R. Bras. Zootec., 54:e20240113, 2025
https://doi.org/10.37496/rbz5420240113

Breeding and genetics
Full-length research article

Revista Brasileira de Zootecnia
Brazilian Journal of Animal Science
e-ISSN 1806-9290
www.rbz.org.br

Phenotypical and biometrical characterization of Creole goats in northeastern Mexico

Jorge Alva-Pérez[1], **Gerardo Noé Rosales-Martínez**[1], **Ivonne Ceballos-Olvera**[1], **Luz Yosahandy Peña-Avelino**[1]*

[1] Universidad Autónoma de Tamaulipas, Facultad de Medicina Veterinaria y Zootecnia "Dr. Norberto Treviño Zapata", Ciudad Victoria, Tamaulipas, México.

***Corresponding author:**
lypena@docentes.uat.edu.mx

Received: July 16, 2024
Accepted: July 13, 2025

How to cite: Alva-Pérez, J.; Rosales-Martínez, G. N.; Ceballos-Olvera, I. and Peña-Avelino, L. Y. 2025. Phenotypical and biometrical characterization of Creole goats in northeastern Mexico. Revista Brasileira de Zootecnia 54:e20240113.
https://doi.org/10.37496/rbz5420240113

Editors:
Lucas Lima Verardo
Carina Visser

ABSTRACT - This study aimed to describe the phenotypical and biometrical characteristics of Creole goats on the Tamaulipas Plateau (TP) and San Fernando Valley (SFV) agroecological zones in northeastern Mexico. Eight hundred fifty-eight goats (70 males and 788 females) were studied to collect qualitative and quantitative information. Data were analyzed for male and female goats separately using frequency and general linear models. Pearson's correlation was used to analyze linear body measurements (LBM) for morpho-structural homogeneity. The canonical discriminant analysis and a multiple correspondence analysis were made for examined the presence of any subpopulations on seven municipalities of the two districts. The northeastern Mexican Creole goats are light-colored with arched horns, large pendulous ears, convex cephalic profile, and dual-purpose productive aptitude. Live weight was higher in SFV than in TP female goats (35.4 + 4.4 kg vs. 30.3 + 4.6 kg, P = 0.0001). No weight differences were observed between male goats. More than 65% of the LBM correlations (regardless of sex or agroecological zone) were positive, indicating balanced physical growth and environmental adaptation. The Creole goat breed predominance in both goat ecotypes is primarily of African origin. The multivariate analysis showed dissimilarities between SFV and TP, but similarities among the sampled localities in each district. Additionally, the morpho-structure of the TP goats is adequate for a dual purpose, whereas the SFV goats are adequate for kid meat production. This study could be complemented by molecular characterization, which could describe the northeastern Mexican Creole goat based on specific genetic background.

Keywords: body indices, conformation, linear body measurements, morphology

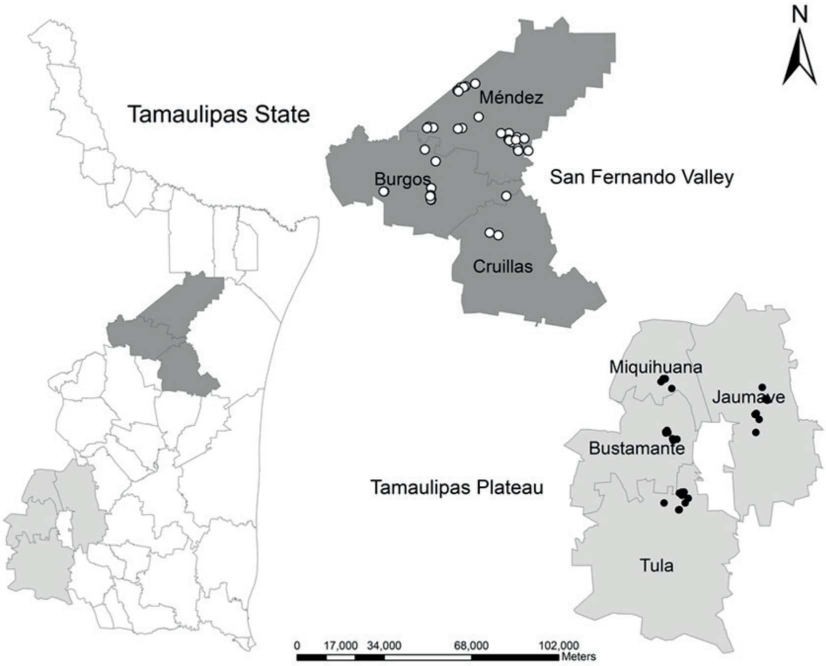
1. Introduction

Goats are multi-functional animals with the ability to tolerate harsh climates. They exhibit useful recovery capacity from drought and are used primarily for milk and meat production (Yakubu et al., 2010a). Overall, there are approximately 8.8 million goats in Mexico, while in Tamaulipas state, the goat population is 278,450 (SIACON-SIAP, 2022).

Tamaulipas state is found in northeastern Mexico, and it has two goat production areas, the San Fernando Valley (SFV) and the Tamaulipas Plateau (TP) (Figure 1). In this state, goat production is developed with crosses of breeds under an extensive system (Vázquez-Rocha et al., 2019). The Tamaulipas Plateau has a maximum flock size of 200 and the goat population is predominantly Creole (Alva-Pérez et al., 2019). Productive units are represented by extensive conditions, lack reproductive records, and are totally dependent on bushes and harvest residues (Alva-Pérez et al., 2019). The information on linear body measurements (LBM) of goats in Tamaulipas is virtually non-existent. Empirical evidence is needed to identify and understand the conformation and productivity of these populations in their regions (Hernández et al., 2013). The phenotypic and biometrical characterization is essential for the identification for production purposes (Lanari et al., 2003; Getaneh et al., 2022). The goat characterization is one of the most affordable, indirect, and alternative ways of improving productivity (Chiemela et al., 2016).

In the southeast of Mexico, Pastoreña goats have been biometrically characterized; this goat breed is rustic for transhumant production systems for meat production (Villarreal-Arellano et al., 2018). Another example of goat breed characterization is the black goat grenadine in north-central, Mexico (Silva-Jarquin et al., 2019). The information gathered in different research studies aided in live weight determination and production purpose identification. Herd size was identified as a food security factor (Getaneh et al., 2022); so, it is expected that information on phenotypic characteristics will allow farmers to select better-quality animals for reproduction.

To our knowledge, there is no published information on biometrical characterization in Creole goats of Tamaulipas state. The morphological characterization could gather information for productive improvement. The objective of the current study is the phenotypical and biometrical characterization of Creole goats in TP and SFV districts in the northeast of Mexico.



Black circles represent production units of Tamaulipas Plateau, while open circles represent production units of San Fernando Valley.

Figure 1 - Spatial location of the 80 productive units of Creole goats in Tamaulipas, Mexico.

2. Material and methods

2.1. Ethical consideration and sample size determination

For this study, all animal protocols were approved by the Animal Welfare Committee of the Autonomous University of Tamaulipas (CBBA-18-011). For animal selection, 80 goat production units were randomly selected from two agroecological zones (AZ, Table 1). Only animals in breeding state were chosen (> 2 years). Productive units are located in the northeastern Tamaulipas state of Mexico (Figure 1), and AZ selected were TP and SFV. The TP is composed of four districts (Jaumave, Tula, Miquihuana, and Bustamente), with a mean elevation of 1,962.5 m asl. Meanwhile, the SFV is composed of three districts (Méndez, Burgos, and Cruillas), with a mean elevation of 375 m asl.

Table 1 - Summary of the total number of goats (n = 858) measured and productive units by districts

District/Municipality	Locality	Productive unit	Goat		Coordinate
			Frequency	%	
San Fernando Valley					
Méndez	Guadalupe	4	42	9.85	25°6'44" N, 98°39'46"W
	Pedro Jose	6	62	14.55	25°5'47" N, 98°28'56" W
	Comas Altas	1	11	2.58	25°4'54'' N, 98°26'26" W
	Las Agujitas	2	22	5.16	25°2'33" N, 98°26'14" W
	Candido Aguilar	1	11	2.58	26°6'39" N, 98°40'31" W
	Carlos Valdez	1	11	2.58	25°2'04" N, 98°23'51" W
	Candelario Reyes	1	11	2.58	25°09'15'' N, 98°35'19" W
	Hugo Pedro Gonzalez	8	87	20.42	25°15'27'' N, 98°39'33" W
Burgos	San Isidro	8	83	19.48	24°52'46'' N, 98°46'29" W
	El Mulato	2	22	5.16	24°53'27" N, 98°57´0" W
	Labores de la Paz	3	30	7.04	25°0'3.9'' N, 98°45'18'' W
	Las Adjuntas	1	9	2.11	25°03'55" N, 99°0'56" W
Cruillas	El Ranchito	1	12	2.81	24°52'34'' N, 98°28'57'' W
	El Divisadero	1	13	3.05	24°44'16" N, 98°30'50" W
	Total	40	426	100	
Tamaulipas Plateau					
Jaumave	Independencia	4	46	10.79	23°32'49" N, 99°23'19" W
	Jose Maria Morelos	5	55	12.91	23°30'22" N, 99°22'24" W
	San Juanito	3	32	7.51	23°27'19" N, 99°24'40" W
Tula	Alvaro Obregon	6	63	14.78	23°10'26" N, 99°41'40" W
	Rancho Nuevo	1	10	2.34	23°10'26" N, 99°41'40" W
	Crucitas	1	11	2.58	23°10'0.6" N, 99°41'35" W
	Ruiz Molina	2	22	5.16	23°28'24" N, 99°22'50" W
Miquihuana	Miquihuana	5	58	13.61	23°34'33" N, 99°45'33" W
	Rancho La Tristeza	1	11	2.58	23°33'56" N, 99°46'29" W
	El Pinal	2	18	4.22	23°32'31" N, 099°44'5" W
Bustamante	Felipe Angeles	10	106	24.88	23°06'57" N 99°42'12" W
	Total	40	432	100	

Eight hundred fifty-eight goats were studied, including 70 males (all male goats in every productive units were measured) and 788 females (an average of 10 goats by productive units were sampled). Morphological characteristics and linear body measurements were collected through the visual appraisal of creole goats, and their morphological descriptions. For sample size determination, the formula described by Scheaffer et al. (1991) (Equations 1 and 2) was used:

$$n = \frac{N \times p \times q}{(N-1)\,D + (p \times q)} \tag{1}$$

$$D = \frac{B^2}{4} \tag{2}$$

in which n = required sample size; N = total population size; p and q are the generally unknown probability proportions; D = sample variability; and B = allowable error margin, in this case 0.05.

2.2. Morphological characteristics

These were assessed using the FAO descriptive tool (FAO, 2012): coat color (black, brown, toasted, grey, moor, or white), ear size (large, medium, or short), ear orientation (erect, horizontal, or pendulous), facial profile (convex, straight, or concave), hair pattern (plain, spotted, or patchy), horn type (lateral, spiral, straight arch, or not horn), hair length (long, medium, or short), beard (presence or absence), pigmentation hooves (pigmented or not pigmented), and wattle (presence or absence). Productive aptitude was recorded based on phenotypic features (milk, meat, or dual-purpose). Finally, phenotypic frequencies were computed by direct count.

2.3. Linear body measurements

Linear body measurements (LBM) were taken on each animal in the morning before they were released for grazing. Fourteen records were taken as described by Chacón et al. (2011) and FAO (2012) with a textile measuring tape. The measurements used included body length (BL), bicoastal diameter (BID), body depth (BD), cannon bone circumference (CC), sternum height (SH), muzzle diameter (MD), ear length (EL), head length (HL), head width (HW), heart girth (HG), rump height (RH), rump length (RL), rump width (RW), and withers height (WH). The sexual dimorphism was calculated according to Legaz et al. (2011).

2.4. Body indices

From the LBM, thirteen structural indices were calculated following indices descriptions of Chacón et al. (2011), Hernández et al. (2013), and Chiemela et al. (2016). Indices were calculated as follows: cephalic index (CI): head width × 100 / head length; body index (BI): body length × 100 / heart girth; pelvic index (PI): rump width × 100 / rump length; weight (W): (0.5 × heart girth) – 14.87; metacarpus-costal index (MCI): cannon bone circumference × 100 / rib distance; transverse pelvic index (TPI): rump width × 100 / rump height; longitudinal pelvic index (LPI): rump length × 100 / rump height; relative depth of thorax index (RDTI): chest depth × 100 / withers height; relative body index (RBI): body length × 100 / withers height; pectoral index (PEI): ((height slope + rump height)/2)/sternum height; thoracic development (TD): heart girth / height slope; body ratio (BR): head width / rump height.

2.5. Statistical analysis

A database on an Excel spreadsheet (Microsoft version 2016) was generated from the data obtained. To identify phenotype frequency and percentage, contingency tables were constructed using the PROC FREQ procedures of the SAS statistical software (Statistical Analysis System, version 9.0), and differences were confirmed using the chi-square test with an alpha of $P<0.05$. Then, the analysis of variance was performed using the PROG GLM procedure of SAS. Subsequently, means were compared using the Duncan test; significant differences were declared with an alpha of $P<0.05$. Afterward, the correlation (Pearson correlation coefficient) between LBM by AZ was separately calculated for both sexes, using the procedure PROC CORR. A stepwise discriminant analysis was conducted using PROC STEPDISC to identify the most informative morphometric traits and morphological indices for subsequent discriminant analyses. The discriminatory power of each quantitative variable was evaluated based on partial R^2, F-value, and significance level (Pr > F). Canonical discriminant analysis was then carried out using PROC CANDISC to perform both univariate and multivariate one-way analyses, generate canonical functions and linear combinations of quantitative variables that capture inter-population variation, and calculate Mahalanobis distances. The classification accuracy of the canonical functions in assigning individual animals to their respective a priori districts was assessed using the discriminant procedure (PROC DISCRIM). Additionally, multiple correspondence analysis (MCA) was performed with PROC CORRESP to explore associations among qualitative physical traits.

3. Results

3.1. Phenotypic characteristics and productive aptitude

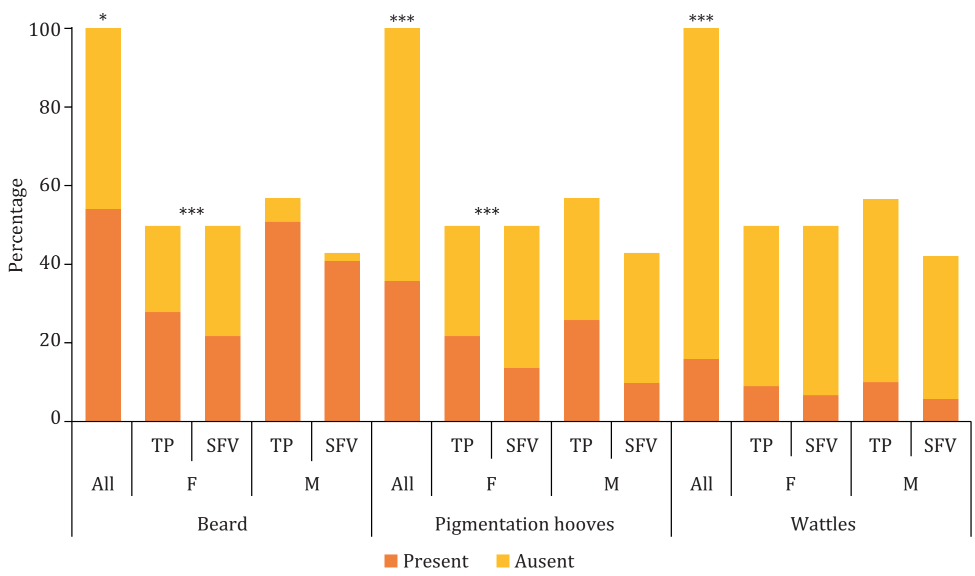
The beard was present in 54% (χ^2: 5.07, P = 0.0242) of the goat population studied. The TP female beard represented 28% and SFV female beard was present in 22% (χ^2: 11.22, P = 0.0008). The TP male beard represented 52%, and SFV male beard was present in 41%, (χ^2: 1.14, P = 0.2838; Figure 2). In this study, we observed differences in the female's beard, in which TP goats exhibit it in greater proportion compared with SFV goats. On the other hand, no differences were observed between male beard by AZ.

Pigmentation hooves were present in 37% of all goats studied (χ^2: 61.65, P = 0.0001). According to sexes distribution, 22% of TP and 14% of SFV female goats had pigmented hooves (χ^2: 19.97, P = 0.0001). At the same time, 26% of TP and 10% of SFV male goats had pigmented hooves (χ^2: 3.50, P = 0.0612; Figure 2). Differences are observed according to sex between the AZ.

The wattles were nearly absent in both regions (83%; χ^2: 988.13, P = 0.0001; Figure 2). The TP female goats presented wattles in 9% of their population, while SFV female goats presented wattles in 7% of them (χ^2: 2.419, P = 0.2983). In male goats, 10% of the TP and 6% of the SFV population presented wattles (χ^2: 2.22, P = 0.6355; Figure 2).

The main coat colors observed in all goats studied were white (38%), brown (23%), and toasted (18%), with differences between coat colors observed (χ^2 : 455.0, P = 0.0001; Table 2). Also, coat color differences were observed between female goats by AZ (χ^2 : 28.25, P = 0.0001).

Most Creole goats had long ears (73%, χ^2 : 617.2, P = 0.0001) with no observable AZ differences. Almost all goats (85%) had pendulous ears, laterally or front folded (χ^2: 1038.1, P = 0.0001; Table 2). The goat's medium ears (19%) usually had a horizontal orientation, while short ears (8%) had a vertical orientation. Long pendulous ears are characteristic of the Nubian breed, the leading ear trait observed.



F - females; M - males; TP - Tamaulipas Plateau; SFV - San Fernando Valley.

Figure 2 - Beard, pigmentation hooves, and wattle phenotype in Creole goats of two agroecological zones in northeastern, Mexico.

Table 2 - Qualitative morphological traits in Creole goats

Character	Trait	All				Female (n = 788)						Male (n = 70)					
				χ2	P-value	TP (n = 392)		SFV (n = 396)		χ2	P-value	TP (n = 40)		SFV (n = 30)		χ2	P-value
		F	%			F	%	F	%			F	%	F	%		
Coat color	Black	121	14	455.0	0.0001	71	9	39	5	28.25	0.0001	7	10	4	6	5.84	0.3219
	Brown	199	23			102	13	85	11			8	11	4	6		
	Toasted	154	18			69	9	77	10			4	6	4	6		
	Grey	22	3			7	1	14	2			0	0	1	1		
	Moor	33	4			21	3	8	1			4	6	0	0		
	White	329	38			121	15	173	21			17	24	17	24		
Ear size	Large	625	73	617.2	0.0001	288	36	290	37	3.10	0.2118	27	39	20	29	5.08	0.0786
	Medium	162	19			68	9	81	10			10	14	3	4		
	Short	71	8			36	5	25	3			3	4	7	10		
Ear orientation	Erect	21	2	1038.1	0.0001	11	1	5	1	24.60	0.0001	2	3	3	4	5.18	0.0748
	Horizontal	10	13			69	9	27	3			11	16	2	3		
	Pendulous	728	85			312	40	364	46			27	38	25	36		
Facial profile	Convex	576	67	442.2	0.0001	252	32	300	38	16.74	0.0002	10	14	14	21	6.99	0.0351
	Straight	128	15			59	8	54	7			7	10	8	11		
	Concave	158	18			81	10	42	5			23	33	8	11		
Hair pattern	Plain	300	35	136.1	0.0001	127	16	156	20	19.26	0.0001	4	6	13	19	12.81	0.0016
	Spotted	418	49			180	23	199	25			24	34	15	21		
	Patchy	140	16			85	11	41	5			12	17	2	3		
Horn type	Lateral	19	2	1704.6	0.001	8	1	10	1	19.84	0.0008	1	1	0	0	6.07	0.1936
	Spiral	49	6			6	1	25	3			7	10	11	16		
	Straight	71	8			24	3	44	6			1	1	2	3		
	Arch	654	76			324	41	292	37			26	38	12	17		
	Not horn	65	8			30	4	25	3			5	7	5	7		
Hair length	Short	368	43	205.4	0.0001	83	10	266	34	169.4	0.0001	4	5	15	22	17.20	0.0002
	Medium	401	47			264	34	107	13			18	26	12	17		
	Large	89	10			45	6	23	3			18	26	3	4		
Productive aptitude	Meat	65	8	854.4	0.0001	8	1	42	5	33.43	0.0001	11	16	4	6	4.28	0.1171
	Milk	104	12			62	8	31	4			8	11	3	4		
	Dual purpose	689	80			322	41	323	41			21	30	23	33		

F - frequency; TP - Tamaulipas Plateau; SFV - San Fernando Valley; χ2 - Chi-square.

The facial profile trait had the following tendency: 67% of goats had convex, 18% had concave, and 15% had straight profile (χ^2: 442.2, P = 0.0001). Facial profile differences between sexes by AZ were observed.

The dominant goat hair pattern observed was spotted (49%), followed by plain (35%) and patchy (16%) patterns (χ^2: 136.1, P = 0.0001). Differences were observed in patchy hair pattern. This trait was present in greater proportion in female and male TP goats than in SFV goats (χ^2: 19.26, P = 0.0001 and χ^2: 12.81, P = 0.0016, respectively). It is interesting to describe that the main coat color observed was white, nevertheless the hair pattern was spotted. The white-spotted coat trait is notorious in Nubian and Boer breeds.

Horns are predominant in Creole goats (92%, χ^2: 1704.6, P = 0.0001), with the arched horn being the principal trait observed. Horn-type differences by AZ were only observed in female goats (χ^2: 19.84, P = 0.0001). Interestingly, male goats displayed spiral and arched horns mainly.

The hair length is another trait that helps characterize the goat population (Table 2). We observed that medium-long hair was prevalent in Creole goats (47%, χ^2: 205.4, P = 0.0001), followed by short-hair pattern (43%). We observed differences in females related to the AZ i.e., in TP goats the medium-long hair was 34% prevalent and in SFV goats the same percentage was observed for short-long hair. The same tendency was observed in male goats: TP goats expressed the medium-long and large-long hair pattern in 26% of them, while SFV goats expressed the short-long hair pattern in 22% of the goat population.

Productive aptitude was reported as a dual purpose in both AZ (80%, χ^2: 854.4, P = 0.0001). However, in both regions, meat aptitude production (observed as the kid goat sale) is the principal economic activity. In TP, the sale or self-consumption of goat milk is common.

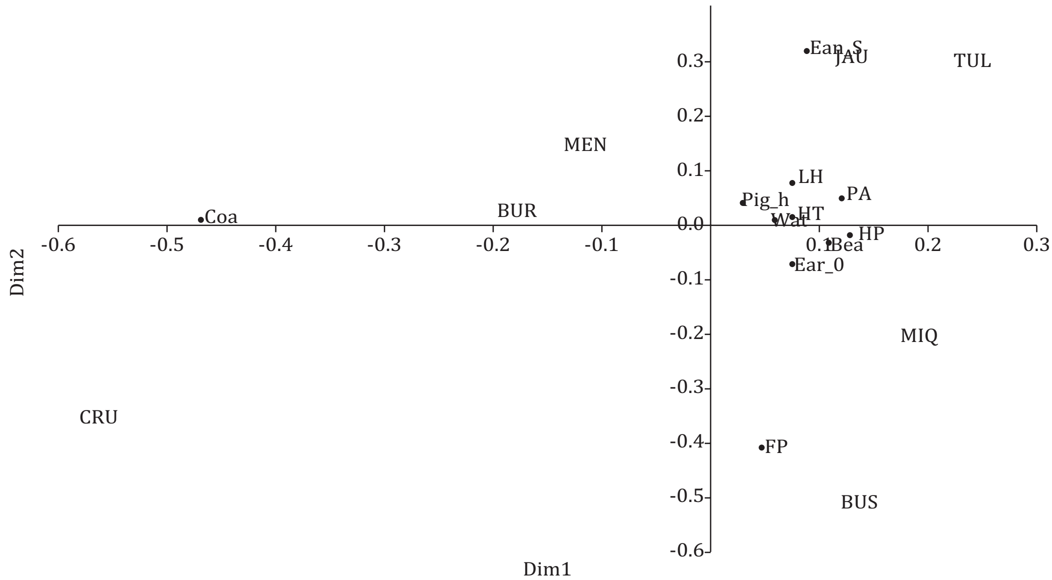
A mix of different breeds forms the Creole goat of Tamaulipas. In the TP, Nubian, followed by Blanca Celtiberica or Blanca Andaluza and Boer are the predominant mix of breeds of TP goats (Figure 3). On the other hand, Boer, Nubian, and in minor proportion Toggenburg are the dominating mix of breeds of SFV goats. In summary, most of the Creole goats of the two AZ have multicolor coats, arched horns, large pendulous ears, beards, and dual-purpose productive aptitude.

TP - Tamaulipas Plateau; SFV - San Fernando Valley.

Figure 3 - Phenotype of TP Creole goats (a) and SFV Creole goats (b) in Tamaulipas, Mexico.

3.2. Multiple correspondence analysis of goats' qualitative traits

The multiple correspondence analysis (MCA) revealed associations between various qualitative physical traits (Figure 4). The first two dimensions (Dim1 and Dim2) accounted for 19.95 and 19.24% of the total variance, respectively. On the right side of the plot, Méndez, Jaumave, and Bustamante were strongly associated with a convex facial profile, spotted hair patterns, long hair, and pendulous ears. Jaumave and Tula were linked to dairy aptitude, characterized by erect ear orientation and white coat color, whereas Cruillas was primarily associated with meat aptitude. In contrast, the left side of the plot showed that Miquihuana and Tula were associated with a moor-colored coat, while Bustamante, Jaumave, Méndez, and Burgos were linked to toasted and brown coat colors, indicating a dual-purpose aptitude. Additionally, Tula and Jaumave exhibited black coat coloration and shorter ear size.



JAU - Jaumave; MIQ - Miquihuana; TUL - Tula; BUS - Bustamante; BUR - Burgos; MEN - Méndez; CRU - Cruillas; Bea - beard; Coa - coat color; Ear_O - ear orientation; Ear_ S - ear size; FP - facial profile; HP - hair pattern; HT - horn type; LH - long hair; PA - productive aptitude; Pig_ h - pigmentation hooves; Wat - wattle.

Figure 4 - Multiple correspondence analysis of the qualitative physical traits of the Creole goat population of northeastern Mexico.

3.3. Linear body measurements and body indices

All LBM for female goats were different between the AZ ($P<0.05$), except for HW (Table 3). In contrast, LBM for male goats were different in BID, EL, HW, RL, CC, and MD by AZ ($P<0.05$). The SFV female goats had the highest values for LBM compared with TP goats, except for BID. In contrast, SFV male goats had high values for EL, RL, and CC, while TP bucks were superior for BID, HW, and MD. The results showed heterogeneity among the local goats of two AZ. The global mean of sexual dimorphism was higher in TP compared with SFV (1.13 and 1.06, respectively; Table 3). As expected, males were higher than female LBM.

Except for CI, variations in body indices were observed in female goats by AZ ($P<0.05$; Table 4). The SFV female goats had higher MCI, LPI, W, RBI, and TD, and lower TPI, BI, PI, RDTI, PEI, and BR indices than TP female goats. In addition, male quantitative body indices had differences ($P<0.05$; Table 4), except for MCI, W, RBI, and BR. The TP male goats showed higher (CI, BI, PI, TPI, RDTI, PEI) and lower (LPI, TD) body indices compared with SFV males.

Table 3 - Means and standard deviation (±SD) of linear body measurements (in cm) in male and female goats of two agroecological zones in Tamaulipas, Mexico

	Females (n = 788)		P-value	Males (n = 70)		P-value	Sexual dimorphism	
	TP (n = 392)	SFV (n = 396)		TP (n = 40)	SFV (n = 30)		TP	SFV
BID	30.7±7.06a	25.5±6.46b	0.0001	33.8±8.65a	26.8±4.36b	0.0001	1.1	1.05
BL	64.9±7.04b	70.3±5.37a	0.0001	74.2±6.32	73.5±8.7	0.7282	1.14	1.05
CC	8.7±1.01b	11.1±1.2a	0.0001	10.6±1.33b	12.7±1.66a	0.0001	1.22	1.15
EL	17.4±3.56b	20.7±3.56a	0.0001	17.9±3.57a	20.6±5.29b	0.0269	1.03	1.0
MD	23.5±2.6b	24.1±1.91a	0.0001	29.1±4.77a	25.6±3.55b	0.0022	1.24	1.06
HG	89.8±10.37b	100.1±10.7a	0.0001	100.0±10.34	105.8±14.57	0.0873	1.11	1.06
HL	21.3±1.96b	22.2±2.08a	0.0001	24.5±2.32	23.6±2.43	0.1493	1.15	1.06
HW	12.5±1.45	12.5±1.8	0.7563	14.2±1.51a	13.3±1.38b	0.0006	1.13	1.07
BD	77.4±7.26b	84.1±5.75a	0.0001	89.3±7.42	90.9±10.27	0.4947	1.15	1.08
RH	70.4±4.54b	72.3±3.77a	0.0001	78.1±6.017	77.5±6.95	0.6848	1.11	1.07
RL	15.3±2.59b	17.9±2.18a	0.0001	16.5±2.54b	18.5±2.93a	0.0074	1.08	1.04
RW	15.0±1.78b	16.7±1.58a	0.0001	16.7±2.19	17.0±2.21	0.5708	1.11	1.02
SH	47.2±5.19b	49.3±5.56a	0.0001	52.5±3.66	54.1±5.2	0.1807	1.11	1.1
WH	69.6± 4.67b	73.2±3.99a	0.0001	80.6±6.47	80.1±8.16	0.8232	1.16	1.09

TP - Tamaulipas Plateau; SFV - San Fernando Valley; BID - bicoastal diameter; BL - body length; CC - cannon bone circumference; EL - ear length; MD - muzzle diameter; HG - heart girt; HL - head length; HW - head width; BD - body depth; RH - rump height; RL - rump length; RW - rump width; SH - sternum height; WH - withers height.
a-b - Means within the rows with different letters are significantly different at P<0.05.

Table 4 - Means, standard deviation (±SD) of body indices in male and female goats of two agroecological zones in Tamaulipas, Mexico

	Females (n = 788)		P-value	Males (n = 70)		P-value
	TP (n = 392)	SFV (n = 396)		TP (n = 40)	SFV (n = 30)	
BR	1.02±0.112a	0.9±0.06b	0.0001	1.02 ±0.06	1.032±0.049	0.8446
CI	58.95±9.11	57.34±16.81	0.1107	60.35±6.48a	56.82±5.67b	0.0283
BI	72.75±9.36a	70.35±6.41b	0.0001	78.50±5.22a	70.00±7.43b	0.0103
PI	100.06±15.71a	94.73±14.71b	0.0001	102.36±17.93a	93.36±13.64b	0.0249
MCI	57.87±8.69b	63.05±11.69a	0.0001	64.94±8.95	70.19±13.23	0.0847
TPI	100.06±15.71a	94.73±14.71b	0.0001	102.75±17.93a	93.36±13.64b	0.0249
LPI	102.74±18.76b	107.85±15.47a	0.0001	99.72±14.79b	109.73±19.24b	0.0304
RDTI	35.14±4.56a	31.90±6.56b	0.0001	34.69±3.71a	32.34±3.76b	0.0188
PEI	1.51±0.13a	1.4±0.16b	0.0004	1.51±0.10a	1.45±0.08b	0.0326
RBI	0.90±0.097b	0.97±0.07a	0.0001	0.92±5.32	0.91±5.46	0.7308
TD	1.25±0.12b	1.39 ±0.12a	0.0001	1.24±0.09b	1.32±0.13a	0.0118
W	30.27±4.63b	35.40±4.43a	0.0001	35.11±5.16	39.00±7.28	0.0874

TP - Tamaulipas Plateau; SFV - San Fernando Valley; BR - body ratio; CI - cephalic index; BI - body index; PI - pelvic index; MCI - metacarpus-costal index; TPI - transverse pelvic index; LPI - longitudinal pelvic index; RDTI - relative depth of thorax index; PEI - pectoral index; RBI - relative body index; TD - thoracic development; W - weight.
a-b - Means within the rows with different letters are different at P<0.05.

The LBM correlations are represented in Table S1 for males and Table S2 for females, respectively. The LBM correlations in TP males were as follows: 69.2% positive and 30.7% non-significant. No negative LBM correlations were observed. Meanwhile, LBM correlations of SFV males were as follows: 77% positive and 23% non-significant. Again, no negative correlations were detected. For TP females, correlations were as follows: 73.6% positive, 3.3% negative, and 23.1% non-significant. The LBM correlations of SFV females had a similar tendency to TP females. In SFV female goats, positive LBM correlations were 65.9%, negative LBM correlations were 4.4%, and non-significant correlations were 29.7%. Correlations among morphological measurements of Creole goats were mainly positive and high, indicating a strong association between measurements. These correlations demonstrate that the Creole goat populations of TP and SFV agroecological zones in northeastern Mexico are uniformly conformed. This reflects a balanced physical development (growth) and reveals that populations have adapted to their environmental conditions.

3.4. Identification of goat sub-populations using multivariate analyses

The results of the stepwise discriminant analysis (Table 5) indicated that 18 out of the 26 quantitative variables analyzed (comprising 14 linear body measurements and 12 morphological indices) significantly contributed to differentiating among the districts (P<0.0001). Among these, CC and BID exhibited the highest partial R^2 and F-values, reflecting their superior discriminant capacity in characterizing morphological variation within the Creole goat populations. Subsequently, canonical discriminant analysis using the 18 significant variables (P<0.0001 for Pr > F) (specifically, 11 linear body traits and seven morphological indices) yielded two highly significant canonical functions (CAN1 and CAN2), collectively explaining 89% of the total morphological variation. This was supported by the standardized discriminant function coefficients, canonical correlations, eigenvalues, and the proportion of variance accounted for (Table 6).

Table 5 - Summary of the stepwise selection of quantitative traits obtained from the stepwise discriminant analysis performed on morphometric variables (n = 858)

Step	Number of traits	Partial R^2	F value	Pr > F	Wilks' Lambda (l)	Pr < Lambda (l)	Average squared canonical correlation	Pr > ASCC
1	CC	0.4901	136.30	0.0001	0.50994	<0.0001	0.0816	<0.0001
2	BID	0.2885	57.44	0.0001	0.36282	<0.0001	0.1214	<0.0001
3	RL	0.1844	31.99	0.0001	0.29591	<0.0001	0.1395	<0.0001
4	TD	0.0999	15.68	0.0001	0.26636	<0.0001	0.1498	<0.0001
5	HW	0.1028	16.18	0.0001	0.23897	<0.0001	0.1642	<0.0001
6	CI	0.1258	20.30	0.0001	0.20890	<0.0001	0.1737	<0.0001
7	BL	0.1140	18.12	0.0001	0.18508	<0.0001	0.1889	<0.0001
8	MD	0.0682	10.29	0.0001	0.17246	<0.0001	0.1984	<0.0001
9	RH	0.0638	9.58	0.0001	0.16146	<0.0001	0.2064	<0.0001
10	RDTI	0.0670	10.08	0.0001	0.15064	<0.0001	0.2109	<0.0001
11	EL	0.0540	7.99	0.0001	0.14251	<0.0001	0.2168	<0.0001
12	W	0.0385	5.61	0.0001	0.13702	<0.0001	0.2210	<0.0001
13	HL	0.0357	5.18	0.0001	0.13212	<0.0001	0.2256	<0.0001
14	SH	0.0237	3.39	0.0026	0.12899	<0.0001	0.2288	<0.0001
15	LPI	0.0242	3.47	0.0022	0.12587	<0.0001	0.2319	<0.0001
16	RW	0.0347	5.01	0.0001	0.12505	<0.0001	0.2371	<0.0001
17	MCI	0.0200	2.83	0.0098	0.11908	<0.0001	0.2398	<0.0001
18	PEI	0.0155	2.19	0.0415	0.11722	<0.0001	0.2412	<0.0001

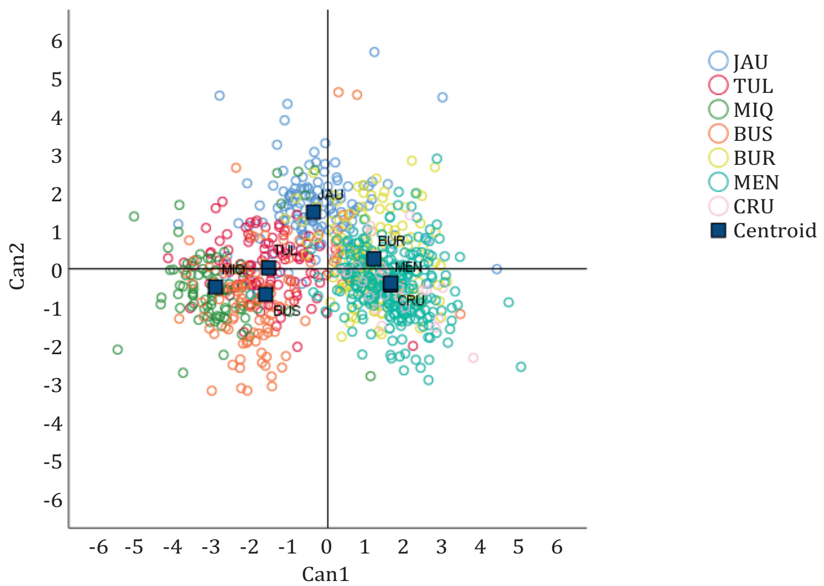
Number of the traits is the number of variable in the model; F - F value for entering or removing the variables; Pr >F - the probability level for the Fstatistic; Pr <Lambda is based on the F approximation to Wilks' lambda; Pr > ASCC is based on the approximation to Pilla's trace; CC - cannon bone circumference; BID - bicoastal diameter; RL - rump length; TD - thoracic development; HW - head width; CI - cephalic index; BL - body length; MD - muzzle diameter; RH - rump height; RDTI - relative depth of thorax index; EL - ear length; W - weight; HL - head length; SH - sternum height; LPI - longitudinal pelvic index; RW - rump width; MCI - metacarpus-costal index; PEI - pectoral index.

Canonical loadings, which reflect the linear correlations between individual variables and the canonical functions, are also reported in Table 6. The first canonical variable (CAN1) was primarily influenced by positive loadings for RL, CC, and CI, and by negative loadings for BID, RDTI, and RH. The second canonical variable (CAN2) was shaped by positive loadings for SH, BID, and PEI, as well as negative loadings for LPI, HW, and HL. The plot of centroid values for the first two canonical functions (Figure 5) revealed several distinct and homogeneous goat subpopulations, although some degree of overlap was observed.

Table 6 - Canonical discriminant analysis descriptions (n = 858)

Variable	Can1	Can2
CC	0.67	0.08
BID	−0.67	0.52
RL	0.84	0.43
TD	0.03	0.20
HW	−0.51	−0.75
CI	0.52	−0.08
BL	0.25	0.46
MD	−0.21	0.09
RH	−0.53	0.01
RDTI	−0.60	−0.09
EL	0.21	0.09
W	0.47	0.014
HL	−0.05	−0.57
SH	0.28	0.79
LPI	−0.08	−0.82
RW	−0.07	−0.37
MCI	0.32	0.19
PEI	0.47	0.62
Adjusted canonical correlation	0.85	0.58
Approximate standard error of the canonical correlations	0.009	0.022
Eigenvalue	2.2146	0.5510
Proportion of the eigenvalue sum	0.7438	0.1482
Cumulative proportion of the eigenvalue sum	0.7438	0.8920

CC - cannon bone circumference; BID - bicoastal diameter; RL - rump length; TD - thoracic development; HW - head width; CI - cephalic index; BL - body length; MD - muzzle diameter; RH - rump height; RDTI - relative depth of thorax index; EL - ear length; W - weight; HL - head length; SH - sternum height; LPI - longitudinal pelvic index; RW - rump width; MCI - metacarpus-costal index; PEI - pectoral index.



JAU - Jaumave; TUL - Tula; MIQ - Miquihuana; BUS - Bustamante; BUR - Burgos; MEN - Méndez; CRU - Cruillas.

Figure 5 - Scatterplot visualizing the individual goats sampled from the seven districts of Tamaulipas on the first two canonical discriminant functions.

All pairwise comparisons yielded significant differences (P<0.0001). The largest squared Mahalanobis distances were observed between the Cruillas and Miquihuana regions (23.26), and between Miquihuana and Méndez (22.10), whereas the smallest distance (1.27) was recorded between Burgos and Méndez (Table 7). The discriminant functions correctly classified 57.53% of individual goats into their respective *a priori* groups (Table 8).

Table 7 - Mahalanobis distances between goat populations identified by districts (n = 858) obtained from canonical discriminant analysis

	Jaumave	Tula	Miquihuana	Bustamante	Burgos	Méndez	Cruillas
Jaumave	0						
Tula	5.10	0					
Miquihuana	11.88	4.60	0				
Bustamante	7.38	2.20	4.33	0			
Burgos	5.46	9.03	19.35	10.17	0		
Méndez	8.37	11.83	22.10	11.91	1.27	0	
Cruillas	9.54	11.97	23.26	13.14	2.58	1.63	0

Table 8 - Percentage of individual goat classified into districts (n = 858) based on discriminant analysis

Districts	Posterior probability (%)						
	Jaumave	Tula	Miquihuana	Bustamante	Burgos	Méndez	Cruillas
Jaumave	**70.68**	10.53	3.01	3.01	6.77	3.01	3.01
Tula	9.43	**61.32**	13.21	10.38	3.77	0.94	0.94
Miquihuana	5.75	3.45	**82.76**	6.90	0	0	1.15
Bustamante	6.60	15.09	16.98	**50.00**	9.43	0.94	0.94
Burgos	7.52	0	0	0.75	**38.35**	37.59	15.79
Méndez	2.99	0.37	0	1.49	17.54	**55.60**	22.01
Cruillas	4.00	0	0	0	12.0	40.0	**44.00**
Rate	0.29	0.38	0.17	0.50	0.61	0.44	0.56
Priors	0.14	0.14	0.14	0.14	0.14	0.14	0.14

Rate - proportion of misclassified observation in each zone; Priors - prior probabilities of group membership.
Values above and/or below the diagonal represent the percentage of individuals from other zones present in the zone considered by the diagonal value.

4. Discussion

4.1. Phenotypic characteristics and breed definition

The phenotypic characteristics analyzed were different in females, rather than males. Almost one-third of TP female goats had a beard, white or brown, spotted hair color, and medium-long hair. In contrast, most SFV female goats did not have a beard, and the main coat colors were white and brown, but also toasted, with plain and spotted hair patterns. The long hair observed was mainly short. Beard presence is related to sexual dimorphism, in which males express it (dominant locus) in higher numbers than females (recessive locus) (Yakubu et al., 2010b). This could explain this phenotypic trait, in which male beard was present in nearly 50% of male goats sampled. Pigmentation and coat color in goats are controlled genetically and epigenetically (Arenas-Báez et al., 2023). Moreover, color inheritance is not monogenic, as 11 genetic loci are responsible for this phenotype (Martin et al., 2016; Ren et al., 2016). Besides that, coat color could explain producer breeding preferences; this phenotype has an important significance in environmental adaptation.

Light coat color (like white) has better heat elimination, on the other hand, dark coats absorb more heat (Joy et al., 2020; Ferreira et al., 2021). Furthermore, light color is advantageous in environments with intense solar radiation and humid environments (Hagan et al., 2012). Thus, different coat colors give different thermoregulatory abilities. In this study, the observed light-colored goats (mainly white and brown) could reflect better adaptation and tolerance to semi-arid weather of the northeastern region of Mexico, where SFV (50-300 m asl) and TP (400-2800 m asl) mean annual temperatures are 20-24 and 12-24 °C, respectively (INEGI, 2017). The long-hair patterns observed in this study are similar to those observed in Equatorian and Brazilian goats. Short to medium-long hair is observed in the Santa Elena Province in Ecuador (Solís-Lucas et al., 2020), while Brazilian goat is described as short-haired (Ferreira et al., 2021). Conversely, goats with long hair are observed in mountainous ecosystems, where climate are milder than in the tropics (Benjelloun et al., 2015). Moreover, short hair in small ruminants is directly linked to hot weather adaptation (Leite et al., 2020). Based on these reports, the short hair in SFV goats could be explained somewhat due to more annual heat in SFV than in TP. Additionally in TP, the altitude is higher, and medium-long hair could serve as a thermoregulatory advantage for a wide variation of temperature, observed in this semi-mountainous ecosystem.

Minimal variations are observed between ear orientation, facial profile, horn type, and productive aptitude. These phenotypic traits could emphasize the breeding phenomenon that could arise in this territory. For example, based on phenotypic characteristics, live weight, and zoometric measures, Dorantes-Coronado et al. (2015) suggested that local goats of Amatepec (State of Mexico) had Nubian breed influence (Dorantes-Coronado et al., 2015). Furthermore, it has been speculated that goat facial profile, horns, and ears characters would determine the breed origin (Lanari et al., 2003). In this context, Solís-Lucas et al. (2020) characterized the Santa Elena Province Creole goat as a mix of European and Asian breeds (Solís-Lucas et al., 2020). In contrast Villarreal-Arellano et al. (2020) reported breed homogeneity in Pastoreña goats. In their study, researchers argued that environmental conditions contribute to breed definition. Nubian and Boer breeds have convex facial profiles that thrive in tropical, sub-tropical, or semiarid weather, while Saanen, Alpine, and Toggenburg breeds thrive in cool or template weather (Gómez-González et al., 2009).

Remarkably, convex facial profile (67%) and large ear size (73%) could corroborate that Creole goats in these AZ are the result of the breeding between indigenous goats and African breeds, mainly Nubian for TP goats and Boer for SFV goats, with minor presence of other breeds. Villarreal-Arellano et al. (2020) analyzed a PCoA with 15 qualitative variables in Mexican pastoral goats and reported Euclidean distances of 76%. They indicated that the difference between females could be due to the geographic location where nearby localities maintain females with similar characteristics. This coincides with our study, in which females share similar characteristics with nearby districts. This can be explained by factors such as the purchase or commercial exchange, in which producers have cheaper and closer access to their localities to make male replacement that will mate their females. It also coincides with Whannou et al. (2021), who mentioned that adaptation to the environment and management is due to the purchase or exchange of nearby locations.

4.2. Linear body measurements and body indices

Linear body measurements results observed in this study demonstrated heterogeneity between female and male goats of both AZ. It was observed that the TP female goat was smaller but wider at the trunk than the SFV goat. In contrast, differences in male goats are observed in specific anatomical sites. The cephalic measures showed that TP males had larger heads compared with SFV males. Conversely, SFV males showed larger CC and EL. These phenotypic characteristics could confirm that SFV males had features of the Boer breed.

Our LBM had higher values compared with crossbreed goats of Cuba (Chacón et al., 2011; La O-Arias et al., 2012), indigenous goats of Ethiopia (Hassen et al., 2012), and local goats of southern Mexico (Dorantes-Coronado et al., 2015). Differences with our study could be due to better nutrient availability in northeastern Mexico. Environmental influence (climate, altitude) promoted different body measurements, which should be expected because of differences in nutrient supply in pastoralist systems (Chacón et al., 2010; Legaz et al., 2011; Dorantes-Coronado et al., 2015). In contrast, Villarreal-Arellano et al. (2020), observed higher body length, head length, rump width, rump length, and cannon bone circumference but lower withers height and head width values in Pastoreña goats than the Creole goats of our study. La O-Arias et al. (2012) described that European breeds have withers height greater than 75 cm. Our withers height measure in females could demonstrate that Creole goats are not mainly derived from European breeds. Sexual dimorphism explains the difference between sexes. Phenotypic differences in skeletal size and body mass are associated with sexual dimorphism wherein hormones promote differences in growth rates in mammalian taxa (Okpeku et al., 2011). Additionally, sexual dimorphism in goats showed that male goats are larger than female goats (Polák and Frynta, 2009), which agrees with our results. In agreement with the current findings, La O-Arias et al. (2012) observed similar differences in Cuban Creole goats and Villarreal-Arellano et al. (2018) observed similar findings in Pastoreña goats.

The morpho-structural conformation of goat populations has been evaluated through analyses of correlations among morphometric measurements (Villarreal Arellano et al., 2018; Silva-Jarquin et al., 2019). In the present study, the significant and predominantly positive correlations observed among LBM suggest that both female and male goats from the SFV and TP agroecological zones possess balanced and harmonious morpho-structural profiles, as evidenced by the high magnitude of most associations.

Nevertheless, SFV female goats' positive and high correlations had a lower percentage compared with that of TP female goats (65.5 vs. 73.6%). The opposite tendency, on positive correlations, was observed for bucks (69.2% for TP vs. 73.6% for SFV). These observations could be explained by male trading between AZ in addition to male sharing by producers. Our LBM correlations were lower than Pastoreña (Villarreal-Arellano et al., 2018), east Amhara region (but higher than west Amhara region (Hassen et al., 2012), and Amatepec (but similar to Tejupilco (Dorantes et al., 2015) goat correlations. On the other hand, Cuban Creole goats and their crossbreeds had medium LBM correlations (Chacón et al., 2011), indicating morpho-structural variation between animals.

The body indices contribute to the understanding of corporal proportionality, conformation, and type of breed and could give indications of environmental adaptation (Chacón et al., 2011). The SFV female goats had a different conformation compared with the TP goats. The SFV female goats had stronger extremities (higher IMC), were heavier (higher W), were larger at the back (higher PLI), had longer bodies (higher RBI), and had better thorax development than TP female goats. On the other hand, TP female goats were wider at the back (higher PI and TPI), had longer legs (higher RDTI), bodies were further away from the ground (higher PI), and were taller (higher BR) than SFV female goats. Male goat differences were less evident than female goats.

The carcass yield could be estimated by RBI, in which the higher values expected the better carcass yield (Salako, 2006). Our RBI values were lower than the Creole goats of Cuba (Chacón et al., 2011) but were similar to the Boer and Crossbreed goats of Ethiopia (Chiemela et al., 2016).

It is noteworthy to argue that both AZ goats had meat-type traits (higher LPI and TPI) compared to Cuban Creole goats (Chacón et al., 2011) and Boer and Crossbreed goats of Ethiopia (Chiemela et al., 2016). Overall, indices observations could illustrate that SFV goats are stronger and heavier, while TP goats are lighter and adapted to long treks, as Chacón et al. (2011) stated before. Also, it is important to acknowledge that the BI values obtained (less than 85) indicate that Creole goats (males and females) of our study are considered breviline (Chacón et al., 2011; Vargas-López, 2003).

The creole goats of both AZ are animals well adapted to their specific environmental conditions, establishing economic resources in these regions. It will be important to conceive a specific program for the conservation of these goat resources, with less interference from other breeds.

4.3. Identification of goat sub-populations using multivariate analyses

Multivariate discriminant analyses confirmed significant morphological variability among goats from the two AZ. The observed proximity among goats from Cruillas, Méndez, and Burgos, and their marked separation from those originating from Miquihuana, Bustamante, Tula, and Jaumave may be attributed to geographic closeness and the consequent exchange of animals, as well as ecological similarities and differences across regions. The relatively low proportion of correctly classified individuals from Cruillas, Méndez, and Burgos along with the small Mahalanobis distances observed among these districts, suggest a degree of overlap among the goat populations in these areas. A similar pattern of low intergroup distances was also noted between Tula and Bustamante. This observation could be due to crossbreeding, particularly between the localities nearby. The differentiation between the two AZ is potentially driven by environmental factors — vegetation types, climate, altitude, and humidity — and livestock management practices and cultural preferences as indicated by Whannou et al. (2021).

5. Conclusions

The Creole goats of the different agroecological zones of northeastern Mexico are primarily the result of the rearing of African breeds, with minor participation with other breeds. Several observations in our study confirm this affirmation (i.e., convex cephalic profile, ear size and orientation, cannon bone circumference, and head width, among others). Additionally, body indices analysis results could confirm the morpho-structural harmonic conformation of Creole goats. Moreover, LBM high and positive correlations demonstrate balanced physical development, indicating goat adaptation to the environment. On the other hand, it is important to state that the results of this study revealed phenotypical and biometrical variations among Creole goat populations from seven agroecological zones of the northeastern region of Mexico (Tamaulipas state), indicating two goat ecotypes. The morpho-structure of the Tamaulipas Plateau goats is adequate for a dual purpose, whereas the San Fernando Valley goats are adequate for kid meat production. Molecular characterization would be useful to determine specific genetic backgrounds.

Supplementary material

The supplementary material of this article can be found online at: https://www.rbz.org.br/wp-content/uploads/articles_xml/1806-9290-rbz-54-e20240113/1806-9290-rbz-54-e20240113-suppl01.pdf

Data availability

The entire dataset supporting the results of this study was made available on figshare.com and can be accessed at: https://doi.org/10.6084/m9.figshare.26299039.v2

Author contributions

Conceptualization: Alva-Pérez, J. and Peña-Avelino, L. Y. **Data curation:** Ceballos-Olvera, I. and Peña-Avelino, L. Y. **Formal analysis:** Peña-Avelino, L. Y. **Investigation:** Alva-Pérez, J.; Rosales-Martínez, G. N. and Ceballos-Olvera, I. **Methodology:** Rosales-Martínez, G. N. and Peña-Avelino, L. Y. **Supervision:** Peña-Avelino, L. Y. **Validation:** Alva-Pérez, J. and Ceballos-Olvera, I. **Writing – original draft:** Alva-Pérez, J. **Writing – review & editing:** Alva-Pérez, J.; Rosales-Martínez, G. N.; Ceballos-Olvera, I. and Peña-Avelino, L. Y.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgments

The authors wish to thank all goatherds for their support in the generation of this work. All authors wish to thank specially Universidad Autónoma de Tamaulipas, Facultad de Medicina Veterinaria y Zootecnia, for all the support granted.

Financial support

The present study was partially funded by the Project "Caracterización morfológica y genotípica de la cabra Criolla Tamaulipeca" (grant number PFI2018-01), Universidad Autónoma de Tamaulipas.

References

Alva-Pérez, J.; López-Corona, L. E.; Zapata-Campos, C. C.; Vázquez-Villanueva, J. and Barrios-García, H. B. 2019. Condiciones productivas y zoosanitarias de la producción caprina en el Altiplano de Tamaulipas, México. Interciencia 44:152-158.

Arenas-Báez, P.; Torres-Hernández, G.; Castillo-Hernández, G.; Hernández-Rodríguez, M.; Sánchez-Gutiérrez, R. A.; Vargas-López, S.; González-Maldonado, J.; Domínguez-Martínez, P. A.; Granados-Rivera, L. D. and Maldonado-Jáquez, J. A. 2023. Coat color in local goats: Influence on environmental adaptation and productivity, and use as a selection criterion. Biology 12:929. https://doi.org/10.3390/biology12070929

Benjelloun, B.; Alberto, F. J.; Streeter, I.; Boyer, F.; Coissac, E.; Stucki, S.; BenBati, M.; Ibnelbachyr, M.; Chentouf, M.; Bechchari, A.; Leempoel, K.; Alberti, A.; Engelen, S.; Chikhi, A.; Clarke, L.; Flicek, P.; Joost, S.; Taberlet, P. and Pompanon, F. 2015. Characterizing neutral genomic diversity and selection signatures in indigenous populations of Moroccan goats (*Capra hircus*) using WGS data. Frontiers in Genetics 6:107. https://doi.org/10.3389/fgene.2015.00107

Chacón, E.; Macedo, F.; Velázquez, F.; Paiva, S. R.; Pineda, E. and McManus, C. 2011. Morphological measurements and body indices for Cuban Creole goats and their crossbreds. Revista Brasileira de Zootecnia 40:1671-1679. https://doi.org/10.1590/S1516-35982011000800007

Chacón, E.; Martínez, A.; La O., M.; Velázquez, F. J.; Pérez, E. and Delgado, J. V. 2010. Caracterización genética de la cabra Criolla Cubana mediante marcadores microsatélites. Revista Cubana de Ciencia Agrícola 44:221-226.

Chiemela, P. N.; Sandip, B.; Mestawet, T. A.; Egbu, C. F.; Ugbo, E. H.; Akpolu, E. S. and Umanah, I. J. 2016. Structural indices of Boer, central highland and their F_1 crossbred goats reared at Ataye farm, Ethiopia. Journal of Agricultural and Research 2:1-21.

Dorantes-Coronado, E. J.; Torres-Hernández, G.; Hernández-Mendo, O. and Rojo-Rubio, R. 2015. Zoometric measures and their utilization in prediction of live weight of local goats in southern México. SpringerPlus 4:695.

Dorantes, C.; Gómez, T. G.; Jasso, A. X.; Mondragón, A. J. and García, H. P. 2015. Utilización de las medidas zoométricas para predecir el peso corporal en cabras criollas, en el sur del estado de México. Actas Iberoamericanas de Conservación Animal 6:525-534.

FAO - Food and Agriculture Organization of the United Nations. 2012. Phenotypic characterization of animal genetic resources. FAO Animal Production and Health Guidelines No. 11. FAO, Rome.

Ferreira, J.; Silveira, R. M. F.; Sousa, J. E. R.; Vasconcelos, A. M.; Guilhermino, M. M. and Façanha, D. A. E. 2021. Evaluation of homeothermy, acid-base and electrolytic balance of black goats and ewes in an equatorial semi-arid environment. Journal of Thermal Biology 100:103027. https://doi.org/10.1016/j.jtherbio.2021.103027

Getaneh, M.; Taye, M. and Kebede, D. 2022. Conformation trait characterization of indigenous goats in selected districts of East Gojjam zone, Amhara region, Ethiopia. Journal of Applied Animal Research 50:225-238. https://doi.org/10.1080/09712119.2022.2058516

Gómez-González, A.; Pinos-Rodríguez, J. M. and Aguirre-Rivera, J. 2009. Manual de producción caprina. Universidad Autómoma de San Luis Potosí, México.

Hagan, J. K.; Apori, S. O.; Bosompem, M.; Ankobea, G. and Mawuli, A. 2012. Morphological characteristics of Indigenous goats in the Coastal Savannah and Forest Eco-Zones of Ghana. Journal of Animal Sciences Advances 2:813-821.

Hassen, H.; Baum, M.; Rischkowsky, B. and Markos, T. 2012. Phenotypic characterization of Ethiopian indigenous goat populations. African Journal of Biotechnology 11:13838-13846.

Hernández, I.; Rodríguez, J. V.; Romero, O.; Hernández, J.; Macías, A.; López, H. and Herrera, J. G. 2013. Morphometric characterization of Creole sheep without ear of the Sierra North State of Puebla-Mexico International Research Journal of Biological Sciences 2:1-8.

INEGI - Instituto Nacional de Estadística y Geografía. 2017. Anuario Estadístico y Geográfico de Tamaulipas 2017. Available at: <https://www.inegi.org.mx/contenidos/productos/prod_serv/contenidos/espanol/bvinegi/productos/nueva_estruc/anuarios_2017/702825094928.pdf>. Accessed on: May 10, 2025.

Joy, A.; Dunshea, F. R.; Leury, B. J.; Clarke, I. J.; DiGiacomo, K. and Chauhan, S. S. 2020. Resilience of small ruminants to climate change and increased environmental temperature: A review. Animals 10:867. https://doi.org/10.3390/ani10050867

La O-Arias, M.; Guevara-Hernandez, F.; Fonseca-Fuentes, N.; Gomez-Castro, H.; Pinto-Ruiz, R.; Ley-De Coss, A.; Medina-Jonapa, F. J.; Coutino-Ruiz, R. R.; Ruiz-Najera, R. E.; Espinosa-Moreno, J. A. and Rodriguez-Larramendi, L. A. 2012. Morphological characterizaction of the Cuban Creole goat: Basis for participatory management of a zoogenetic resource. Research Journal of Biological Sciences 7:270-277.

Lanari, M. R.; Taddeo, H.; Domingo, E.; Centeno, M. P. and Gallo, L. 2003. Phenotypic differentiation of exterior traits in local Criollo goat population in Patagonia (Argentina). Archives Animal Breeding 46:347-356. https://doi.org/10.5194/aab-46-347-2003

Legaz, E.; Cervantes, I.; Pérez-Cabal, M. A.; de la Fuente, L. F.; Mártinez, R.; Goyache, F. and Gutiérrez, J. P. 2011. Multivariate characterisation of morphological traits in Assaf (Assaf.E) sheep. Small Ruminant Research 100:122-130. https://doi.org/10.1016/j.smallrumres.2011.06.005

Leite, J. H. G. M.; Da Silva, R. G.; Asensio, L. A. B.; Sousa, J. E. R.; Silva, W. S. T.; Silva, W. E. and Façanha, D. A. E. 2020. Coat color and morphological hair traits influence on the mechanisms related to the heat tolerance in hair sheep. International Journal of Biometeorology 64:2185-2194. https://doi.org/10.1007/s00484-020-02014-8

Martin, P. M.; Palhière, I.; Ricard, A.; Tosser-Klopp, G. and Rupp, R. 2016. Genome wide association study identifies new loci associated with undesired coat color phenotypes in Saanen goats. PLoS One 11:e0152426. https://doi.org/10.1371/journal.pone.0152426

Okpeku, M.; Yakubu, A.; Peters, S. O.; Ozoje, M. O.; Ikeobi, C. O. N.; Adebambo, O. A. and Imumorin, I. G. 2011. Application of multivariate principal componet analysis to morphological characterization of indigenous goats in Southern Nigeria. Acta Agriculturae Slovenica 98:101-109. https://doi.org/10.2478/v10014-011-0026-4

Polák, J. and Frynta, D. 2009. Sexual size dimorphism in domestic goats, sheep, and their wild relatives. Biological Journal of the Linnean Society 98:872-883. https://doi.org/10.1111/j.1095-8312.2009.01294.x

Ren, H.; Wang, G.; Chen, L.; Jiang, J.; Liu, L.; Li, N.; Zhao, J.; Sun, X. and Zhou, P. 2016. Genome-wide analysis of long non-coding RNAs at early stage of skin pigmentation in goats (*Capra hircus*). BMC Genomics 17:67. https://doi.org/10.1186/s12864-016-2365-3

Salako, A. E. 2006. Application of morphological indices in the assessment of type and function in sheep. International Journal of Morphology 24:13-18. https://doi.org/10.4067/S0717-95022006000100003

Scheaffer, R. L.; Mendenhall, W. and Ott, L. 1991. Elementary survey sampling. In: Biometrics, B. C. Thompson, United States of America. 76-116.

SIACON-SIAP. 2022. Población Ganadera. Información sobre el número de animales que se crían en el país con fines de producción. Servicio de Informacion Agroalimentaria y pesquera. Gobierno de México. Available at: <https://www.gob.mx/cms/uploads/attachment/file/564339/Inventario_2019_caprino.pdf>. Accessed on: July 20, 2024.

Silva-Jarquin, J. C.; Andrade-Montemayor, H.; Vera-Ávila, H.; Durán-Aguilar, M.; Román-Ponce, S.; Landi, V.; Martínez-Martínez, A. and Delgado Bermejo, J. V. 2019. Diversidad y estructura genética de una población de cabras criollas negras de tres municipios del estado de Querétaro, México. Revista Mexicana de Ciencias Pecuarias 10:801-818.

Solís-Lucas, L. A.; Lanari, M. R. and Oyarzabal, M. I. 2020. Phenotypic characterization of the goat population of Santa Elena Province (Ecuador). Archivos de Zootecnia 69:22-29.

Vargas-López, S. 2003. Análisis y desarrollo del sistema de producción agrosilvopastoril caprino para carne en condiciones de subsistencia de Puebla, México. Tesis de Doctorado. Universidad de Córdoba, España.

Vázquez-Rocha, L.; López-Aguirre, D.; Peña-Avelino, L. Y.; Limas-Martínez, A. G.; Lucero-Magaña, F. A. and García-Martínez, A. 2019. Estacionalidad de la producción caprina en el Altiplano de Tamaulipas, México. Revista Acadêmica Ciência Animal 17(Supl 1):245-248.

Villarreal-Arellano, H. R.; Fuentes-Mascorro, G.; Ramírez-Bribiesca, J. E. and Torres-Hernández G. and Domínguez-Martínez, M. A. 2018. Modelo morfoestructural en la cabra criolla pastoreña de la region Mixteca del estado de Oaxaca, México. Actas Iberoamericanas de Conservación Animal 12:155-163.

Villarreal-Arellano, H. R.; Fuentes-Mascorro, G.; Ramírez-Bribiesca, J. E.; Torres-Hernández, G.; Ricardi-De-la-Cruz, C. and Vargas-López, S. 2020. Morphostructural variability in the Pastoreña goat in different regions of the Mixteca of México: A phenotypic study to establish the racial profile. Revista de la Facultad de Ciencias Agrarias 52:360-375.

Yakubu, A.; Raji, A. O. and Omeje, J. N. 2010a. Genetic and phenotypic differentiation of qualitative traits in Nigerian indigenous goat and sheep populations. Journal of Agricultural and Biological Science 5:58-66.

Yakubu, A.; Salako, A. E.; Imumorin, I. G.; Ige, A. O. and Akinyemi, M. O. 2010b. Discriminant analysis of morphometric differentiation in the West African Dwarf and Red Sokoto goats. South African Journal of Animal Science 40:381-387.

Whannou, H. R. V.; Afatondji, C. U.; Ahozonlin, M. C.; Spanoghe, M.; Lanterbecq, D.; Demblon, D.; Houinato, M. R. B. and Dossa, L. H. 2021. Morphological variability within the indigenous sheep population of Benin. PloS One 16:e0258761.