



Goat Milk Production and Valorization in Southeastern Tunisia: Breed Performance, Adaptive Strategies, and Socioeconomic Importance

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Abstract

Climate change poses significant challenges to goat farming systems in arid regions, requiring integrated approaches combining genetic diversity, adaptive management, and value chain optimization. This study assessed breed performance, climate adaptation strategies, and dairy valorization potential in southeastern Tunisia's Gabes region. A comprehensive survey of 110 goat farmers documented climate perceptions and adaptation practices, while experimental analysis of 40 dairy goats representing four breeds (Local, Alpine, Maltese, Damascus) evaluated milk composition and cheese yield through 120 samples collected over nine weeks at three-week intervals. Statistical power analysis confirmed adequacy (>0.80) for detecting breed differences in key parameters. Morphometric characterization included 50 animals across five breeds and dairy valorization assessment complemented the analysis.

Damascus goats demonstrated superior milk quality with significantly higher fat content (5.51% vs 3.83% in Local breeds, $F=5.254$, $p=0.004$) and lactose levels (3.98% vs 3.61%), but paradoxically achieved the lowest cheese yield (78.07% vs 85.57% in Maltese breeds, $p<0.001$). Alpine and Maltese breeds optimized processing efficiency with 84-86% cheese yields. Farmers implemented comprehensive adaptation strategies including crossbreeding (76%), infrastructure renovation (60%), and reduced grazing dependence (3.74 h/day average). Women dominated dairy processing (87%) with traditional products achieving 3.3-fold value multiplication over raw milk. Results reveal sophisticated breed-environment interactions where genetic specialization for arid conditions does not automatically translate to processing advantages. Strategic breed portfolio management combining Damascus for premium products, Alpine/Maltese for commercial efficiency, and Local breeds for climate resilience offers optimal sustainability outcomes.

1. INTRODUCTION

Goat farming represents a cornerstone of global agricultural systems, particularly in dryland regions, with an estimated population of over one billion animals worldwide (World Population Review, 2024). Renowned for their remarkable adaptability, goats play a multifaceted role in agricultural sustainability, contributing to biodiversity conservation and landscape management due to their ability to thrive in diverse and often marginal ecosystems (Haenlein, 2007; Afsic, 2025). Although they contribute a

relatively small fraction (approximately 1.3%) to global ruminant milk production compared to cattle (82.9%) and buffalo (13.4%), they remain an indispensable source of nutrition and income, underpinning livelihoods and food security for millions of people in rural communities (FAO, 2007; Sessarego et al., 2025)

In Tunisia, the goat sector has a complex history. Historically perceived as a driver of environmental degradation, government policies led to a drastic reduction in herds over 90% in the north and 50% in central regions (Gaddour &

Najari, 2009). Despite this, the sector is experiencing a significant resurgence, particularly in southern Tunisia, which now hosts approximately 60% of the national herd, estimated at 922,000 heads (ONAGRI, 2022). Southern Tunisia, characterized by its climatic harshness and diverse ecosystems, provides a critical context for this revival. Here, goats are prized for their resilience to heat stress and water scarcity, profoundly contributing to household dietary diversity and economic stability through both meat and milk production (Khemiri et al., 2022; Chniter et al., 2024).

The Gabes region in southeastern Tunisia is a prime example of this dynamic. Geographically, it is a coastal oasis bordered by the Mediterranean Sea to the east and arid plains to the south and west, encompassing an area of approximately 7,166 km² (Souissi et al., 2018). Climatically, Gabes is characterized by a semi-arid Mediterranean regime, with mean daily maximum temperatures ranging from 17.1°C in January to 32.5°C in August, and peak summer temperatures often surpassing 40°C (National Meteorological Institute, 2023). Precipitation is low and highly seasonal, averaging just 189.5 mm annually, which critically influences forage availability for livestock (Souissi et al., 2018). Within this challenging environment, livestock farming is a vital component of the local economy. The region's herds are primarily composed of small ruminants, with recorded populations of 440,822 sheep and 276,903 goats in 2022, supported by local forage production yielding 201,320 tonnes from 4,220 hectares (ODS, 2023).

This region represents a mosaic of genetic resources integral to the country's goat farming landscape. According to the Office de l'Élevage et des Pâturages (OEP, 2021), the breeds cultivated in Gabes encompass local ecotypes, Maltese, Damascus, Alpine, Hijazi, and Saanen. This diversity offers promising avenues for enhancing productivity; while exotic breeds like the Alpine are distinguished by high milk yield potential (Biffani et al., 2020), indigenous breeds exemplify superior resilience to the region's harsh climatic conditions (Najari et al., 2010; Gaddour & Najari, 2011). These animals are managed within heterogeneous and intricate farming systems ranging from integrated and oasis-based practices to transhumant pastoralism all attuned to the specific socio-economic and environmental challenges of the region (Nafti et al., 2009; Sessarego et al., 2025).

However, the sector's sustainability is threatened by a complex interplay of challenges. Climate variability, manifesting as rising temperatures, prolonged droughts, and reduced grazing days, intensifies pressure on already constrained resources (Amamou et al., 2018; El Bilali et al., 2021). While local populations exhibit admirable resilience, they often show limited productivity, prompting farmers to integrate improved breeds, a strategy that risks eroding valuable local genetic adaptations (Najari, 2005). Furthermore, the potential for valorizing goat milk, a key strategy for improving economic returns, remains underdeveloped. The composition of goat milk, which is paramount for product quality and yield, is not a constant; it is significantly influenced by a multitude of factors including breed genotype, lactation stage, parity, diet, and environmental conditions (dos Santos et al., 2023). Understanding these breed-specific effects on physicochemical milk parameters and their subsequent influence on cheese yield is vital for developing robust dairy industries and optimizing product marketability (Park et al., 2007).

Crucially, any strategy for development must also consider the socio-economic fabric of the sector. The perceptions and adaptation strategies of breeders themselves are the first line of defense against climate change. Moreover, the valorization chain, particularly the transformation of milk into cheese and other products, is often a gendered activity, with women playing a dominant yet frequently overlooked role that represents significant social and economic capital (Katimbo et al., 2015; Yurco, 2024).

Therefore, a holistic understanding that links breed performance under arid conditions to processing quality, farmer knowledge, and socio-economic dynamics is urgently needed. This study adopts such an integrated approach to goat farming in the Gabes region, moving beyond a singular focus on productivity to encompass the environmental and human dimensions that ultimately define the sector's sustainability and resilience.

The specific objectives of this study were:

1. To assess breeders' perceptions of climate change and document the adaptive management strategies they employ to mitigate its impacts on herd health and productivity.
2. To evaluate the impact of breed genotype on the physicochemical composition of milk from

four predominant breeds: Local, Alpine, Maltese, and Damascus.

3. To determine the cheese yield potential of milk from each breed and analyze the relationships between its compositional quality and technological performance.

4. To conduct a morphometric characterization of the main goat breeds to document phenotypic diversity in an arid environment.

5. To analyze the local valorization chain for goat milk products, with a specific focus on traditional techniques, economic potential, and the gendered division of roles.

By integrating these analyses, this research provides a comprehensive evidence base to support strategic breed management, enhance the valorization of dairy products, and support the development of a more competitive, resilient, and equitable goat sector in southern Tunisia.

2. MATERIALS AND METHODS

2.1. Study Context

The study was conducted during May–June 2022 in the Gabes region of southeastern Tunisia (7,166 km²), a semi-arid coastal oasis bounded by the Mediterranean to the east and arid plains inland. Gabes features low, seasonal rainfall (annual average 189.5 mm) and experiences extreme summer heat (up to 40°C), directly affecting forage resources and livestock activities (National Meteorological Institute, 2023; Souissi et al., 2018). The area's agricultural economy centers on small ruminant husbandry, particularly goats, with local breeds adapted to these challenging environmental conditions (ODS, 2023).

2.2. Farming Practices

2.2.1. Demographic Description of the Population

A structured socio-technical survey was administered to 110 goat farmers across the Gabes region. Survey participants were predominantly male (96%), reflecting the gendered nature of herd management in the region. Respondents averaged 49 years of age (range: 20–82) with substantial farming experience (22 years average). Educational attainment was categorized as: undergraduate level (76% comprising primary and secondary education) and graduate level (12% with university degrees). The survey was conducted through face-to-face interviews in Arabic during

May–June 2022, with prior informed consent obtained from all participants.

2.2.2. Climatic Perception

The questionnaire specifically investigated farmers' perceptions of climate change, including observed shifts in temperature patterns, precipitation changes, drought frequency, and impacts on grazing availability. This component was essential for understanding local adaptation strategies in arid zone livestock systems (Nafti et al., 2021), particularly how environmental stressors influence herd management decisions.

2.2.3. Breeding Techniques

Survey questions documented breeding management practices including crossbreeding strategies (76% adoption rate), genetic selection criteria, reproductive techniques (21% artificial insemination vs. natural mating), and herd health management protocols (97% vaccination coverage).

2.3. Breeds description: Morphometrics measurements

Twelve external morphometric (Table 1) traits were recorded on 40 goats representing the four main breeds studied (Local, Alpine, Maltese, Damascus) using flexible measuring tape while animals stood calmly on flat ground. The breed and sex distribution was as follows: Local (5♀, 5♂), Alpine (5♀, 5♂), Maltese (5♀, 5♂), and Damascus (10♀). This sampling strategy allowed

Table 1. Anatomical landmarks and measurement protocols followed Belkhadem (2017).

Code	Trait	Definition
LT	Head length	Occipital crest to nose tip
LO	Ear length	Base to distal end
LQ	Neck length	Throat to shoulder point
LC	Body length	Shoulder to pin bone
TP	Thoracic perimeter	Chest circumference behind withers
PP	Chest depth	Vertical from withers to bottom of chest
HG	Height at withers	From withers to ground
HD	Back height	Dorsal spine to ground vertical
PF	Flank depth	Hip to stifle joint vertical
LPI	Hair length	Along dorsal midline

for comprehensive breed characterization while maintaining focus on dairy-producing females that were the primary subject of milk composition analysis.

To standardize measurements and account for size variation, two indices were calculated:

$$\text{Head to body Ratio} = \left(\frac{\text{Head Length}}{\text{Body Length}} \right) \times 100$$

$$\text{Body Compactness Index} = \left(\frac{\text{Chest Girth}}{\text{Wither Height}} \right) \times 100$$

2.4. Milk and Production Variability

2.4.1. Sample Collection

The experimental cohort consisted of 40 dairy goats equally representing four breeds typical of Gabes: Alpine, Local, Maltese, and Damascus (Table 2). Purebred animals were selected per phenotypic standards, verified through farmer expertise and OEP collaboration from 14 Gabes farms and based on uniformity criteria including age (2–4 years) and health status to reduce inter-individual variability.

Table 2. Characteristics of herd used during the experimental period.

Breed	Number of goats	Average age (Year)	Weight (Kilogram)	Average quantity/goat/day(Liter)
Alpine	10	2.50±0.20	43±1.40	2±0.10
Maltese	10	3±0.0	35±1.10	1±0.00
Local	10	3.50±0.30	35±1.20	0.50±0.00
Damascus	10	3±0.00	45±1.20	1±0.10

Animals were maintained under comparable semi-intensive systems across farms, with daily supplementation standardized at approximately 500 g barley and 200–250 g commercial concentrate per goat, in addition to ~3 h of grazing. This nutritional harmonization minimized farm-to-farm variation and allowed valid inter-breed comparisons.

The study was conducted between May and June 2022, corresponding to the mid-lactation period, which is considered representative of steady-state milk composition and limits confounding effects related to early- or late-lactation variability.

Each goat was sampled thrice at 3-week intervals to capture physiological and temporal variability

in milk composition. A total of 120 milk samples were collected immediately post-milking, cooled to 4 °C, and transported under refrigerated conditions to the Institut des Régions Arides laboratory for analysis.

2.4.2. Physicochemical Analysis

Milk pH was measured using a calibrated HANNA HI 2211 pH meter following methods standardized by the International Dairy Federation (IDF, 2004). Additional compositional parameters: fat, protein, lactose, density, freezing point, and electrical conductivity were assessed using an ultrasonic milk analyzer (Lactoscan MCCW-K3051, Foss Analytical). The Lactoscan employs lactometric principles relying on refraction and density analysis. Samples were analyzed in 25 mL tubes, and results compared against established quality benchmarks for milk (IDF, 2004).

Prior to analysis, milk samples were homogenized by heating in a water bath at 40±2°C for 15–20 minutes and visually examined and those exhibiting coagulation, abnormal odor, or altered texture (indicative of spoilage) were excluded from further analysis to ensure sample quality and analytical consistency. Only fresh, homogeneous samples were retained, as elimination of defective samples is standard to

avoid artifacts in downstream physicochemical measurements (IDF, 2004). Measurements were conducted at ambient temperature with aliquots of 10 mL aspirated for each analysis.

2.5. Cheese Production

Cheese yield was assessed following a standardized coagulation and drainage protocol adapted for micro-volume analysis (10 mL milk samples) in accordance with Raynal-Ljutovac et al. (2005). Milk was coagulated at 35°C using commercial rennet at a standardized dilution. Resultant curd weights were obtained after 24 hours of draining at ambient conditions. Cheese yield was computed as:

$$CheeseYield = \frac{\text{Volume of Milk Used (L)}}{\text{Weight of Cheese Produced (kg)} \times 100}$$

This measurement allowed for evaluation of milk's technological value across breeds in relation to compositional differences.

Climate variability and aridity represent persistent and intensifying challenges for livestock systems in southeastern Tunisia. A large majority of farmers reported observable shifts in climatic conditions, particularly rising temperatures, more frequent and prolonged

Table 3. Farmer Demographics and Climate Adaptation Strategies in Gabes Region (n=110)

Demographic Category	Value	Adaptation Strategy	Implementation Rate
Male farmers	96%	Crossbreeding practiced	76%
Average age	49 ± 8.30 years	Artificial insemination	21%
Average experience	22 ± 12.70 years	Shelter renovation	60%
University education	12%	Commercial concentrate use	60%
Water Management		Health & Production	
Piped/purchased water	69%	Vaccination coverage	97%
Well dependence	31%	Regular milking	86%
No longer grazing	34%	Artisanal processing	71%
Average grazing time	3.74 ± 1.2 0h/day	Specialized dairy feeds	10%

2.6. Statistical Analyses

Statistical Power Estimation: Prior to data collection, a power analysis was conducted using G\Power software to determine sample adequacy for detecting significant differences among breeds. Utilizing an F-test framework (variance between groups divided by within groups), 120 samples (40 goats × 3 replicates) achieved power values exceeding 0.80 for key parameters including lactose (0.805), fat (0.807), protein (0.820), cheese yield (0.820), conductivity (0.801), density (0.812), and freezing point (0.812).

This confirms that the sample size, although moderate, provided sufficient statistical power for robust inter-breed comparisons and biologically meaningful interpretation of results. Milk pH was excluded from power consideration due to expected uniformity (Bhandari, 2021).

Data analyses were performed using IBM SPSS Statistics version 22. One-way analysis of variance (ANOVA) tested breed effects on measured parameters, with multiple comparisons executed via Tukey's post hoc test. Linear regression was employed to assess interactions between breed and physicochemical traits influencing cheese yield. Statistical significance was set at p<0.05.

3. RESULTS

3.1 Farmers Climate Perception and Adaptive Strategies

droughts, and a notable reduction in available grazing days due to vegetation degradation and heat stress. These perceptions are objectively confirmed by meteorological records, demonstrating that farmer observations align with empirical climate data. A long-term analysis reveals a significant warming trend in the Gabes region, with temperatures increasing by 0.47°C per decade between 1973 and 2020 (Dahech et al., 2025). Furthermore, recent data shows a marked rise in the frequency of extreme heat events; the number of days exceeding 40°C increased from 1 day in 2018 to a peak of 11 days in 2021 (National Meteorological Institute, 2023). Water scarcity was commonly cited by farmers, especially among those relying on wells (31%) or seasonal rainfall, a vulnerability exacerbated by these established climatic trends (Table 3).

These climate pressures have led to significant shifts in herd management practices (Amamou et al., 2018; El Bilali et al., 2021). The comprehensive adaptation strategies (Table 3) documented among Gabes farmers represent sophisticated, multi-dimensional responses to intensifying climate pressures documented across North Africa (El Bilali et al., 2021; Amamou et al., 2018). Crossbreeding, practiced by 76% of respondents, emerged as the primary genetic strategy to improve resilience and maintain milk productivity under stress conditions. This prevalence reflects rational genetic management combining exotic productivity with indigenous resilience, consistent with successful adaptation

strategies in Morocco and Algeria (Petit & Boujenane, 2017).

However, only 21% utilized artificial insemination, reflecting technical and logistical limitations in rural areas consistent with other North African studies (Petit & Boujenane, 2017). This limited artificial insemination adoption indicates technical constraints requiring targeted support.

Infrastructure adaptations were substantial: 60% renovated shelters for improved thermal regulation and animal hygiene, while 69% transitioned to piped/purchased water systems, demonstrating proactive investment in climate resilience. The transition from well dependence to purchased water systems reflects adaptive capacity under increasing scarcity but raises economic sustainability concerns for small-scale operators (Rathnayaka et al., 2023).

Feeding practices evolved dramatically in response to declining pasture quality, with 60% supplementing commercial concentrates, though only 10% used specialized dairy formulations. These feeding system transformations reveal profound ecological adjustments. The reduction in grazing dependence was pronounced: 34% no longer relied on grazing, and those maintaining grazing averaged only 3.74 hours per day a significant reduction representing adaptation to declining pasture quality and heat constraints. However,

factor for system resilience. This proactive health management demonstrates farmers' sophisticated understanding of climate-disease interactions under environmental stress.

These adaptive patterns align with documented responses across North African pastoral systems (Martin-Collado et al., 2025; Aribi & Sghaier, 2021), where livelihood vulnerability depends on farm typology, pastoral mobility, and household assets. The blend of technical, genetic, and infrastructural strategies observed in Gabes provides a comprehensive model for climate-smart livestock development.

3.2 Breed-Specific Milk Composition and Environmental Interactions

3.2.1 Primary Composition Parameters and Their Adaptive Significance

The significant breed variations in milk composition reflect complex interactions between genetic specialization and environmental adaptation to hot-dry conditions (Table 4). Milk pH remained remarkably stable across breeds ($p = 0.551$), ranging from 6.44 to 6.51, indicating robust physiological buffering mechanisms consistent with heat stress adaptation studies (Hamzaoui et al., 2013; Singh et al., 2024). This stability suggests effective metabolic adaptation to environmental stressors across genetic backgrounds, representing a conserved physiological trait essential for maintaining milk quality under thermal stress.

Table 4. Milk Composition, Physicochemical Properties, and Cheese Yield by Breed

Parameter	Local (L)	Alpine (A)	Damascus (D)	Maltese (M)	F-value	p-value	Significance
pH	6.45±0.02	6.44±0.03	6.50±0.04	6.51±0.03	0.85	0.55	ns
Fat (%)	3.83±0.98 ^c	4.42±0.98 ^b	5.51±0.98 ^a	4.34±0.98 ^b	5.25	0.00**	D>A=M>L
Protein (%)	2.42±0.15	2.77±0.18	2.87±0.21	2.79±0.17	1.94	0.14	ns
Lactose (%)	3.61±0.12 ^c	3.92±0.14 ^b	3.98±0.16 ^a	3.79±0.13 ^b	3.07	0.04*	D=A>M>L
Added Water (%)	18.80±1.25 ^a	15.58±1.12 ^b	7.52±0.89 ^c	15.86±1.18 ^b	9.50	0.00***	L>A=M>D
Conductivity (mS/cm)	6.18±0.22 ^c	6.97±0.28 ^a	6.65±0.25 ^b	6.99±0.29 ^a	2.99	0.04*	A=M>D>L
Freezing Point (°C)	-0.42±0.01 ^a	-0.44±0.012 ^{ab}	-0.51±0.02 ^c	-0.48±0.01 ^{bc}	4.12	0.01*	L>A>M>D
Density (g/cm ³)	1.02±0.00 ^c	1.02±0.00 ^b	1.03±0.01 ^a	1.02±0.00 ^b	3.85	0.03*	D>A=M>L
Cheese Yield (%)	81.96±2.31^b	84.02±1.98^a	78.07±2.45^c	85.57±2.14^a	-	-	M=A>L>D
Yield Efficiency	Moderate	High	Paradoxical	Optimal	-	-	-

Different superscripts (a,b,c) within rows indicate significant differences (P<0.05)

increased concentrate dependence (60%) without dairy specialization (10%) suggests suboptimal resource utilization requiring technical support for feed conversion efficiency (Wróbel et al., 2023).

Animal health management remained exemplary with 97% vaccination coverage, indicating strong awareness of disease risks in changing environments and representing a critical success

Fat content exhibited highly significant breed variation ($F(3, 116) = 5.254$, $p = 0.004$), with Damascus goats producing exceptional milk richness (5.51%), representing 44% superiority over Local breeds (3.83%). This exceptional performance in fat content, combined with minimal water dilution (7.52%), represents a sophisticated evolutionary adaptation to water-scarce environments where concentrated milk

maximizes nutrient delivery while conserving maternal resources (Singh et al., 2024). This genetic optimization for dryland conditions aligns with studies documenting physiological adjustments to heat stress in Middle Eastern breeds (Hamzaoui et al., 2013; Kaushik et al., 2023).

Lactose content differed significantly ($p = 0.040$), following similar hierarchical patterns with Damascus (3.98%) and Alpine (3.92%) exceeding Maltese (3.79%) and Local (3.61%) breeds. Despite challenging environmental conditions, these elevated lactose levels suggest maintained osmoregulatory mechanisms preserving milk quality under heat stress (Antanaitis et al., 2024). The inverse relationship between water content and milk quality parameters ($r = -0.742$, $p < 0.001$) suggests that genetic selection under water scarcity has favored concentration mechanisms over volume production.

The convergence of protein levels across breeds (2.42-2.87%, $p = 0.141$) indicates environmental buffering effects where nutritional constraints override genetic differences (Muñoz-Salinas et al., 2022). Limited high-protein forage availability in Gabes, combined with standardized barley-based supplementation and heat stress exceeding 40°C in summer, likely masked genetic potential for protein synthesis (Danso et al., 2024).

3.2.2 Physical Properties as Indicators of Technological Value and Environmental Adaptation

Added water content showed highly significant breed differences ($p < 0.001$), with Damascus milk exhibiting minimal dilution (7.52%) compared to Local breeds (18.80%). This 2.5-fold difference represents a genetic adaptation to arid environments, where concentrated milk maximizes nutrient delivery while conserving maternal water resources (Singh et al., 2024).

Electrical conductivity varied significantly ($p = 0.044$), with Damascus showing intermediate values (6.65 mS/cm) between Local breeds (6.18 mS/cm) and Alpine/Maltese (6.97-6.99 mS/cm). Lower conductivity generally indicates better mineral balance and reduced subclinical mastitis risk (Cais-Sokolinska et al., 2016).

Freezing point depression was most pronounced in Damascus (-0.507°C), reflecting higher solids concentration and osmotic pressure, consistent with their superior milk density (1.0261

g/cm³). These physical parameters confirm the technological superiority of Damascus milk for value-added processing applications.

Alpine and Maltese breeds demonstrated intermediate performance, reflecting balanced adaptation strategies that maintain productivity under semi-arid conditions without extreme specialization. Their moderate fat content (4.34-4.42%) combined with optimal water levels (15.58-15.86%) provides versatility for diverse processing applications (Vacca et al., 2018).

Local breeds' performance reflects millennia of co-evolution with semi-arid environments, maintaining adequate productivity (3.83% fat) while preserving stress tolerance mechanisms evidenced by stable pH buffering and moderate conductivity levels. Their higher water content (18.80%) may represent a thermoregulatory strategy facilitating heat dissipation under thermal stress (El Bilali et al., 2021).

3.3. Cheese Yield Performance and Processing Optimization

3.3.1 Breed-Specific Yield Performance and the Cheese Yield Paradox

Cheese yield exhibited significant breed-dependent variation, with Maltese achieving optimal performance (85.57%), followed by Alpine (84.02%), Local (81.96%) (Table 4), and Damascus (78.07%) breeds. This pattern reveals a counterintuitive yield paradox where Damascus breeds, despite producing the highest fat content, generated the lowest cheese yield.

This counterintuitive relationship between milk richness and cheese yield provides critical insights into artisanal processing dynamics under traditional production systems. Damascus milk's highest fat content but lowest yield (78.07%) illustrates how excessive solid concentration can impair curd formation, syneresis, and moisture distribution during traditional cheese-making (Aldalur et al., 2021). This yield paradox has been documented in other studies comparing breed-specific processing characteristics (Lucey & Kelly, 1994; Verruck et al., 2019).

Maltese and Alpine breeds' superior yields (85.57% and 84.02%) reflect optimal composition balance between solid concentration and processing functionality. Their intermediate fat levels combined with moderate hydration provide ideal rheological properties for traditional Mediterranean cheese-making techniques documented in North African

studies (Hamidi et al., 2023; Mallatou & Pappa, 2005).

3.3.2 Predictive Regression Analysis and Processing Implications

To identify the key milk components predicting cheese yield, a multiple linear regression was performed focusing on the main effects of the most significant compositional parameters.

Regression analysis identified critical predictive factors for cheese yield optimization (Table 5). The model was statistically significant ($F(3, 36) = 25.73, p < 0.001$) and explained 68.2% of the variance in cheese yield. Fat content ($B = +8.15, p < 0.001$) and milk density ($B = +86.45, p = 0.002$) emerged as primary positive predictors, confirming established relationships between milk solids and cheese recovery (Bencini & Pulina, 1997; Zeng et al., 2007).

that higher solids automatically improve processing outcomes (Arab et al., 2022).

The failure of a more complex model incorporating all breed-specific interactions to reach significance ($F(8, 31) = 1.087, p = 0.398$) indicates that the relationship between milk composition and yield is not easily captured by simple linear interactions. This underscores the complex, multifactorial nature of the cheese yield paradox, where the breed with the highest fat content produces the lowest yield. The significant breed-composition interactions observed in preliminary analyses indicate genetic-specific processing sensitivities requiring tailored processing protocols. Damascus breeds' heightened sensitivity to hydration effects suggests specialized techniques may be needed to optimize their exceptional milk quality for cheese production (Hadaya et al., 2017).

These findings have practical implications for

Table 5. Regression Model for Predicting Cheese Yield from Key Milk Components.

Variable	Coefficient (B)	Standard Error	t-value	p-value	95% CI
Fat Content	+17.86	4.23	4.22	0.001***	9.25 to 26.47
Added Water	+4.55	1.48	3.07	0.003**	1.54 to 7.56
Density	+11.66	3.12	3.74	0.001***	5.32 to 18.00
Model R ²	0.742				

Table 6. Morphometric Characteristics by Breed and Sex (cm).

Measurement	Alpine ♀ (n=5)	Alpine ♂ (n=5)	Damascus ♀ (n=10)	Maltese ♀ (n=5)	Maltese ♂ (n=5)	Local ♀ (n=5)	Local ♂ (n=5)
Head Length (cm)	25.5 ± 2.12	21.85 ± 1.06	24.0 ± 1.00	21.5 ± 0.70	23.0 ± 1.41	21.5 ± 0.70	23.0 ± 1.4
Body Length (cm)	77.0 ± 5.65	65.85 ± 4.33	80.0 ± 8.71	62.5 ± 4.94	67.5 ± 7.77	62.5 ± 4.94	67.5 ± 4.5
Ear Length (cm)	29.5 ± 0.70	17.0 ± 2.36	15.33 ± 1.52	22.0 ± 8.48	18.5 ± 3.53	22.0 ± 8.48	20.0 ± 3.5
Wither Height (cm)	79.5 ± 4.94	69.83 ± 2.64	78.0 ± 10.23	64.0 ± 2.82	75.5 ± 0.70	64.0 ± 2.82	69.0 ± 3.0
Chest Girth (cm)	86.5 ± 2.12	82.83 ± 2.78	95.0 ± 3.60	78.5 ± 6.36	84.0 ± 4.24	78.5 ± 6.36	83.0 ± 5.0
Head:Body Ratio %	33.10	33.20	30.00	34.40	34.10	34.40	34.10
Body Compactness Index %	108.80	118.60	121.80	122.70	111.30	122.70	120.30

The positive correlation between added water and yield ($B = +1.02, p = 0.005$) suggests that optimal hydration facilitates protein network formation and whey separation efficiency in traditional processing methods lacking industrial equipment. This finding challenges assumptions

breed selection strategies based on intended applications: Damascus for premium artisanal products requiring concentrated solids, Alpine/Maltese for commercial cheese production optimizing yield efficiency, and Local breeds for subsistence systems balancing productivity with resilience. Future research

using multivariate techniques like Principal Component Analysis would be valuable to further elucidate the complex interactions between breed, milk composition, and processing outcomes.

3.4 Morphometric Diversity and Breed Differentiation

3.4.1 Comprehensive Morphometric Analysis and Adaptive Significance

Morphometric analysis revealed substantial phenotypic diversity across the four studied breeds, reflecting ongoing genetic transformation within traditional pastoral systems and providing insights into breed adaptations to arid environments (Table 6).

The Alpine goats in Gabes were distinguished by their generally dark fawn coat with short hair, straight profile, and erect medium-sized ears, showing robust conformation with deep chests and voluminous udders that retract well after milking. These animals exhibited the largest frame sizes among the studied populations, with females showing substantial wither height (79.50 ± 4.94 cm) and body length (77.0 ± 5.65 cm), characteristics that support their reputation for good milk potential and adaptability to various farming systems.

Damascus (Shami) goats displayed tall stature with short hair and characteristic long drooping ears, consistent with their Nubio-Syrian lineage. Damascus females showed intermediate-to-large body dimensions (78.0 ± 10.23 cm wither height) with notably high chest girth (95.0 ± 3.60 cm) and the highest body compactness index (121.80%), indicating a barrel-shaped conformation favorable for milk production capacity. These exceptional dimensions demonstrate improved growth potential but may compromise drought resilience compared to compact indigenous breeds, representing a productivity-adaptation trade-off that parallels findings across Mediterranean goat populations where body size correlates inversely with environmental stress tolerance (Serranito et al., 2021).

Local breeds from Gabes retained ancestral characteristics with predominantly black coat (>60% of individuals) featuring long dark brown to black hair, providing optimal protection against intense solar radiation. This compact breed exhibited the highest head-to-body ratio (34.40%) among females, with coloration and proportions representing major adaptive traits

for desert conditions that enable superior thermoregulation.

Maltese goats, originating from Sicily/Malta, were recognizable by long pendulous ears reaching the head attachment point, with compact frames adapted to resource-scarce environments. They demonstrated compact morphology with high body compactness indices (122.7% in females), showing proportions typical of Mediterranean island breeds adapted to resource constraints (Grech, 2024).

The substantial morphometric diversity documented across breeds presents both opportunities and risks: genetic diversity enhancement versus potential dilution of indigenous adaptations. This dynamic requires strategic conservation approaches balancing productivity improvement with genetic heritage preservation (Mustefa, 2025).

Body compactness indices reveal breed-specific adaptations: Maltese (122.70) and Damascus (121.80) showed barrel-shaped conformations favoring milk production, while Local breeds (122.70) exhibited balanced proportions suitable for multipurpose use in arid environments. These morphological signatures provide phenotypic markers for breed identification and genetic management programs (Dea et al., 2020).

Sexual dimorphism was evident across all breeds, with males typically exhibiting different proportions than females. Notably, Alpine males showed substantial differences in ear length and body dimensions compared to females, while Damascus breeds (represented by females only in this study) displayed homogeneous characteristics suited for dairy production in arid environments.

3.5. Gendered Dairy Valorization and Socioeconomic Impacts

3.5.1. Production Metrics, Processing Engagement, and Economic Significance

Dairy production averaged 1.25 L/goat/day with significant breed variation (Alpine: 2.0 L; Local: 0.50 L), generating 218.75 ± 75.78 L annually per goat during the 175-day lactation period (Table 7). Despite modest individual yields, processing engagement remained high (71%), demonstrating strong cultural commitment to dairy valorization and reflecting sophisticated traditional knowledge systems that have evolved to maximize resource utilization in arid environments.

Table 7. Dairy Production and Valorization Characteristics

Production Parameter	Value	Valorization Aspect	Rate/Price
Daily milk yield/goat	1.25 ± 0.43L	Processing participation	71%
Lactation period	175 days	Women's processing role	87%
Annual milk/goat	218.75 ± 75.78 L	Leben/Raïeb production	Most common
Product Distribution		Economic Value	
Raw milk household use	80%	Simple cheese	12-15 TND/kg
Processed household use	62%	Mozzarella/Ricotta	15 TND/kg
Raw milk commercial	5%	Smen (fermented ghee)	50 TND/kg
Processed commercial	2%	Value addition ratio	3.3× (Smen/raw)

The subsistence orientation (80% raw milk, 62% processed products consumed domestically) reflects rational risk management in uncertain environments, prioritizing household food security over market exposure. This pattern mirrors findings from pastoral communities across the Sahel where dairy products serve as nutritional insurance against seasonal variability (Lombard & Parsons, 2015).

3.5.2. Gendered Knowledge Systems and Cultural-Economic Integration

Dairy transformation was overwhelmingly female-dominated (87% women involvement), representing a widespread pattern across arid Africa where women's traditional knowledge preserves cultural food heritage while providing economic flexibility and household food security (Katimbo et al., 2015; Yurco, 2024). This gendered specialization aligns with studies from Ethiopia, Kenya, and Uganda documenting women's central roles in dairy value addition (Nagasha et al., 2024; Yurco, 2024).

Women controlled technical processing, quality standards, and direct marketing decisions, representing significant social capital for value chain development and constituting irreplaceable human resources for sustainable value chain development respecting cultural frameworks (Malhotra et al., 2024).

Product diversity reflected sophisticated traditional knowledge systems, with three primary artisanal processes:

- **Leben (Sour Buttermilk) and Raïeb (Fermented Milk Curd)**

Raïeb refers to raw goat milk that is poured into clay pots or modern containers and allowed to **spontaneously ferment** at ambient temperature

(25-35 °C) for 24 to 48 hours using native lactic acid bacteria. The resulting thickened curd is then churned (by hand or with wooden sticks) until it separates into two fractions:

- **Leben (Lben):** The **tangy liquid** (fermented buttermilk) that serves as a refreshing probiotic beverage.
- **Butter grains (Zbouda/Zebda):** The fat component used as the base for Smen.

This ubiquitous production process provides both a drink and a cooking base, and is prepared daily by 62% of processing women.

- **Simple Fresh Cheese (Drained Fresh Curd)**

To make fresh cheese, fresh raw milk either sours naturally over 12 to 24 hours or is gently warmed (35-40°C) with a pinch of previous curd (starter culture). Coagulation occurs spontaneously via lactic acid production; the soft curd is then drained in a clean cheesecloth for 4 to 6 hours. This yields a mild-flavored fresh cheese (65-70% moisture) consumed within 2 to 3 days. No rennet is used, distinguishing it from pressed cheeses. This product is prepared by 71% of women processors.

- **Smen (Fermented Clarified Butter)**

Smen is a high-value fermented clarified butter. The butterfat (butter grains, *Zbouda*) separated from the Leben is collected over 3 to 4 days, then fermented and matured in sealed earthenware jars for 2 to 3 weeks at cool temperatures. After churning, this matured fermented cream is heated gently to separate the Smen (clarified butter) from the residual solids, and then filtered. The resulting product stores for months without refrigeration, commanding premium pricing (50 TND/kg). This high price is due to its dual role as an aromatic cooking fat and a traditional

medicine for respiratory ailments, digestive issues, and skin conditions.

This transition from traditional shakwa goat skin fermenters to modern kitchen equipment illustrates adaptive innovation while maintaining product authenticity, demonstrating how traditional knowledge systems evolve to contemporary contexts.

Smen production exemplifies cultural-economic integration, achieving 3.3× value multiplication over raw milk while serving simultaneously as nutrition source, traditional medicine, and premium income generator. Its medicinal applications reflect indigenous knowledge systems requiring urgent documentation and preservation before erosion occurs.

3.5.3. Market Integration Patterns and Development Potential

Commercial integration remained minimal (5% raw milk, 2% processed products), indicating substantial untapped potential for heritage product development. The premium pricing structure (Smen (fermented ghee): 50 TND/kg vs simple cheese: 15 TND/kg) suggests significant market opportunities for culturally authentic products with appropriate certification and marketing support.

Women's decision-making authority in processing and marketing represents significant social capital that could support scaled valorization initiatives. Their intimate knowledge of quality standards, consumer preferences, and traditional techniques provides a strong foundation for developing gender-inclusive value chains that simultaneously advance economic development and cultural preservation.

The minimal market integration, while indicating untapped economic potential, also reflects the strategic prioritization of household food security in climate-vulnerable regions. This balanced approach to subsistence and commercial production represents a resilient adaptation strategy that could inform development initiatives across similar arid regions in North Africa and beyond.

3.6. Integrated Sustainability Framework

The integration of genetic diversity, environmental adaptation, and cultural valorization documented in this study provides a comprehensive model for sustainable goat production in arid regions. Climate projections indicate increasing aridity across southeastern

Tunisia (El Bilali et al., 2021), making heat-tolerant, water-efficient genetic resources increasingly valuable.

Strategic breed combinations rather than single-breed approaches may optimize multiple sustainability objectives (Ramón et al., 2021): Damascus for quality-focused artisanal processing, Alpine/Maltese for commercial production efficiency, and Local breeds for climate resilience maintenance. This portfolio approach provides risk distribution and market flexibility under uncertain environmental conditions.

The documented gendered knowledge systems offer scalable models for rural development that respect cultural frameworks while enhancing economic outcomes. Supporting women's leadership in value chain development could simultaneously advance gender equity and agricultural sustainability objectives through targeted training, equipment access, and market facilitation (Adefila et al., 2024).

Conservation priorities should focus on documenting traditional processing techniques, preserving indigenous breed characteristics, and supporting community-based genetic management. The irreplaceable adaptation potential represented by local genetic resources merits immediate conservation investment alongside productivity enhancement efforts (Darmawan et al., 2023).

4. CONCLUSION

This study demonstrates that goat production systems in southeastern Tunisia employ sophisticated, integrated strategies to navigate climate challenges, effectively blending genetic diversity, environmental adaptation, and cultural valorization. The documented breed-specific performances reveal a clear functional differentiation: Damascus goats provide superior milk quality with 44% higher fat content, Alpine and Maltese breeds offer optimal cheese yield efficiency, while Local breeds constitute an irreplaceable genetic reservoir for climate resilience. The counterintuitive cheese yield paradox underscores the need for breed-specific processing protocols to fully exploit their potential.

Complementing these genetic resources, farmers exhibit remarkable adaptive capacity through diversified management practices, including strategic crossbreeding, infrastructure renovation, and reduced grazing dependence.

Simultaneously, the female-dominated dairy valorization system (87% women's participation) represents significant social and economic capital, achieving 3.3-fold value multiplication through traditional products like Smen, while ensuring household food security.

Strategic interventions should prioritize breed portfolio management, climate-resilient infrastructure, and gender-inclusive value chain development. Immediate research should focus on elucidating the genetic basis of heat tolerance, optimizing traditional processing techniques, and developing climate-smart feeding systems. The Gabes model integrating genetic conservation, adaptive management, and cultural valorization provides a replicable framework for sustainable livestock development in arid regions globally, demonstrating that environmental sustainability, cultural preservation, and economic development can be mutually reinforcing when building upon existing community knowledge and assets.

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Statement of Animal Rights

All procedures involving animals were conducted in accordance with ethical standards and followed the Declaration of Helsinki principles. Animal welfare was prioritized throughout the study period.

Institutional Review Board Statement

Ethical approval was not required for this study, as it involved non-interventional research (surveys and questionnaires) conducted in accordance with ethical standards. However, all procedures involving human participants were conducted following the Declaration of Helsinki (1975, revised in 2013). The study was carried out with the ethical standards of the Arid Region Institute (IRA Medenine).

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Abbreviations

OEP: Livestock and Pasture Office.

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