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Integrated multivariate morphometric analysis reveals distinct body conformation and enables breed-specific body weight prediction in Molai Adu and Pallai Adu goats

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Abstract

Objective morphometric differentiation of closely related indigenous goat populations is essential for accurate breed characterization, conservation and sustainable genetic improvement. The present study evaluated morphometric variation, body conformation, breed discrimination and body weight prediction in 564 adult goats comprising 277 Molai Adu and 287 Pallai Adu using nine morphometric traits. An integrated multivariate analytical framework involving correlation analysis, structural body indices, principal component analysis, canonical discriminant analysis and regression modelling was employed to investigate morphometric relationships and develop breed-specific body weight prediction models. The analyses consistently demonstrated clear morphometric differentiation between the two indigenous goat populations. Molai Adu exhibited a distinct morphometric architecture and body conformation compared with Pallai Adu, while canonical discriminant analysis achieved a cross-validated classification accuracy of 95.6%, confirming excellent breed discrimination. Breed-specific stepwise regression models accurately predicted body weight using only a few morphometric measurements, with body length and height at withers identified as the most informative predictors in Molai Adu and Pallai Adu, respectively. These findings demonstrate that integrating multivariate morphometric analyses with breed-specific prediction models provides a robust and practical framework for objective breed characterization, breed discrimination and on-farm body weight estimation. The study provides valuable baseline information to support breed registration, conservation planning and genetic improvement of indigenous goat genetic resources.

1. Introduction

Indigenous goat populations constitute an important component of global animal genetic resources because of their unique adaptation to diverse agro-ecological environments, disease tolerance and ability to sustain production under low-input production systems. These populations have evolved through long-term natural and farmer-driven selection, resulting in distinct phenotypic characteristics that reflect both genetic background and environmental adaptation (Dixit et al. 2010). Accurate characterization of indigenous goat genetic resources is therefore fundamental for breed recognition, conservation planning, sustainable utilization and genetic improvement (Hoffmann et al. 2011). Although molecular tools have become increasingly accessible, phenotypic characterization remains an indispensable first step in documenting breed identity and evaluating morphological diversity, particularly for locally adapted populations where genomic information is still limited (Groeneveld et al. 2010; Chacon et al. 2011; FAO 2012; Magaco and Felimone 2020).

Morphometric measurements provide an objective and economical means of evaluating body size, shape and conformation and have consequently become one of the most widely used approaches for breed characterization in livestock. Beyond their descriptive value, body measurements are closely associated with economically important traits such as body weight, growth performance and production potential (Melesse et al. 2013; Arandas et al. 2017; Valsalan et al. 2020). Consequently, morphometric traits are frequently used to develop practical body weight prediction models, particularly under field conditions where weighing facilities are unavailable (Khargharia et al. 2015). However, body measurements are biologically interrelated because they collectively describe different dimensions of body conformation. Evaluating these traits individually using conventional univariate approaches often overlooks their underlying relationships and limits the ability to objectively distinguish closely related populations.

Multivariate statistical approaches provide a comprehensive framework for analysing complex morphometric data by simultaneously evaluating the relationships among multiple body measurements. Correlation analysis quantifies the associations among morphometric traits, while structural body indices facilitate the assessment of body proportions and functional conformation (Gelaye et al. 2022; Selvan et al. 2023). Principal component analysis (PCA) summarizes correlated measurements into a smaller number of independent components representing the major dimensions of body architecture, thereby reducing data redundancy and identifying the traits that account for most of the observed variation (Okpeku et al. 2011; Mishra et al. 2017; Okoro et al. 2023; Dinesh et al. 2024). Canonical discriminant analysis (CDA) further evaluates the discriminatory ability of morphometric traits and objectively distinguishes phenotypically similar populations (Yakubu et al. 2010, b; Legaz et al. 2011; Selolo et al. 2015; Arandas et al. 2017). In addition, regression analysis enables the development of reliable body weight prediction equations based on easily measurable morphometric traits, providing practical decision-support

tools for livestock production and management (Thiruvenkadan, 2005; Sebolai et al. 2012; Raja et al. 2015; Karna et al. 2020, 2022). The integration of these complementary analytical approaches therefore offers a robust framework for understanding morphometric architecture, breed differentiation and practical trait prediction.

India possesses one of the richest repositories of indigenous goat genetic resources, with numerous recognized and unrecognized populations adapted to diverse ecological niches. Among these, Molai Adu is a distinctive indigenous meat-type goat population native to western Tamil Nadu and is recognized as the only naturally polled goat population reported in India (Seevagan et al. 2026a). Pallai Adu, in contrast, is a closely related horned indigenous goat population distributed in the adjoining regions of the state (Seevagan et al. 2026b). Although the phenotypic characteristics of these two populations have recently been documented, their underlying morphometric architecture, structural body conformation and the extent of phenotypic differentiation have not been investigated using an integrated multivariate analytical framework. Furthermore, breed-specific body weight prediction models based on morphometric traits have not been developed for either population, limiting their practical application under field conditions.

Addressing these knowledge gaps is important for objective breed discrimination, conservation planning and sustainable utilization of these indigenous genetic resources. Understanding the relationships among morphometric traits, identifying the principal dimensions governing body conformation and determining the measurements responsible for breed differentiation will strengthen phenotypic characterization and facilitate evidence-based breed management. Likewise, accurate breed-specific body weight prediction models based on easily measurable morphometric traits can provide valuable tools for farmers, veterinarians and extension personnel where weighing scales are unavailable.

Therefore, the present study aimed to comprehensively investigate the morphometric architecture of Molai Adu and Pallai Adu goats using an integrated multivariate analytical framework. Specifically, the study examined the interrelationships among morphometric traits, evaluated structural body conformation, quantified morphometric differentiation between the two indigenous goat populations, and developed breed-specific regression models for accurate prediction of body weight using easily measurable morphometric traits.

2. Materials and Methods

2.1. Study animals and morphometric measurements

The present study was conducted using two indigenous goat populations of Tamil Nadu, namely Molai Adu and Pallai Adu. A total of 564 apparently healthy adult goats comprising 277 Molai Adu (56 males and 221 females) and 287 Pallai Adu (67 males and 220 females) were included in the investigation. The animals were maintained under traditional extensive and semi-intensive production systems within their respective native breeding tracts. Only adult animals with fully developed body conformation were considered in order to minimize age-related variation in morphometric characteristics.

The morphometric dataset analysed in the present investigation was derived from the phenotypic characterization studies of Molai Adu and Pallai Adu goats previously conducted by our research group. The descriptive morphometric characteristics and breed-specific phenotypic attributes of these two indigenous goat populations have been reported elsewhere (Seevagan et al. 2026a, 2026b). The present investigation represents an independent multivariate evaluation of the same dataset, thereby enabling a comprehensive assessment of morphometric relationships, structural body conformation, breed discrimination and body weight prediction beyond the scope of the original phenotypic characterization studies.

Body weight (BW) was recorded using a portable electronic weighing balance prior to morphometric measurements. Subsequently, nine morphometric traits, namely height at withers (HW), chest girth (CG), pelvic girth (PG), body length (BL), face length (FL), ear length (EL), tail length (TL), skin fold thickness at the flank (SFT-F) and skin fold thickness at the neck (SFT-N), were measured following standard procedures in accordance with the phenotypic characterization guidelines for animal genetic resources outlined by the Food and Agriculture Organization (FAO 2012). All linear body measurements were recorded in centimetres, except body weight, which was expressed in kilograms, and skin fold thickness, which was measured in millimetres. To minimize measurement error and observer bias, all observations were recorded by the same investigator using

a standardized measurement protocol. The recorded morphometric measurements were subsequently used to evaluate the relationships among body dimensions, assess structural body conformation through body indices and principal component analysis, quantify breed differentiation using canonical discriminant analysis and develop breed-specific regression models for predicting body weight.

2.2. Structural body indices

To facilitate the functional interpretation of body conformation beyond individual morphometric measurements, a set of structural body indices was computed from the recorded morphometric traits. These indices provide quantitative measures of body proportions and have been widely used for evaluating breed characteristics, functional morphology and production aptitude in small ruminants (Tyasi and Tada, 2023; Shahnaz et al. 2025). Seven structural indices, namely body index (BI), length index (LI), area index (AI), thoracic development index (TDI), compact index (CI), conformation index (COMI) and height index (HI) were calculated using standard morphometric measurements. The calculated indices were subsequently compared between Molai Adu and Pallai Adu goats to assess differences in body conformation and structural proportions.

2.3. Statistical analyses

Prior to statistical analyses, the dataset was examined for completeness, consistency and potential data entry errors. All statistical analyses were performed using IBM SPSS Statistics version 27.0 (IBM Corp., Armonk, NY, USA). Statistical significance was declared at $P < 0.05$ unless otherwise stated.

Pearson's correlation coefficients were computed separately for Molai Adu and Pallai Adu goats to quantify the relationships between body weight and morphometric traits, as well as the interrelationships among morphometric measurements. The strength and direction of the associations were interpreted based on the correlation coefficients, and statistical significance was evaluated at the 5% and 1% probability levels.

Principal component analysis (PCA) was performed separately for each breed using the correlation matrix of the morphometric traits to identify the principal sources of variation and to reduce data dimensionality. The suitability of the dataset for PCA was assessed using the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity. Principal components with eigenvalues greater than one were retained according to the Kaiser criterion. To facilitate interpretation, the retained components were subjected to orthogonal Varimax rotation with Kaiser normalization. Variables with rotated factor loadings of ≥ 0.40 were considered to contribute meaningfully to a principal component, and communalities were examined to evaluate the proportion of variance explained by the retained components.

Canonical discriminant analysis (CDA) was performed using the combined dataset of Molai Adu and Pallai Adu goats to evaluate the effectiveness of morphometric traits in discriminating between the two indigenous goat populations. Standardized canonical discriminant function coefficients were used to assess the relative contribution of individual morphometric traits to breed differentiation. The significance of the discriminant function was evaluated using Wilks' Lambda and the associated chi-square test. The classification performance of the discriminant model was assessed using both the original grouped cases and leave-one-out cross-validation to estimate the robustness of breed classification.

Body weight prediction models were developed separately for Molai Adu and Pallai Adu goats using simple linear regression and multiple linear regression analyses. Initially, individual morphometric traits were evaluated as independent predictors of body weight using simple linear regression. Subsequently, multiple regression models were developed using both the ‘enter’ and ‘stepwise’ variable selection procedures. Body weight was considered the dependent variable, while the recorded morphometric traits served as independent variables. Model performance was evaluated using the coefficient of determination (R^2), adjusted coefficient of determination (adjusted R^2), standard error of estimate (SEE) and Durbin–Watson statistic, and the final prediction equations were derived from the best-performing stepwise regression models.

3. Results

3.1. Correlation among body weight and morphometric traits

Body weight exhibited significant positive correlations with most morphometric traits in both Molai Adu and Pallai Adu goats, although the magnitude and pattern of these associations differed between the two breeds (Tables 1 and 2). In Molai Adu goats, body weight showed significant (P < 0.01) positive correlations with all measured morphometric traits. The strongest association was observed with body length (r = 0.590), followed by skin fold thickness at the flank (r = 0.545), face length (r = 0.535), pelvic girth (r = 0.516) and tail length (r = 0.469), whereas comparatively weaker correlations were observed with chest girth (r = 0.211) and ear length (r = 0.280). Significant positive interrelationships were also evident among most morphometric traits, with particularly high correlations observed between skin fold thickness at the flank and neck (r = 0.765), face length and skin fold thickness at the neck (r = 0.683), body length and skin fold thickness at the neck (r = 0.670), and body length and tail length (r = 0.653).

Table 1
Pearson's correlation coefficients among body weight and morphometric traits in adult Molai Adu goats

Traits	BW	HW	CG	PG	BL	FL	EL	TL	SFT(F)	SFT(N)
BW	1									
HW	0.431**	1								
CG	0.211**	0.363**	1							
PG	0.516**	0.321**	0.100	1						
BL	0.590**	0.413**	0.473**	0.445**	1					
FL	0.535**	0.479**	0.445**	0.329**	0.506**	1				
EL	0.280**	0.211**	0.214**	0.580**	0.386**	0.325**	1			
TL	0.469**	0.260**	0.295**	0.537**	0.653**	0.556**	0.367**	1		
SFT_F	0.545**	0.348**	0.413**	0.547**	0.507**	0.630**	0.491**	0.591**	1	
SFT_N	0.387**	0.266**	0.435**	0.438**	0.670**	0.683**	0.507**	0.605**	0.765**	1

BW - Body Weight; HW - Height at Withers; CG - Chest Girth; PG - Pelvic Girth; BL - Body Length; FL - Face Length; EL - Ear Length; TL - Tail Length; SFT(F) - Skin Fold Thickness (Flank); SFT(N)- Skin Fold Thickness (Neck); ** p < 0.01

Table 2
Pearson's correlation coefficients among body weight and morphometric traits in adult Pallai Adu goats

Traits	BW	HW	CG	PG	BL	FL	EL	TL	SFT(F)	SFT(N)
BW	1									
HW	0.588**	1								
CG	0.365**	0.492**	1							
PG	0.342**	0.168**	0.260**	1						
BL	0.308**	0.227**	0.260**	0.489**	1					
FL	0.115	0.152**	-0.018	-0.217**	0.032	1				
EL	0.024	-0.014	-0.076	0.090	0.095	-0.057	1			
TL	0.122*	0.053	0.003	-0.131	0.116	0.114	0.036	1		
SFT_F	0.029	-0.030	-0.001	-0.167	-0.074	0.129*	0.039	0.135*	1	
SFT_N	0.101	0.127*	-0.030	-0.137	-0.111	0.297**	-0.078	0.092	0.268**	1

BW - Body Weight; HW - Height at Withers; CG - Chest Girth; PG - Pelvic Girth; BL - Body Length; FL - Face Length; EL - Ear Length; TL - Tail Length; SFT(F) - Skin Fold Thickness (Flank); SFT(N)- Skin Fold Thickness (Neck); * $p < 0.05$; ** $p < 0.01$.

In Pallai Adu goats, body weight was most strongly correlated with height at withers ($r = 0.588$; $P < 0.01$), followed by chest girth ($r = 0.365$), pelvic girth ($r = 0.342$) and body length ($r = 0.308$). In contrast, face length, ear length, tail length, skin fold thickness at the flank and skin fold thickness at the neck exhibited weak or non-significant associations with body weight. Correlations among morphometric traits were generally lower than those observed in Molai Adu goats, although significant positive relationships were identified between height at withers and chest girth ($r = 0.492$), pelvic girth and body length ($r = 0.489$), and skin fold thickness at the flank and neck ($r = 0.268$). A few significant negative correlations were also observed, particularly involving pelvic girth with face length ($r = -0.217$), tail length ($r = -0.131$), skin fold thickness at the flank ($r = -0.167$) and skin fold thickness at the neck ($r = -0.137$).

3.2. Comparison of structural indices

The structural indices of adult Molai Adu and Pallai Adu goats are presented in Table 3. Significant differences ($P < 0.05$) were observed between the two breeds for all structural indices evaluated. Molai Adu goats exhibited significantly higher values for body index (99.72 vs. 94.97), length index (106.33 vs. 102.68), area index (4514.34 vs. 3358.94), compact index (74.21 vs. 67.02) and conformation index (47.09 vs. 44.48) than Pallai Adu goats ($P < 0.001$). In contrast, Pallai Adu goats showed significantly higher thoracic development index (108.26 vs. 106.69; $P = 0.016$) and height index (98.16 vs. 94.58; $P < 0.001$) compared with Molai Adu goats. The largest between-breed difference was observed for area index ($t = 28.454$; $P < 0.001$), whereas thoracic development index exhibited the smallest, although statistically significant, difference ($t = -2.406$; $P = 0.016$).

Table 3
Comparison of structural indices between adult Molai Adu and Pallai Adu goats

Structural Index	Formula	Molai Adu (Mean ± SE)	Pallai Adu (Mean ± SE)	t-value	P-value
Body Index (BI)	(BL / CG) x 100	99.72 ± 0.13	94.97 ± 0.46	9.778	< 0.001
Length index (LI)	(BL / HW) x 100	106.33 ± 0.48	102.68 ± 0.55	4.992	< 0.001
Area index (AI)	HW x BL	4514.34 ± 34.22	3358.94 ± 22.37	28.454	< 0.001
Thoracic development index (TDI)	(CG / HW) x 100	106.69 ± 0.52	108.26 ± 0.39	-2.406	0.016
Compact index (CI)	(BW / HW) x 100	74.21 ± 0.65	67.02 ± 0.39	9.524	< 0.001
Conformation index (COMI)	$(CG)^2$ / HW	47.09 ± 0.49	44.48 ± 0.37	4.209	< 0.001
Height index (HI)	(HW / BL) x 100	94.58 ± 0.44	98.16 ± 0.52	-5.220	< 0.001

BL - Body Length; CG - Chest Girth; HW - Height at Withers; BW - Body Weight; Molai Adu (n = 277) and Pallai Adu (n = 287).

3.3. Principal component analysis

The suitability of the morphometric data for principal component analysis (PCA) was confirmed by the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity (Table 4). The KMO values were 0.852 for Molai Adu and 0.601 for Pallai Adu goats, indicating adequate sampling adequacy for PCA. Bartlett's test of sphericity was highly significant ($P < 0.001$) in both breeds, confirming that the correlation matrices were appropriate for factor extraction. Based on the Kaiser criterion (eigenvalue > 1), two principal components were retained for Molai Adu goats, accounting for 68.96% of the total variance, whereas three principal components were retained for Pallai Adu goats, explaining 54.70% of the total variance. The scree plots illustrating the distribution of eigenvalues and the number of principal components retained for each breed are presented in Fig. 1.

Table 4
Summary statistics of principal component analysis for morphometric traits in adult Molai Adu and Pallai Adu goats

Breed	KMO	Bartlett's χ^2	df	P-value	Components Retained	Total Variance Explained (%)
Molai Adu	0.852	1891.721	36	< 0.001	2	68.96
Pallai Adu	0.601	342.493	36	< 0.001	3	54.70

KMO = Kaiser-Meyer-Olkin measure of sampling adequacy. Principal components with eigenvalues > 1 were retained according to the Kaiser criterion.

The Varimax-rotated component matrix revealed distinct patterns of trait clustering between the two breeds (Table 5 and Fig. 2). In Molai Adu goats, the first principal component (PC1), which explained 56.07% of the total variance, exhibited high positive loadings for face length (0.848), body length (0.819), chest girth (0.749), skin fold thickness at the flank (0.703), skin fold thickness at the neck (0.633) and height at withers (0.577). The second principal component (PC2), accounting for an additional 12.89% of the variance, was characterized primarily by pelvic girth (0.864), ear length (0.793), tail length (0.623) and skin fold thickness at the flank (0.608). Communality estimates ranged from 0.564 for chest girth to 0.887 for body length, indicating that a substantial proportion of the variance of each trait was explained by the retained principal components.

Table 5
Eigenvalues, variance explained and Varimax-rotated component loadings of morphometric traits in adult Molai Adu and Pallai Adu goats

Traits	Molai Adu			Pallai Adu			
	PC1	PC2	Communalities	PC1	PC2	PC3	Communalities
HW	0.577	-	0.344	-	0.786	-	0.660
CG	0.749	-	0.564	-	0.784	-	0.630
PG	-	0.864	0.755	-0.637	0.489	-	0.692
BL	0.819	0.464	0.887	-	0.587	0.479	0.622
FL	0.848	-	0.831	0.608	-	-	0.398
EL	-	0.793	0.640	-	-	0.713	0.538
TL	0.470	0.623	0.609	-	-	0.544	0.443
SFT_F	0.703	0.608	0.863	0.572	-	-	0.392
SFT_N	0.633	0.559	0.713	0.730	-	-	0.549
Eigenvalue	**5.046**	**1.160**		**2.093**	**1.690**	**1.140**	
Variance explained (%)	**56.07**	**12.89**		**23.25**	**18.78**	**12.66**	
Cumulative variance (%)	**56.07**	**68.96**		**23.25**	**42.04**	**54.70**	

Principal component loadings < 0.40 were suppressed. HW - Height at Withers; CG - Chest Girth; PG - Pelvic Girth; BL - Body Length; FL - Face Length; EL - Ear Length; TL - Tail Length; SFT(F) - Skin Fold Thickness (Flank); SFT(N)- Skin Fold Thickness (Neck);

In Pallai Adu goats, PC1 explained 23.25% of the total variance and was mainly associated with skin fold thickness at the neck (0.730), face length (0.608) and skin fold thickness at the flank (0.572). The second principal component (PC2), accounting for 18.78% of the total variance, was primarily represented by height at withers (0.786) and chest girth (0.784), body length (0.587) and pelvic girth (0.489), while the third principal component (PC3), explaining 12.66% of the variance, was characterized by ear length (0.713), tail length (0.544) and body length (0.479). The communalities of the retained variables ranged from 0.392 for skin fold thickness at the flank to 0.692 for pelvic girth.

3.4. Canonical discriminant analysis

Canonical discriminant analysis (CDA) was performed to evaluate the ability of morphometric traits to differentiate adult Molai Adu and Pallai Adu goats. As only two breeds were included in the analysis, a single canonical discriminant function was extracted (Table 6). The discriminant function had an eigenvalue of 3.487 and a canonical correlation of 0.882, indicating a strong relationship between the discriminant scores and breed membership. Wilks' Lambda was 0.223 and the associated chi-square test was highly significant ($\chi^2 = 830.214$, df = 9; $P < 0.001$), confirming that the morphometric traits collectively provided significant discrimination between the two breeds.

Table 6
Summary statistics of canonical discriminant analysis for differentiation of adult Molai Adu and Pallai Adu goats

Parameter	Value
Number of discriminant functions	1
Eigenvalue	3.487
Canonical correlation	0.882
Wilks' Lambda	0.223
Chi-square	830.214
Degrees of freedom	9
P-value	< 0.001

The standardized canonical discriminant function coefficients indicated that body length (0.731), height at withers (0.684), pelvic girth (0.612), chest girth (-0.541), ear length (-0.463) and skin fold thickness at the neck (0.438) contributed most to breed differentiation, whereas face length, tail length and skin fold thickness at the flank had comparatively smaller contributions (Table 7).

Table 7
Standardized canonical discriminant function coefficients of morphometric traits

Morphometric traits	Standardized coefficient
Height at withers	0.684
Chest girth	-0.541
Pelvic girth	0.612
Body length	0.731
Face length	0.214
Ear length	-0.463
Tail length	0.188
Skin fold thickness (Flank)	0.296
Skin fold thickness (Neck)	0.438

The discriminant function achieved high classification accuracy for both breeds (Table 8). Based on the original grouped cases, 96.4% of Molai Adu and 96.1% of Pallai Adu goats were correctly classified, resulting in an overall classification accuracy of 96.2%. Cross-validation using the leave-one-out method yielded comparable results, with correct classification rates of 95.0% for Molai Adu and 96.2% for Pallai Adu goats, corresponding to an overall cross-validated accuracy of 95.6%. The distribution of individual canonical discriminant scores is illustrated in Fig. 3, demonstrating the clear separation between Molai Adu and Pallai Adu goats.

Table 8
Classification accuracy of canonical discriminant analysis for breed assignment

Breed	Original grouped cases correctly classified (%)	Cross-validated correctly classified (%)
Molai Adu	96.4	95.0
Pallai Adu	96.1	96.2
Overall accuracy	**96.2**	**95.6**

3.5. Prediction of body weight using morphometric traits

The predictive ability of individual morphometric traits for body weight was first evaluated using simple linear regression analysis (Table 9). In Molai Adu goats, body length was the best single predictor of body weight (R^2 = 0.357; adjusted R^2 = 0.354), followed by pelvic girth (R^2 = 0.275), chest girth (R^2 = 0.267) and height at withers (R^2 = 0.186), whereas face length, ear length, tail length and skin fold thickness measurements exhibited poor predictive ability ($R^2 \leq 0.011$). In Pallai Adu goats, height at withers was the most effective individual predictor (R^2 = 0.346; adjusted R^2 = 0.344), followed by chest girth (R^2 = 0.133), pelvic girth (R^2 = 0.117) and body length (R^2 = 0.095), while the remaining morphometric traits explained only a small proportion of the variation in body weight.

Table 9
Simple linear regression equations for prediction of body weight from individual morphometric traits in adult Molai Adu and Pallai Adu goats

Morphometric trait	Molai Adu (n = 277)					Pallai Adu (n = 287)				
	Regression equation	R^2	Adjusted R^2	SEE (kg)	P-value	Regression equation	R^2	Adjusted R^2	SEE (kg)	P-value
HW	BW = −2.614 + 0.511(HW)	0.186	0.183	5.429	< 0.001	BW = −11.056 + 0.639(HW)	0.346	0.344	3.480	< 0.001
CG	BW = −9.598 + 0.582(CG)	0.267	0.264	5.150	< 0.001	BW = −1.505 + 0.437(CG)	0.133	0.130	4.001	< 0.001
PG	BW = −18.676 + 0.673(PG)	0.275	0.273	5.121	< 0.001	BW = −0.975 + 0.390(PG)	0.117	0.114	4.044	< 0.001
BL	BW = −20.258 + 0.738(BL)	0.357	0.354	4.825	< 0.001	BW = 8.474 + 0.291(BL)	0.095	0.092	4.093	< 0.001
FL	BW = 26.093 + 0.236(FL)	0.005	0.001	6.000	0.237	BW = 20.809 + 0.236(FL)	0.013	0.010	4.274	0.052
EL	BW = 31.607 − 0.050(EL)	0.000	-0.003	6.015	0.803	BW = 24.601 + 0.064(EL)	0.001	-0.003	4.302	0.688
TL	BW = 36.937 − 0.384(TL)	0.011	0.007	5.983	0.085	BW = 20.123 + 0.315(TL)	0.015	0.011	4.271	0.039
SFT_F	BW = 27.685 + 1.018(SFT-F)	0.011	0.007	5.984	0.089	BW = 24.968 + 0.175(SFT-F)	0.001	-0.003	4.301	0.623
SFT_N	BW = 29.955 + 0.240(SFT-N)	0.001	-0.003	6.012	0.579	BW = 23.690 + 0.544(SFT-N)	0.010	0.007	4.281	0.088

Multiple linear regression analysis substantially improved body weight prediction in both breeds. The enter method included all measured morphometric traits, whereas the stepwise method retained only the most informative predictors while maintaining comparable predictive performance. The stepwise models showed adjusted R^2 values of 0.463 and 0.429, with standard errors of estimate of 4.401 kg and 3.245 kg for Molai Adu and Pallai Adu goats, respectively, indicating that reliable body weight prediction could be achieved using a reduced number of morphometric measurements (Table 10).

Table 10
Comparison of multiple linear regression models for prediction of body weight in adult Molai Adu and Pallai Adu goats

Regression method	Molai Adu				Pallai Adu			
	Variables retained	Adjusted R^2	SEE (kg)	Durbin–Watson	Variables retained	Adjusted R^2	SEE (kg)	Durbin–Watson
Enter	HW, BL, CG, PG, FL, EL, TL, SFT-F, SFT-N	0.459	4.418	0.869	HW, BL, CG, PG, FL, EL, TL, SFT-F, SFT-N	0.432	3.238	0.486
Stepwise	BL, PG, HW, CG, TL	0.463	4.401	0.874	HW, PG, TL, SFT-N	0.429	3.245	0.475

The stepwise regression procedure sequentially identified the most informative predictors of body weight in the two goat populations (Table 11). In Molai Adu goats, body length entered the model first, followed by pelvic girth, height at withers, chest girth and tail length, resulting in a final adjusted R^2 of 0.463. In Pallai Adu goats, height at withers was selected as the primary predictor, followed by pelvic girth, tail length and neck skin fold thickness, producing a final adjusted R^2 of 0.429. The corresponding breed-specific prediction equations were:

Table 11
Development of stepwise multiple regression models for prediction of body weight in adult Molai Adu and Pallai Adu goats

Model	Molai Adu			Pallai Adu		
	Variable entered	Adjusted R^2	SEE (kg)	Variable entered	Adjusted R^2	SEE (kg)
1	Body length	0.354	4.825	Height at withers	0.344	3.480
2	+ Pelvic girth	0.411	4.610	+ Pelvic girth	0.403	3.320
3	+ Height at withers	0.439	4.497	+ Tail length	0.417	3.281
4	+ Chest girth	0.456	4.429	+ Skin fold thickness (Neck)	0.429	3.245
5	+ Tail length	0.463	4.401			

Molai Adu: BW (kg) = − 34.964 + 1.061(BL) + 0.290(PG) + 0.224(HW) − 0.545(CG) − 0.354(TL).

Pallai Adu: BW (kg) = − 38.644 + 0.556(HW) + 0.360(PG) + 0.321(TL) + 0.705(SFT-N).

The agreement between observed and predicted body weights obtained from the final stepwise regression models is illustrated in Fig. 4, where the predicted values closely followed the observed measurements in both breeds, demonstrating the reliability and practical applicability of the developed breed-specific prediction models.

4. Discussion

4.1. Correlation among morphometric traits and structural body conformation

The present study revealed distinct patterns of morphometric relationships between Molai Adu and Pallai Adu goats, reflecting differences in their body conformation and phenotypic organization. Body weight showed stronger and more consistent positive correlations with morphometric traits in Molai Adu than in Pallai Adu, indicating a greater degree of coordinated body development. Such integrated growth patterns are generally associated with morphologically homogeneous populations, whereas weaker correlations may reflect greater phenotypic variability arising from differences in genetic background, environmental influences or management practices. Similar breed-dependent variation in morphometric relationships has been reported in several indigenous goat populations, highlighting that the strength of trait associations is closely related to body conformation and population structure (Yadav et al. 2016; Mishra et al. 2017).

Among the recorded measurements, body length exhibited the strongest association with body weight in Molai Adu, while height at withers was the best single correlate in Pallai Adu. These findings suggest that the principal determinant of body size differs between the two breeds, emphasizing the importance of developing breed-specific morphometric criteria for body weight estimation and selection. Comparable observations have been reported in indigenous goats from different production systems, where body length, chest girth or height at withers emerged as the most informative predictors depending on breed characteristics and production objectives (Salako, 2006; Yakubu and Ayoade, 2009; Yunusa et al. 2013).

Structural body indices further supported the differences revealed by the correlation analysis. Molai Adu exhibited significantly higher body, length, compact and conformation indices, indicating a relatively larger body frame with well-developed body proportions. In contrast, Pallai Adu showed higher thoracic development and height indices, suggesting differences in body

proportions and conformational architecture rather than overall body size. These contrasting structural profiles demonstrate that, despite their apparent phenotypic resemblance, the two indigenous goat populations differ substantially in body conformation. Similar applications of structural body indices have proven useful for evaluating functional body conformation and distinguishing indigenous goat populations (Tyasi and Tada, 2023; Shahnaz et al. 2025).

Collectively, the correlation analysis and structural body indices indicate that Molai Adu possesses a relatively taller and more integrated body conformation, whereas Pallai Adu exhibits comparatively greater body compactness and distinct body proportions. These complementary findings provide quantitative evidence of phenotypic differentiation between the two indigenous goat populations and establish a morphological basis for the subsequent multivariate analyses.

4.2. Principal component analysis

Principal component analysis revealed clear differences in the morphometric organization of Molai Adu and Pallai Adu goats. Although two principal components adequately summarized morphometric variation in Molai Adu, three components were required for Pallai Adu, indicating a comparatively simpler and more integrated body structure in the former and a more heterogeneous conformational pattern in the latter. Similar observations have been reported in indigenous goat populations where morphologically homogeneous breeds generally require fewer principal components to explain a larger proportion of total variation than more variable populations (Okpeku et al. 2011; Dinesh et al. 2024; Karna et al. 2024).

The first principal component represented the major body-size dimension in both breeds, confirming that overall skeletal development is the primary source of morphometric variation. However, the traits contributing to this component differed between breeds. In Molai Adu, body length, chest girth, height at withers and face length showed the highest loadings, suggesting coordinated skeletal growth and proportional body development. In contrast, the first component in Pallai Adu was dominated mainly by height at withers and chest girth, while body length and pelvic girth contributed substantially to subsequent components. This distribution indicates that body conformation in Pallai Adu is governed by multiple structural dimensions rather than a single generalized body-size factor, reflecting greater phenotypic diversity within the population.

The moderate to high communalities observed for most morphometric traits indicate that the retained principal components effectively represented the original measurements with minimal loss of information. Consequently, PCA successfully reduced redundancy among correlated variables while preserving the principal biological variation within each breed. Such dimensional reduction is particularly valuable in morphometric studies because it facilitates the identification of key conformational traits and minimizes multicollinearity in subsequent multivariate analyses (Mishra et al. 2017).

Overall, the contrasting component structures demonstrate that, despite their superficial phenotypic similarity, Molai Adu and Pallai Adu possess distinct underlying morphometric architectures. The relatively compact component structure of Molai Adu reflects greater morphometric integration, whereas the more dispersed component pattern of Pallai Adu suggests increased structural complexity. These findings not only complement the correlation and structural index analyses but also provide the multivariate basis for the high discriminatory power observed in the subsequent canonical discriminant analysis.

4.3. Canonical discriminant analysis

Canonical discriminant analysis demonstrated that the recorded morphometric traits effectively differentiated Molai Adu and Pallai Adu goats, confirming the existence of distinct breed-specific morphometric profiles. The significant discriminant function, together with the high canonical correlation and low Wilks' Lambda, indicates that the combined morphometric measurements possess strong discriminatory ability. These findings support previous reports that multivariate morphometric approaches provide more reliable breed discrimination than individual body measurements by simultaneously capturing variation across multiple anatomical dimensions (Dekhili et al. 2013; Arandas et al. 2017; Melesse et al. 2022).

Body length, height at withers, pelvic girth and chest girth contributed most strongly to breed discrimination, highlighting the importance of major skeletal measurements in defining breed identity. These traits largely determine overall body frame and conformation and therefore capture structural differences that are not readily apparent through visual assessment alone.

Similar observations have been reported in indigenous goat populations where measurements associated with skeletal development consistently showed the greatest discriminatory power among closely related breeds (Selolo et al. 2015).

A major strength of the present study was the high classification accuracy achieved by the discriminant model. More than 96% of animals were correctly assigned to their respective breeds, while the leave-one-out cross-validation procedure maintained an overall classification accuracy exceeding 95%. The close agreement between original and cross-validated classifications demonstrates that the discriminant function is robust and stable, with minimal evidence of model overfitting. Such high predictive performance indicates that the selected morphometric variables provide a reliable basis for objective breed identification and compares favourably with the classification accuracies reported for most indigenous goat populations (Dekhili et al. 2013; Arandas et al. 2017).

The clear separation of canonical scores observed between the two breeds further corroborates the findings obtained from the correlation analysis, structural body indices and principal component analysis. Collectively, these complementary multivariate approaches consistently demonstrate that Molai Adu and Pallai Adu differ not only in individual morphometric traits but also in their overall body conformation and morphometric organization. From a practical perspective, the discriminant function developed in the present study may serve as an objective tool for breed identification, phenotypic characterization and conservation of indigenous goat genetic resources, particularly where visual classification is complicated by overlapping external characteristics.

4.4. Body weight prediction using morphometric traits

Accurate estimation of body weight is essential for effective livestock management, influencing decisions related to nutrition, breeding, health care and marketing. However, access to weighing facilities remains limited under smallholder production systems, making morphometric measurements a practical alternative for estimating live body weight. The present study demonstrated that the predictive ability of individual morphometric traits differed between the two indigenous goat populations, emphasizing that body weight prediction models should be developed on a breed-specific basis rather than applying generalized equations across genetically distinct breeds.

Among the individual body measurements, body length was the best predictor of body weight in Molai Adu, whereas height at withers showed the strongest predictive ability in Pallai Adu. These findings indicate that the principal determinant of body size differs between the two breeds, reflecting differences in skeletal development and body conformation. Similar breed-specific variation in the predictive performance of morphometric traits has been reported in indigenous goats from different production environments, where body length, chest girth or height at withers have each been identified as the most reliable predictor depending on breed characteristics (Eyduran et al. 2013; Karna et al. 2020, 2022).

Multiple regression models improved prediction accuracy over simple linear regression by integrating information from several complementary morphometric traits. Nevertheless, the stepwise regression models achieved predictive performance comparable to the full models while requiring only a limited number of measurements. The retention of major skeletal traits, including body length, height at withers, chest girth and pelvic girth, confirms their central role in explaining body weight variation, whereas less informative measurements were excluded during model selection. Such parsimonious models are particularly advantageous under field conditions because they simplify data collection without substantially compromising predictive accuracy. Similar findings have been reported in several indigenous goat breeds, where stepwise regression has consistently produced efficient and practical prediction equations (Khargaria et al. 2015).

The close agreement between observed and predicted body weights further demonstrates the reliability of the developed regression equations. Although environmental and physiological factors inevitably contribute to variation in live body weight, the relatively low prediction error observed in both breeds indicates that the selected morphometric traits adequately capture the major sources of body weight variation. Consequently, the breed-specific equations developed in the present study provide practical tools for estimating live body weight where weighing scales are unavailable, thereby facilitating appropriate drug dosage, nutritional management, breeding decisions and livestock marketing.

Overall, the regression analyses complement the multivariate findings of the present study by translating morphometric variation into a practical field application. Together with the correlation analysis, structural body indices, principal component analysis and canonical discriminant analysis, the developed prediction models demonstrate that morphometric measurements can be used not only to characterize and discriminate indigenous goat populations but also to support evidence-based management and conservation of these valuable genetic resources.

Conclusion

This study provides the first comprehensive multivariate morphometric evaluation of Molai Adu and Pallai Adu goats by integrating structural body indices, principal component analysis, canonical discriminant analysis and body weight prediction modelling. The results demonstrate that, despite their apparent phenotypic resemblance, the two indigenous goat populations possess distinct morphometric architectures and body conformations. Principal component and canonical discriminant analyses effectively summarized morphometric variation and achieved high breed discrimination, while the breed-specific regression models provided reliable and practical tools for predicting body weight using a limited number of morphometric measurements. Collectively, these findings highlight the value of multivariate morphometric approaches for objective breed characterization, discrimination and field-level management of indigenous goats. The information generated in this study will support breed characterization, conservation and genetic improvement programmes, and provide a valuable foundation for the sustainable utilization of Molai Adu and Pallai Adu goat genetic resources.

Declarations

Declaration of Competing Interest:

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

Ethical Statement

Ethical approval was not applicable as the study involved only non-invasive morphometric measurements and body weight recording of indigenous goats under farmers' field conditions. Prior informed consent was obtained from all animal owners before data collection.

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Author contributions:

M. Seevagan led the study design, data analysis and manuscript writing. T. Ravimurugan, S.M.K. Karthickeyan, T. Anna, R. Rajendran and T. Thamil Vanan provided overall project supervision and critically revised the manuscript.

Data availability:

Data supporting the findings are available from the corresponding author upon reasonable request.

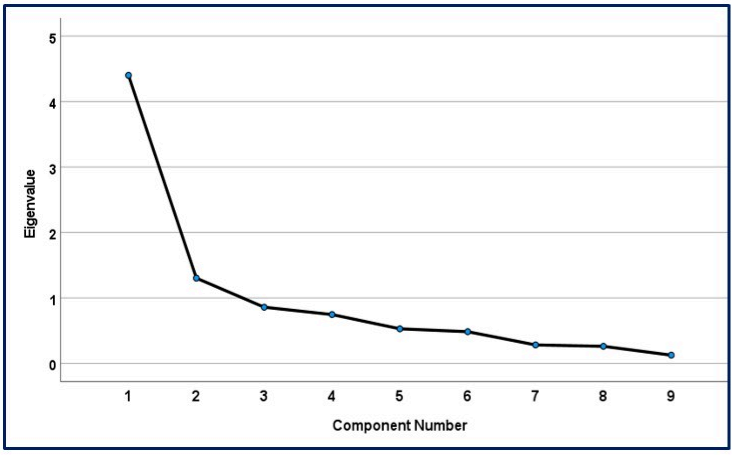
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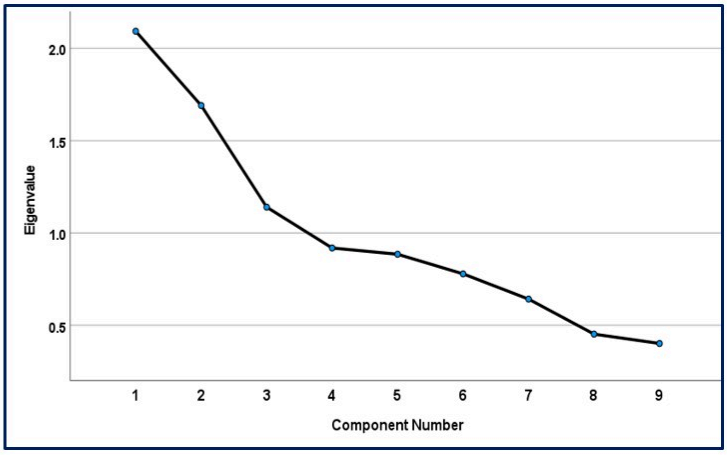
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Figures



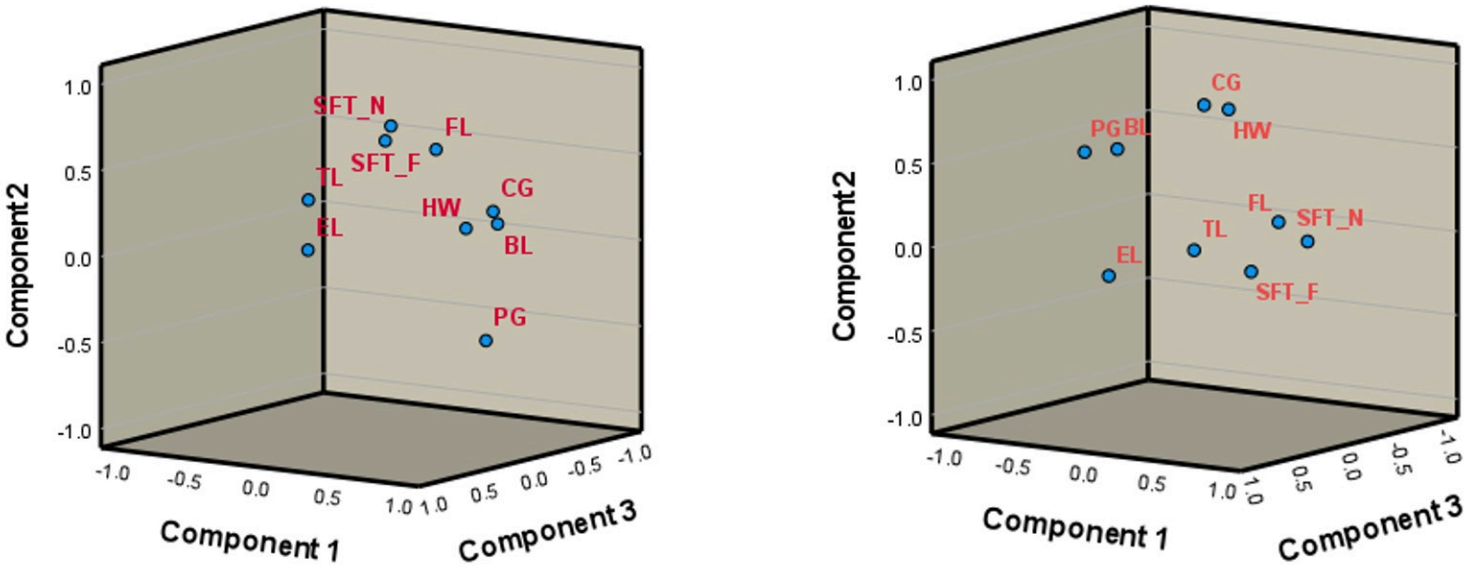
A. Molai Adu



B. Pallai Adu

Figure 1

Scree plots of principal component analysis for morphometric traits in adult Molai Adu (A) and Pallai Adu (B) goats.



A. Molai Adu

B. Pallai Adu

Figure 2

Varimax-rotated component plots of morphometric traits in adult Molai Adu (A) and Pallai Adu (B) goats.

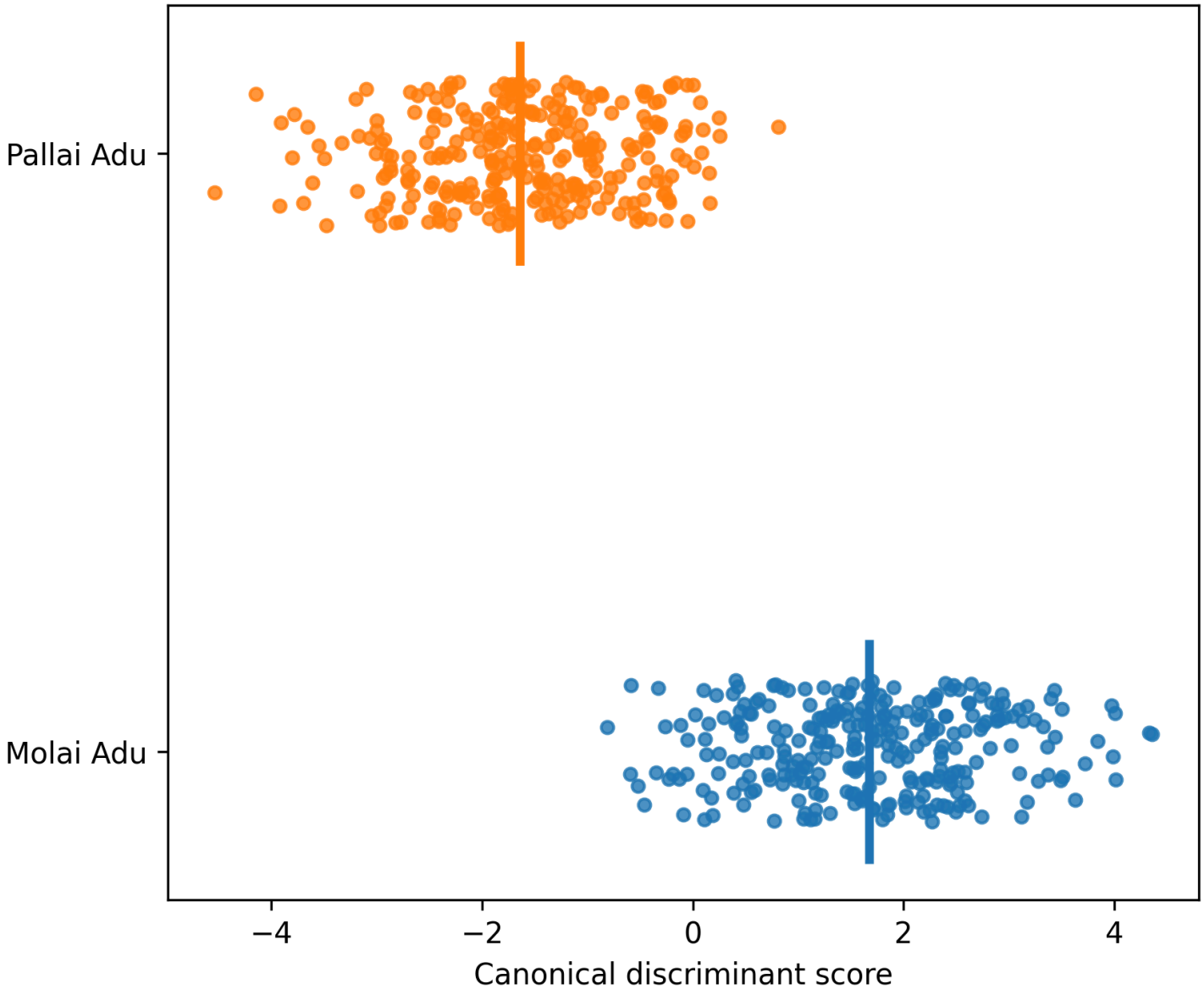


Figure 3

Distribution of canonical discriminant scores for adult Molai Adu and Pallai Adu goats. Each point represents an individual animal.

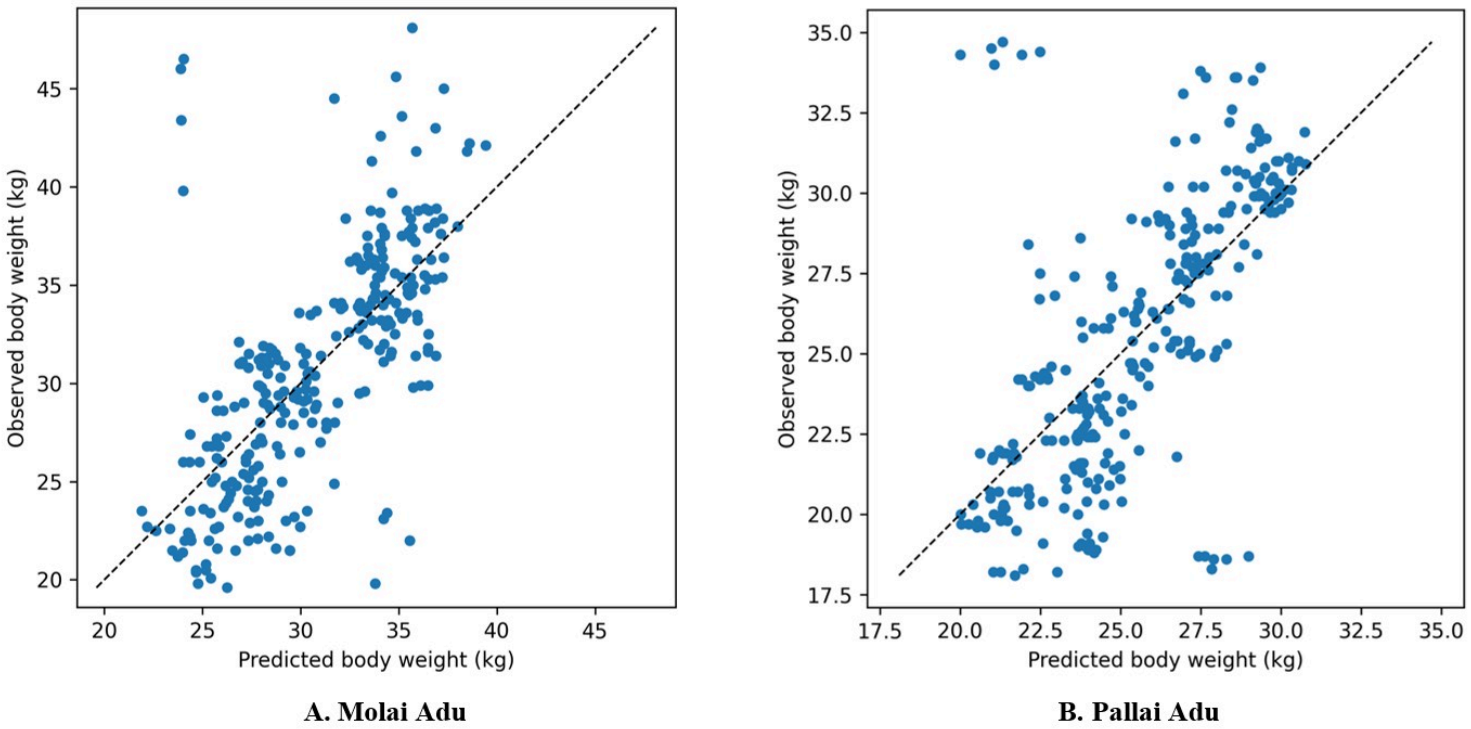


Figure 4

Observed versus predicted body weight in adult Molai Adu (A) and Pallai Adu (B) goats. Each point represents an individual animal. The dashed diagonal line denotes the line of identity (Observed = Predicted).

Supplementary Files

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- GraphicalAbstract.png