL correlated positively with TDTI and LPI and negatively with BI. RW was positively correlated with HW and TP, and negatively with TI. HL showed significant positive correlations with TP, RDTI, and TPI, and a negative correlation with TI. HW correlated positively with TP, RDTI, and TPI, and negatively with TI. TP exhibited additional positive associations with RDTI, TPI, and

LPI, and a negative correlation with TI. BI correlated negatively with RL, and TI showed negative correlations with HL and the composite indices RDTI and TPI. MTI correlated negatively with TD. PRI was positively associated with NB. RDTI correlated positively with TPI, and TPI further showed a positive correlation with weight and a negative correlation with TI. LPI was positively associated with RL and TP.

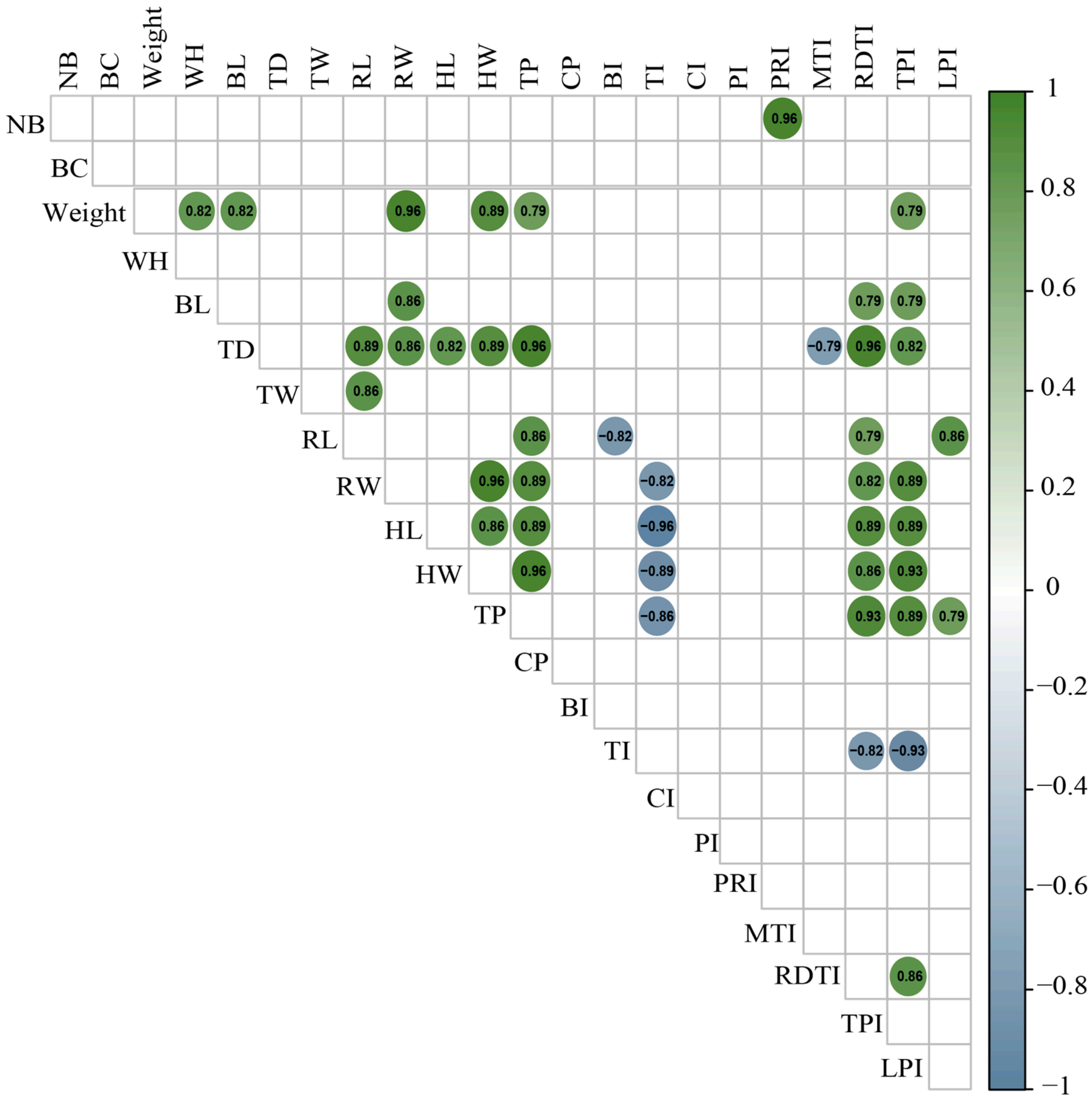

Figure 3. Spearman correlation matrix among morphometric traits and zoometric indices in Criollo sheep. Variables include: NB (Number of Births), BC (Body Condition Score), Weight (Body Weight), WH (Withers Height), BL (Body Length), TD (Dorso-Sternal Diameter), TW (Bicostal Diameter), RL (Rump Length), RW (Rump Width), HL (Head Length), HW (Head Width), TP (Thoracic Perimeter), CP (Cannon Bone Perimeter), BI (Body Index), TI (Thoracic Index), CI (Cephalic Index), PI (Pelvic Index), PRI (Proportionality Index), MTI (Metacarpal–Thoracic Index), RDTI (Relative Thoracic Depth Index), TPI (Transverse Pelvic Index), and LPI (Longitudinal Pelvic Index).

3.5. Effects of Sex and Dental Development on Morphometric Traits of Criollo Sheep

According to the Type III ANOVA results (Table S3), dentition stage exerted a statistically significant effect on TP, weight, CP, RL, and HL ($p < 0.001$). Significant differences by sex were detected in weight ($p = 0.0011$), CP ($p = 0.0046$), and HL ($p < 0.001$), but not in TP or RL. District also influenced weight significantly ($p < 0.001$). Although most interaction terms between sex and dentition were not significant, specific effects emerged for weight (Sex × Teeth 4D, $p < 0.001$) and CP (Sex × Teeth 4D, $p = 0.018$). No interaction effects were identified for TP, RL, or HL. Dentition stage also had a significant impact on TI ($p = 0.039$), RDTI, PRI, and TPI (all $p < 0.001$), whereas sex and interaction terms remained non-significant. Similarly, LPI ($p < 0.001$) and MTI ($p = 0.029$) responded to dentition stage, while PI and BI remained unaffected. No main or interaction effects of sex were recorded for any of these indices.

The stage of dentition significantly affected CI, BL, TD, and TW (all $p < 0.001$). Sex effects reached significance for BL ($p = 0.008$) and TW ($p < 0.001$). Only TW exhibited a significant overall interaction term ($p = 0.012$), with specific differences at stages 4D ($p = 0.002$) and 6D ($p = 0.011$). Significant effects were also identified at 4D for CI ($p = 0.022$) and BL ($p = 0.004$). Moreover, WH, RW, and HW were significantly affected by the teeth stage (all $p < 0.001$). The main effects of sex were significant for WH ($p = 0.002$) and HW ($p = 0.019$), while sex × teeth interactions were significant for WH ($p = 0.005$) and RW ($p = 0.012$), with specific effects observed at stage 4D for all three traits and additional effects at 8D for WH ($p = 0.015$) and 6D for HW ($p = 0.022$).

The LMM results (Table S4) indicate a consistent and positive influence of early dentition stages (1D and 2D) on TP, weight, and CP ($p < 0.001$), as well as on RL ($p < 0.01$). Sex did not contribute significantly to any of these traits ($p > 0.27$). Intercepts were statistically significant across traits, confirming robust baseline estimates. For HL, all tooth eruption stages were positively associated ($p < 0.0001$), with sex presenting a marginal effect ($p = 0.063$). In contrast, for TI, only the 2D stage contributed significantly and negatively ($p = 0.0049$). RDTI exhibited positive associations with all stages, particularly 2D ($p < 0.001$), while no effect of sex was observed. PRI was positively associated with stage 3D ($p = 0.0039$); other variables remained non-significant. TPI was positively related to 2D ($p = 0.0002$), while LPI responded only to stage 1D ($p = 0.032$). No significant effects were observed for PI or MTI, suggesting a limited influence of dentition or sex on these traits. BI decreased significantly with stage 1D ($p = 0.025$), and marginally with 2D ($p = 0.052$). CI presented negative associations with 2D ($p = 0.0001$) and 3D ($p < 0.0001$), with a borderline effect of sex ($p = 0.0517$).

Clear positive trends were documented in BL and TD, especially from 2D onward ($p < 0.001$), with no influence of sex. Lastly, dentition stage contributed significantly to TW, WH, RW, and HW, particularly at stages 1D and 2D ($p < 0.05$). Stage 3D maintained significance for TW ($p = 0.0013$) and WH ($p = 0.0064$), but not for RW or HW. Sex did not influence any of these four traits (Figures S1–S4). Figure 4A displays PT, showing a clear increasing trend with advancing dentition stages, reflecting age-related growth. Notably, individuals from Tisco exhibit consistently higher PT values, particularly in older dentition stages, aligning with the district-level differences observed in the linear mixed-effects models. Figure 4B highlights CP, which also increases with age. While district-level differences are more subtle than in PT, variations are still noticeable in early dentition stages, especially between Yanque and Tisco. Figure 4C represents RL, which steadily increases across dentition stages; however, the values overlap considerably among districts, suggesting that RL is primarily influenced by age rather than location. Figure 4D shows HL, which follows a similar increasing pattern with dentition stage and shows minimal spatial differentiation.

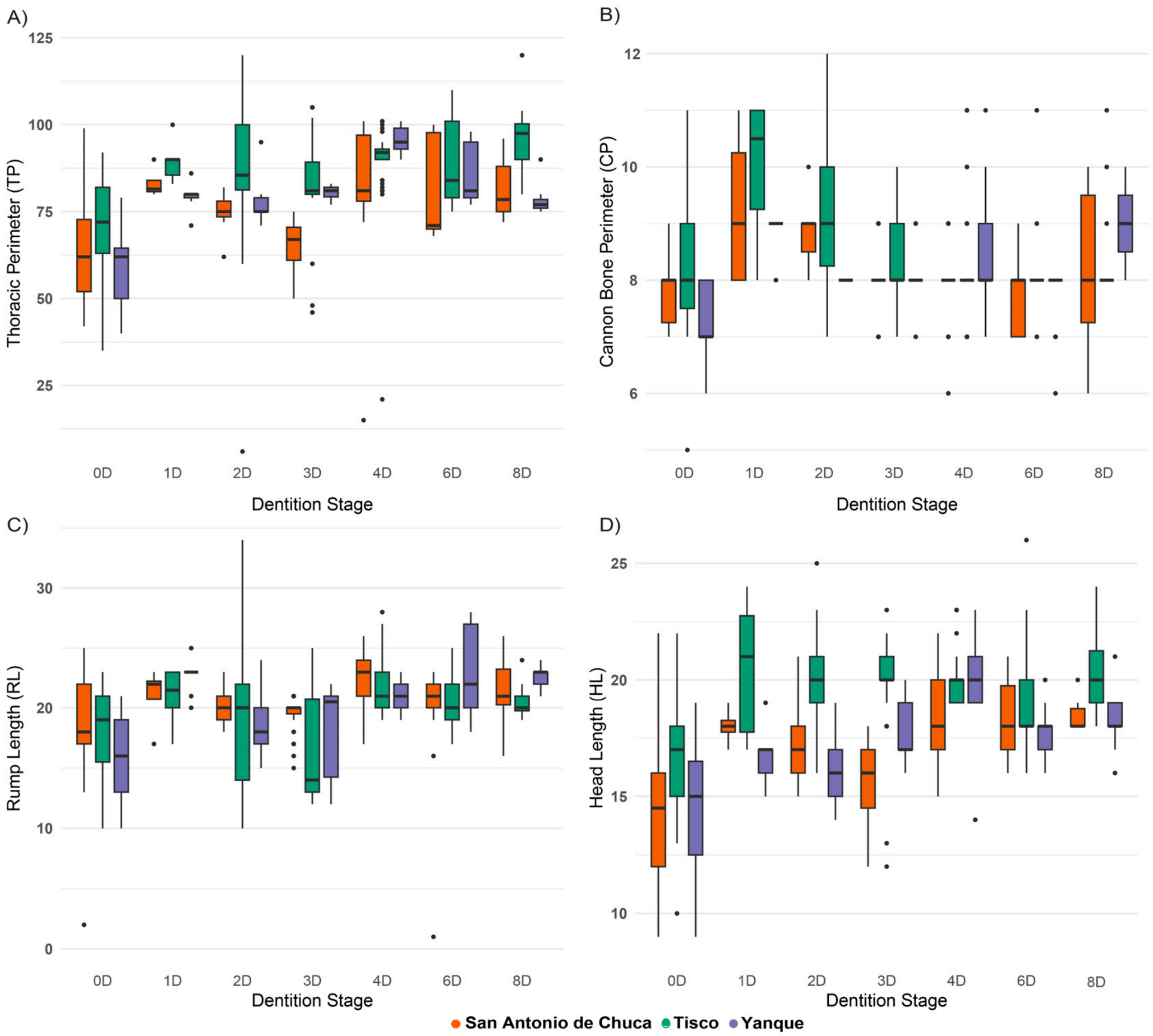

Figure 4. Boxplots of thoracic perimeter (**A**), cannon bone perimeter (**B**) rump length (**C**), head length (**D**), by district and dentition stage in Criollo sheep from Tisco, San Antonio de Chuca, and Yanque.

4. Discussion

The sociodemographic and productive characterization of sheep farmers in Caylloma reveals structural limitations commonly observed in high Andean livestock systems. The low level of formal education, with primary schooling predominating, aligns with reports from Peru and Argentina and restricts technological adoption [12]. Nevertheless, the activity demonstrates strong cultural rootedness, with decades of experience reflecting inherited practices [13]. However, the aging of producers and the limited generational renewal—also observed in Bolivia—threaten the long-term sustainability of these systems [14]. The high economic dependence on sheep farming, particularly in extensive pastoral systems, reinforces its role in rural food security [15]. Still, the progressive reduction of flocks and limited access to specialized technical assistance highlight its vulnerability [16,17]. Without targeted institutional support, these systems risk stagnation, making it urgent to integrate training strategies, extension services, and the valorization of local knowledge [12].

The sanitary management of Creole sheep flocks in Caylloma highlights the structural limitations of extensive high-Andean sheep production systems. The complete absence of health calendars and the low frequency of deworming (1–2 times per year) favor the persistence of diseases such as pneumonia, ectoparasitosis, and fascioliasis, whose prevalence has been previously documented in the Peruvian highlands [18]. The widespread preference for veterinary pharmaceuticals over ethnoveterinary practices [19], along with the near-total absence of hoof trimming, reflects an empirical management style with minimal technical support. Additionally, reproduction without andrological control hampers genetic improvement and is common in traditional communal grazing systems [20,21]. The morphological differences observed between sexes and districts—greater body development in males and intra-breed variability—are consistent with studies describing marked sexual dimorphism [22] and phenotypic plasticity influenced by the local environment [23].

Morphometric variation in Creole sheep showed significant structuring influenced by age (dentition), sex, and district of origin, highlighting the interaction between biological and geographical factors. This pattern is consistent with the findings of Ormachea et al. [24], reported progressive increases in body dimensions with age in Creole sheep from the Peruvian Altiplano, emphasizing the role of the environment in morphological development. Similarly, Megdiche [25] identified marked differences among sheep populations based on their geographic origin, attributed to the combined influence of environmental adaptation and genetic variability. Thutwa et al. [7] also reported that sex and region significantly affect live weight and linear body measurements in sheep from Botswana, with a clear expression of sexual dimorphism.

The strong positive correlations among morphometric variables in Creole sheep from Caylloma suggest a harmonious body growth pattern, in which increases in size are accompanied by proportional development of the trunk, limbs, and head [24]. In particular, the association between withers height (WH), body length (BL), thoracic perimeter (TP), and their relative indices supports a functionally robust conformation, critical for adaptation to hypobaric high-Andean conditions, where increased respiratory capacity is advantageous [8,9]. Similarly, the correlation between cannon bone perimeter (CP) and other body dimensions reinforces the hypothesis that these animals have developed strong limbs suited to rugged environments. However, some weaker correlations, such as between thoracic width (TW) and limb height, indicate structural independence, which could be selectively leveraged without compromising other functional traits [24].

From an applied perspective, these correlations offer valuable insights for genetic selection programs. Thoracic perimeter, which shows a strong relationship with live weight, can serve as a practical and cost-effective predictor of body mass, as demonstrated in Creole populations from the Peruvian Altiplano with coefficients of $r > 0.9$ [24]. Furthermore, zoometric indices provide a more integrated evaluation of the biotype than isolated linear measurements, allowing for distinction between compact animals (preferable for meat production) and more elongated individuals [26]. Therefore, selecting breeding animals with deep chests, good proportionality, and well-developed bone structure could enhance the flock's rusticity and functional capacity, traits essential in extensive systems.

These findings are consistent with results in other breeds and species. In Dorper lambs, a high correlation has been reported between TP and its relative index (TP/WH), confirming that appropriate thoracic development accompanies general body growth [9]. In Creole goats, structural indices have proven more informative than individual measurements for predicting productive functionality [26]. Likewise, De la Barra et al. [8] observed that indices related to bone and thoracic development explain a large portion of variability among meat sheep breeds in Chile. Taken together, the associations observed in Caylloma align with universal phenotypic patterns, reinforcing their usefulness as technical tools for selection, adaptation, and genetic improvement in Creole breeds from high-Andean regions. When interpreted in a broader Andean context, the morphometric patterns observed in Caylloma are consistent with those reported in other high-altitude Andean sheep populations. Traits such as thoracic development, limb robustness, and body compactness reflect common adaptive responses to hypoxia, limited forage, and rugged terrain [8,27].

Beyond their predictive value, several of these morphometric traits may also reflect deeper adaptive mechanisms. Morphological characteristics, such as increased thoracic depth, body compactness, and robust cannon bone perimeter in Creole sheep likely contribute to their adaptation to high-altitude challenges, including hypoxia, forage scarcity, and disease pressure. Evidence from studies on indigenous cattle indicates that these traits are associated with enhanced oxygen transport, more efficient energy utilization, and increased skeletal robustness, which support mobility and resilience in challenging environments [28]. The expression of these traits, shaped by both genetic differentiation and phenotypic plasticity, highlights their potential use as functional markers of adaptation in harsh ecological conditions [29].

Additionally, the observed increase in thoracic perimeter among Creole sheep may imply a greater thoracic cavity volume, potentially leading to improved lung capacity. In high-altitude environments, such as Caylloma, where oxygen partial pressure is reduced, a larger lung volume could enhance the surface area available for alveolar gas exchange, thereby improving oxygen uptake efficiency. This structural adaptation is critical for sustaining metabolic and thermoregulatory functions under chronic hypoxia. Similar evidence in highland cattle suggests that expanded thoracic dimensions contribute to enhanced pulmonary ventilation and more stable blood oxygen saturation levels in low-oxygen environments [30,31]. Therefore, the strong correlation observed between thoracic perimeter and other morphometric traits in this study not only reflects structural integration but also suggests a potential role as an indirect marker of respiratory adaptation to high-altitude conditions.

Recent scientific evidence supports that dental development, commonly used as an indirect indicator of age, is significantly correlated with body weight and morphometric dimensions in small ruminants. Various studies have shown that as animals progress through dental classes, significant increases are observed in live weight and linear measurements, such as thoracic circumference, body length, and rump length [24,32,33]. For instance, Hagos et al. [33] reported in Ethiopian sheep a progressive increase in weight and most linear morphometric parameters with advancing dental development. Similarly, Tella [32] identified a comparable trend in native goats, where individuals with temporary dentition presented smaller measurements compared to those with complete permanent dentition.

In the case of Creole sheep, Ormachea et al. [24] demonstrated that from the dental stage corresponding to full incisors (around three years of age), there are significant increases in body weight, body volume, thoracic circumference, and rump length. These changes reflect a process of morphostructural maturation, suggesting that zoometric indices derived from these measurements, such as the thoracic index, relative depth index, and pelvic index, also vary according to dentition [24].

Additionally, sexual dimorphism is a relevant factor influencing these traits. Several studies indicate that, within the same age category, males generally exhibit greater body dimensions than females. In this regard, Hagos et al. [33] reported an average weight of 23.23 kg in male lambs compared to 20.81 kg in females, while Tella [32] recorded significant sex-based differences across all evaluated age groups, although in both cases, the measurements increased with age. These findings agree that sex significantly influences body size and morphometric proportions, thereby modifying the calculated body indices.

Although few studies have explicitly analyzed the interaction between sex and dental stage, some evidence suggests that such interaction may modulate the relationship between dental development and morphometry. In this context, Assan et al. [34] evaluated

Matebele goats and observed that the most accurate combination for predicting live weight (thoracic circumference and rump height) varied according to the stage of tooth eruption, reinforcing the notion that the predictive utility of morphometric measurements depends on dental status.

5. Conclusions

This study confirms that dental stage, sex, and geographic origin are key drivers of morphometric variation in Creole sheep from Caylloma, fulfilling the research objectives. Strong associations among body traits support the use of simple, low-cost measurements, such as thoracic circumference and dentition, to estimate body weight and guide sales or management decisions. For example, thoracic perimeter showed a strong positive correlation with live weight (r = 0.84), and males exhibited up to 10% greater values in key dimensions such as body length, withers height, and rump width compared to females. Morphometric traits, such as cannon bone perimeter and rump length, also varied significantly with dentition stage ($p < 0.001$), reinforcing their value as predictors of body development. From a breeding perspective, animals with deep thoracic chests, strong limbs, and balanced proportions should be prioritized to improve resilience under high-altitude conditions. This study also reveals systemic weaknesses in health care and technical access, with 92.3% of producers relying on deworming but none applying structured health calendars, and 100% practicing uncontrolled natural mating. These findings highlight the need for targeted institutional support. Limitations include a small survey sample and the absence of genetic data to evaluate potential introgression effects. Future research should incorporate molecular tools and broader surveys to strengthen genetic improvement and conservation strategies.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agriculture15171860/s1: Figure S1: Boxplots of RDTI (A), PRI (B), TPI (C), LPI (D), IPE (E), and MTI (F) by sex and dentition stage in Criollo sheep from Tisco, San Antonio de Chuca, and Yanque; Figure S2: Boxplots of BI (A), CI (B), BL (C), TD (D), TW (E), and WH (F) by sex and dentition stage in the same populations; Figure S3: Boxplots of RW (A) and HW (B) by sex and dentition stage in the same populations; Figure S4: Boxplots of RW (A), and HW (B), by sex and dentition stage in Criollo sheep from Tisco, San Antonio de Chuca, and Yanque; Table S1: Sanitary and reproductive management; Table S2: Phenotypic traits by sex and district; Table S3: Type III ANOVA summary; Table S4: Fixed effects summary for all traits (LMM).

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