

## CHALLENGES IN THE SUSTAINABILITY OF GOAT PRODUCTION SYSTEMS IN ZACATECAS, MEXICO

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### ABSTRACT

Goat (*Capra hircus* Linnaeus, 1758) production is a key livelihood activity in Zacatecas, Mexico, but it faces increasing environmental, social, and economic pressures typical of dryland systems. This study offers an integrative narrative review with a systematic search and transparent selection criteria to synthesize evidence on the sustainability of goat production systems in Zacatecas. Peer-reviewed literature and technical documents were analyzed alongside official contextual indicators. The synthesis shows a decline in the caprine sector over recent census periods, with a producer profile marked by demographic vulnerability. Across the evidence, sustainability challenges stem from interconnected pathways where drought and rainfall variability decrease forage and water availability, worsen seasonal feed shortages, and boost reliance on purchased inputs, raising costs and increasing land degradation risks. These environmental pressures interact with herd management issues such as feeding, preventive health, parasite control, and reproduction, while limited access to coordinated services, infrastructure, and stable markets hampers value capture and reinvestment. Significant evidence gaps remain for Zacatecas-specific, outcome-based assessments (profitability during drought, rangeland condition metrics, health burdens, and value-chain performance), indicating the need for ongoing monitoring. Key leverage points include drought preparedness and feed planning, improving water access, preventive herd health, strengthening producer organizations and extension services, and developing feasible value-added options for dairy and meat products.

**Keywords:** drylands, drought resilience, rural livelihoods, value chain, feed planning.

### INTRODUCTION

Goat production is a key part of smallholder livelihoods in Mexico's drylands, where herds contribute to household income and food supply through meat and milk. Nationally, goat farming mainly takes place in arid and semi-arid regions and is mostly extensive; more than 70 % of goats are raised in extensive systems, with fewer in intensive and semi-intensive systems (Tajonar *et al.*, 2022). These systems are

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usually multi-functional and rooted in local food traditions, providing kids with meat and various dairy products. Goat milk is known as a nutrient-rich food containing proteins, vitamins, and minerals, and goat meat is often described as a lean red meat with a favorable protein-to-fat ratio (Al-Kaisy *et al.*, 2023; Gawat *et al.*, 2023).

In Zacatecas, goat production operates under environmental constraints and structural limitations that affect both productivity and resilience. The National Institute of Statistics and Geography (INEGI) Agricultural Census 2022 tabulations report 5946 goat-keeping production units in the state, and census comparisons indicate a substantial contraction of the activity since 2007 (INEGI, 2023). This contraction is relevant for sustainability because it is consistent with mounting pressures on dryland livelihoods, including climate-related forage and water constraints, rising costs and market uncertainty, and barriers to upgrading and value addition in smallholder value chains.

Sustainability, broadly defined, means meeting current needs without harming the ability of future generations to meet their own needs by integrating environmental health, economic sustainability, and social fairness (WCED, 1987). Applying this concept to goat production involves examining how climate and resource limits affect household income, animal health, and value-chain performance. This is especially crucial in semiarid areas where rangeland conditions and management are key factors affecting feed availability and environmental outcomes. Studies across the San Luis Potosi-Zacatecas high plateau describe ongoing rangeland decline, emphasizing the need to align livestock practices with ecosystem capacity (Aguirre-Rivera *et al.*, 2023). In these environments, goats can serve as both a flexible resource and a system at risk, depending on forage availability, grazing practices, and access to services and markets (Tajonar *et al.*, 2022).

Goat production systems in Mexico show significant diversity, ranging from extensive to semi-intensive and intensive approaches, each with unique trade-offs in productivity, input needs, welfare, and environmental impact (Chávez-Espinoza *et al.*, 2022; Tajonar *et al.*, 2022). Mixed crop-livestock systems are also common in drylands, where crops and livestock interact through residue use, nutrient cycling, and risk management, which can boost system resilience when managed properly (Schiere *et al.*, 2006). However, in Zacatecas, the evidence remains scattered across environmental, socio-demographic, technical, and market aspects, limiting a full understanding of sustainability challenges and opportunities.

Therefore, this review synthesizes current knowledge on the sustainability of goat production systems in Zacatecas, Mexico, by combining environmental, social, and economic aspects. Key challenges and opportunities for sustainable development were identified, along with suggested research priorities and interventions aimed at enhancing resilience, productivity, and livelihoods within the state's goat production systems sector.

## MATERIALS AND METHODS

This work is an integrative narrative review with a systematized search and transparent selection criteria, designed to synthesize evidence on the sustainability of goat production systems in Zacatecas, Mexico. The integrative review approach was chosen because it allows the inclusion and synthesis of diverse evidence (peer-reviewed studies, technical reports, and institutional documents) while maintaining methodological rigor through clear procedures for identification, screening, and data extraction (Whittemore and Knafl, 2005).

### Information sources

Two complementary evidence streams were used: (1) Official statistical sources for regional context and trend indicators relevant to sustainability: the National Institute of Statistics and Geography (INEGI) (Agricultural Census); the Agri-food and Fisheries Information Service (SIAP)/Ministry of Agriculture and Rural Development (SADER) (livestock and agricultural statistics); and the National Council for the Evaluation of Social Development Policy (CONEVAL) (state poverty and social deprivation context for Zacatecas); and (2) scientific and technical literature (peer-reviewed articles, technical reports) addressing goat production systems, dryland livestock sustainability, value chains, rangeland/feed-water constraints, animal health challenges, and socio-economic/organizational factors relevant to Zacatecas or similar semi-arid regions.

### Search strategy

Searches were carried out in both English and Spanish using combinations of keywords and Boolean operators. Examples of search strings included: (“goat” OR “caprine” OR “caprinos”) AND (“Zacatecas”) AND (“sustainability” OR “resilience” OR “value chain” OR “drought”). Also, (“sistemas de producción caprina” OR “caprinocultura”) AND (“Zacatecas”) AND (“sustentabilidad” OR “sequía” OR “cadena de valor” OR “manejo”).

Additionally, reference lists of relevant documents were screened to identify further sources (snowballing). Given the limited number of publications specifically addressing the “sustainability” of goat systems in Zacatecas, evidence from comparable semi-arid goat systems was included only when mechanisms and constraints were clearly transferable and relevance was explicitly stated. Searches were conducted in Google Scholar, PubMed, Scopus, and Latindex covering 2000–January 2026.

### Eligibility criteria and screening

Documents were eligible if they (i) focused on goat production systems or closely related small-ruminant systems relevant to semi-arid regions; (ii) provided evidence related to at least one sustainability dimension (environmental, economic, or social/cultural), including cross-cutting components such as animal health and the value chain; and (iii) offered verifiable information (data, methods, or clearly documented

technical/policy evidence). Documents were excluded if they were unrelated to small ruminants, lacked methodological clarity, or contained claims without traceable sources.

#### **Search outputs and selection transparency (PRISMA-lite)**

The identification and selection process was reported following PRISMA 2020 as a reporting framework (not as a claim of a full systematic review of interventions) (Page *et al.*, 2021). The search yielded approximately 250 records; after removing duplicates, about 155 records remained for screening of titles and abstracts; roughly 62 full texts were assessed for eligibility; and around 44 documents were included in the qualitative synthesis. The main reasons for exclusion at the full-text stage were irrelevance to goat systems/semi-arid contexts, insufficient methodological detail, or lack of verifiable sources. Records were managed in Zotero, which was used to remove duplicates and support systematic screening and tagging.

#### **Data extraction and analytical framework**

Data were collected into a standardized evidence matrix that captured (i) document type, (ii) geographic scope (Zacatecas vs. comparable semi-arid contexts), (iii) production system type (extensive, semi-intensive, intensive, and mixed crop-livestock when applicable), (iv) drivers and constraints (climate variability/drought, feed and water resources, rangeland condition, animal health, labor/demography, organization and services, and markets and value chain), (v) reported outcomes and indicators (productivity proxies, costs and income proxies, vulnerability, adoption, and coordination), and (vi) evidence direction (constraint vs. opportunity). Synthesis was performed through thematic integration by (1) sustainability dimension, (2) system type, and (3) mechanism and outcome pathways to identify trade-offs, synergies, and evidence gaps (Whittemore and Knafl, 2005).

#### **Use of official datasets in the synthesis**

Official sources (INEGI, SIAP/SADER, and CONEVAL) were used to contextualize and interpret findings from the literature (such as production structure, socio-demographic vulnerability, and socio-economic constraints). These statistics were not considered “results of the review” but rather as contextual evidence supporting the interpretation of sustainability bottlenecks and leverage points in Zacatecas.

#### **Limitation: scarcity of state-specific sustainability literature**

A key limitation was the small number of publications specifically focused on the sustainability of goat production systems in Zacatecas. This was addressed by (a) incorporating robust official datasets for context and (b) selectively using evidence from comparable semi-arid systems to explain mechanisms, while explicitly identifying state-specific knowledge gaps as priorities for future research.

## REGIONAL CONTEXT: GEOGRAPHY, CLIMATE, AND CENSUS-BASED GOAT SECTOR PROFILE

This section offers the regional baseline essential for understanding sustainability challenges in Zacatecas' goat production systems. The state's geographic and climatic limitations that impact forage and water availability are briefly outlined. Following this, a census-based profile of the goat sector is provided, including inventory and production units, to establish a consistent territorial framework for discussing the environmental, social, and economic pressures faced by the industry (INEGI, 2013).

### Geographic and climate constraints

Zacatecas is located in north-central Mexico on the Mexican Plateau, where predominantly dry and semi-dry conditions constrain agricultural and livestock production. Official state profiles report an average annual temperature around 17 °C and an average annual precipitation of approximately 510 mm, with rainfall occurring mainly in the warm season (June–September), which creates strong seasonality in water and forage resources and heightens drought risk. These climatic constraints interact with the state's land cover and rangeland base: nearly half of Zacatecas is covered by natural vegetation, with xerophytic shrubland and grassland as major components, reinforcing the dependence of extensive livestock systems on variable rangeland productivity under dryland conditions (INEGI, 2013).

### Goat sector size and structure (census-based)

INEGI census indicators show a marked long-term contraction of the caprine sector in Zacatecas (Table 1). Between 1991 and 2022, the census-based goat inventory declined by ~55 %, while the number of goat-keeping production units decreased by ~38 % between 2007 and 2022, indicating a substantial reduction in both the animal base and the production-unit base over time (INEGI, 2009, 2013, 2023). This concurrent decline provides a consistent baseline for interpreting sustainability pressures discussed in subsequent sections, particularly under dryland conditions where climate variability,

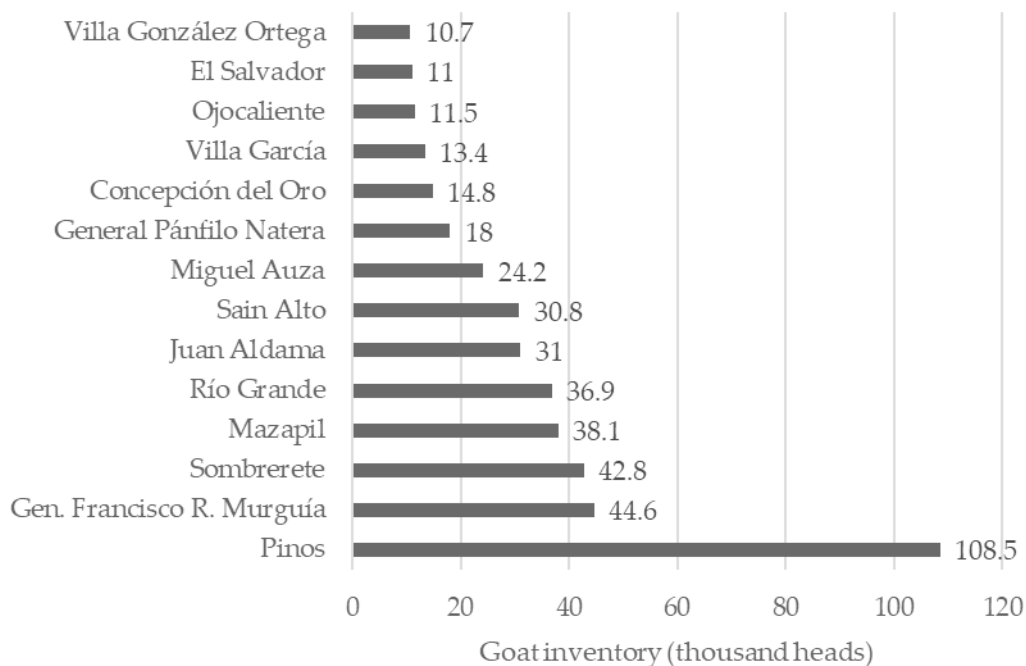
**Table 1.** Census-based caprine sector indicators in Zacatecas, Mexico (INEGI, 1991, 2009, 2023).

Census year	Goat inventory (head)	Goat production units
1991	431 668	Not available
2007	237 534	9659
2022	194 870 (total)	5946

Note: Goat inventory corresponds to INEGI Agricultural Census figures by entity. For 2022, INEGI reports caprine inventory separately for production units and households; the total inventory shown here is the sum of both (189 076 in production units + 5794 in households). Goat production units are reported for 2007 and 2022; a directly comparable production-unit count was not available in the 1991 census compilation used in this review.

resource constraints, and market limitations can jointly affect the viability of goat production systems.

Goat production is also spatially concentrated within the state. Based on the Individual Livestock Identification System (SIINIGA) municipal registry data for 2024, the highest registered inventories are located in Pinos, General Francisco R. Murguía, Sombrerete, Mazapil, and Río Grande, which together account for 53 % of the state's registered goat inventory (SIINIGA, 2024) (Figure 1). To emphasize the main production clusters, only municipalities reporting more than 10 000 head in the SIINIGA 2024 registry were considered.



**Figure 1.** Municipal distribution of goat inventory in Zacatecas (SIINIGA, 2024): municipalities with >10 000 registered heads.

### Socioeconomic context of main goat municipalities

Goat production in Zacatecas is closely linked to rural well-being because it is concentrated in municipalities where poverty and social deprivation persist. This concentration overlaps with municipalities where poverty remains high to moderate; for example, CONEVAL classifies Pinos in the highest municipal poverty bracket, while most of the other high-inventory municipalities fall within moderate poverty categories (CONEVAL, 2020). This socioeconomic environment acts as a cross-cutting

constraint on sustainability by limiting producers' ability to invest in feed and water buffering, preventive health, and collective commercialization, thereby amplifying the effects of drought and market volatility described in the following diagnostic sections (CONEVAL, 2020).

### **SUSTAINABILITY DIAGNOSIS OF GOAT SYSTEMS IN ZACATECAS**

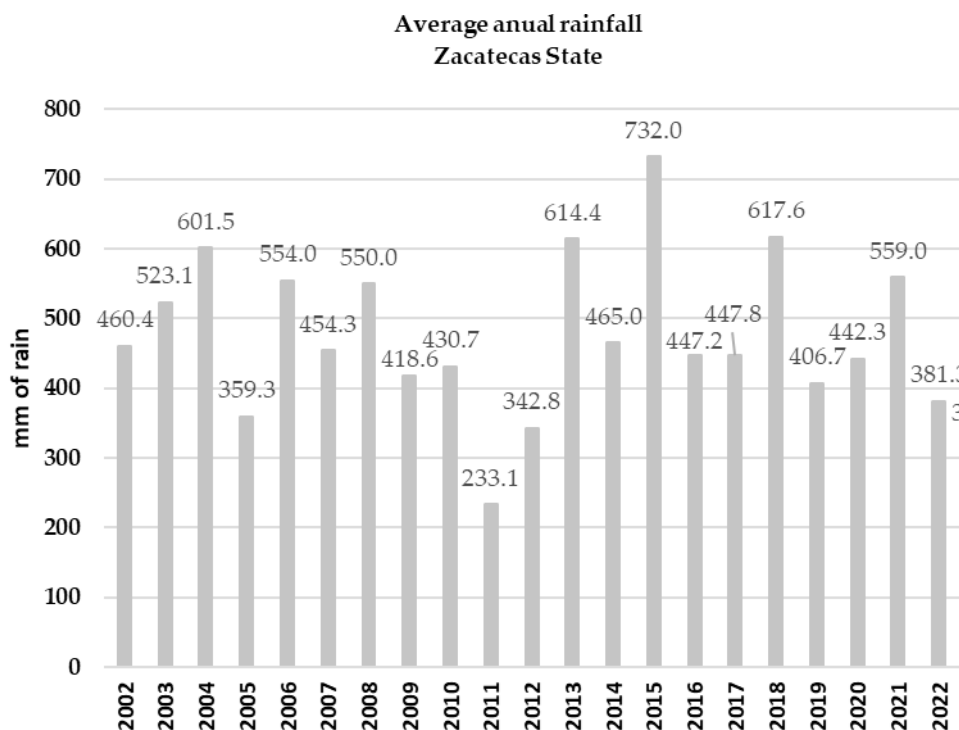
This section synthesizes the main sustainability constraints affecting goat production systems in Zacatecas by integrating (i) official territorial and sectoral evidence (e.g., climate and land-cover context) with (ii) mechanistic insights from the scientific literature on dryland livestock systems. The diagnosis is organized around how environmental pressures translate into forage and water constraints, which then propagate into higher production costs, land degradation risks, and reduced resilience for smallholder goat systems.

#### **Environmental constraints and resource base**

Environmental constraints serve as the main sustainability bottleneck for goat production systems in Zacatecas because herd performance and household profitability heavily rely on the availability of forage and water in a highly variable dryland environment. Recurrent droughts and significant interannual climate fluctuations shape rangeland productivity, influence the length and severity of seasonal feed shortages, and increase dependence on purchased or conserved feeds, thus directly linking environmental stress to production costs and economic vulnerability. These pressures also interact with grazing management and land condition, as reduced vegetation cover during dry periods can heighten erosion risk and hasten the degradation of the resource base that supports extensive goat systems over the long term.

Zacatecas's mostly dry and semi-dry climate creates a structural limit on goat production because rainfall mainly occurs in the summer and varies greatly between years, leading to recurrent periods of feed and water shortages. Under these conditions, drought and climate variability directly reduce the availability of rangeland forage and crop residues, increasing reliance on purchased feed and water strategies, which in turn raises costs and increases vulnerability for smallholders (Thornton *et al.*, 2015). Additionally, long dry spells can worsen soil exposure and erosion risk by reducing plant cover, which diminishes the long-term ability of grazing lands to supply stable forage.

The resource base in Zacatecas supports this reliance on climate-sensitive grazing lands: official land-cover data show that a significant part of the state is covered by natural vegetation, mainly xerophytic shrubland and grassland, which are inherently affected by rainfall pulses and drought conditions. Consistent with the municipal concentration of registered herds in semi-arid areas (Figure 2), the effects of rainfall variability are expected to be particularly relevant for the main goat-producing clusters.



**Figure 2.** Average annual rainfall (2002–2023) in Zacatecas State, Mexico (Medina *et al.*, 2023).

Seasonal forage scarcity is a direct pathway through which rainfall variability affects goat productivity and household profitability in Zacatecas. During dry periods, reduced pasture growth and limited availability of crop residues create feed gaps that often lead producers to increase supplementation, often through purchased feeds, which raises production costs and can erode already narrow margins in smallholder systems (Herrero *et al.*, 2009; Thornton *et al.*, 2015). Nutritional stress during these periods commonly translates into lower growth rates, reduced reproductive performance, and higher susceptibility to disease, thereby amplifying both biological and economic vulnerability (Herrero *et al.*, 2009).

Because feed shortages recur seasonally and intensify in drought years, they make outputs and income more variable and highlight the importance of feed planning, forage conservation, and low-cost supplementation strategies as key resilience measures (Dida, 2021; Thornton *et al.*, 2015). This drought-driven instability of forage supply is consistent with evidence synthesized for Mexican drylands, where recurrent drought can cascade into lower forage reliability and household vulnerability in grassland-based livestock systems (Luna-Coronel *et al.*, 2026).

Water scarcity acts as a coupled constraint in Zacatecas' goat systems because it directly affects animal performance and indirectly limits forage and crop productivity.

Limited access to drinking water during drought can reduce intake and compromise thermoregulation and lactation, with negative consequences for milk and meat outputs (Doreau *et al.*, 2012). At the same time, water shortages constrain rangeland growth and crop production, thereby reducing the availability of both grazing biomass and crop residues that partially buffer seasonal feed gaps in mixed systems (Akinmoladun *et al.*, 2019). For smallholders, these biophysical constraints translate into higher costs through water hauling and/or investments in basic water infrastructure, reinforcing the link between drought, resource scarcity, and economic vulnerability (Pretty, 2008). Mixed crop-livestock strategies can buffer drought-driven feed deficits in Zacatecas by linking crop production to goat feeding through the use of residues and by-products. In the state, the cropping pattern is dominated by beans and maize, which together account for most of the cultivated area and therefore generate substantial amounts of crop residues that can be mobilized as seasonal feed resources (SIAP, 2024). When managed appropriately, this integration can improve resource-use efficiency and reduce dependence on purchased feeds by recycling biomass and nutrients within the farm system (Schiere *et al.*, 2006; Herrero *et al.*, 2013). However, the benefits depend on balancing residue use, grazing pressure, and soil cover: excessive removal of residues or high stocking rates under drought conditions can exacerbate soil degradation and compromise the long-term productivity of the resource base (Lemaire *et al.*, 2014). Evidence from mixed farming systems evaluated in Zacatecas indicates that, even when environmental practices perform relatively well, the main weaknesses tend to concentrate in the technical-productive and climate-resilience dimensions, reinforcing the need to link resource management with practical decision tools for drought adaptation (Luna-Coronel *et al.*, 2025).

Soil condition is a cross-cutting constraint in Zacatecas' dryland goat systems because it regulates both forage production on rangelands and the productivity of crops that generate residues used as seasonal feed. Under drought, reduced vegetative cover and concentrated grazing around water points and settlement areas can accelerate erosion and compaction, lowering infiltration and soil water storage and further destabilizing forage supply (Lal, 2001; Teague and Barnes, 2017). In mixed crop-livestock settings, a key trade-off emerges between using crop residues as livestock feed and retaining sufficient ground cover to protect soil and conserve moisture; excessive residue removal can weaken soil protection and compromise future yields, increasing reliance on purchased feeds over time (Lal, 2001). Therefore, soil-water conservation and grazing management that maintains ground cover are central leverage points for sustaining the feed base and reducing vulnerability to rainfall variability in Zacatecas. These environmental constraints strongly interact with grazing management and soil conditions. In dryland rangelands, insufficient recovery periods or stocking rates that exceed carrying capacity can accelerate vegetation loss and diminish ecosystem function, creating a negative feedback loop between drought, forage scarcity, and land degradation. Evidence reviews on grazing systems highlight that adaptive grazing management, especially strategies that emphasize recovery time and flexibility during

variable rainfall, can enhance socio-ecological resilience and help maintain grazing land function over time (Teague and Barnes, 2017).

In parallel, soil physical condition and organic matter are vital for drought buffering: soils with improved structure and higher organic matter typically hold more plant-available water and support more stable plant growth amid rainfall variability, which is critical to maintaining forage production in semi-arid areas (Lal, 2001). Overall, the interplay of seasonal and variable rainfall, rangeland-based feed resources, and the susceptibility to degradation underscores the importance of drought preparedness, grazing management, and soil-water conservation as key environmental strategies for the sustainability of goat systems in Zacatecas. In this context, drought resilience can be interpreted through resistance, recovery, and persistence mechanisms that link vegetation traits and grazing management to system stability under recurrent drought (Luna-Coronel *et al.*, 2026).

#### **Production and management constraints (feed-health-reproduction)**

In Zacatecas, the performance and resilience of goat systems are heavily influenced by management constraints that follow from the environmental factors described earlier. During dry seasons and recurrent drought, feed planning becomes a key bottleneck: reduced rangeland biomass and lower forage quality during dry months increase nutritional stress. This stress can hinder growth and milk production, diminish reproductive success, and increase susceptibility to disease (Joy *et al.*, 2020). In this context, supplementation strategies, such as using crop residues, conserved forages, or balanced feeds, can help buffer seasonal feed shortages and also raise cash costs and reliance on input markets, creating trade-offs between immediate productivity and long-term economic sustainability, especially for smallholders with limited liquidity. A practical interpretation of this seasonal constraint is the predictable dry-season protein/energy gap in C4 grasslands typical of many Mexican drylands, which can be buffered by integrating forage shrubs and/or targeted supplementation (Luna-Coronel *et al.*, 2026).

Preventive animal health and parasite management are essential pillars for sustainability. Grazing goats are frequently exposed to gastrointestinal nematodes and other endemic health issues; evidence highlights that parasitism is a major obstacle to performance and that repeated anthelmintic use can lead to resistance, making integrated control and targeted treatments increasingly vital (Hoste *et al.*, 2002, 2005; Reyes-Guerrero *et al.*, 2021). In this context, access to veterinary services, vaccination, deworming routines, and producer knowledge are critical for maintaining herd health, kid survival, and overall efficiency. INEGI's 2007 Agricultural Census explicitly captures management indicators for goat production, such as balanced feed, vaccination, and deworming, offering an official framework to describe these practices and their presence or absence at the production-unit level (INEGI, 2009).

Reproductive management and kid survival are particularly vulnerable to nutritional and health constraints in semi-arid systems. Periods of feed scarcity can decrease

body condition and hinder conception and lactation, while disease and parasitism can further impair reproductive success and juvenile survival, reinforcing cycles of low productivity and limited capacity for reinvestment (Hoste *et al.*, 2005; Joy *et al.*, 2020). Therefore, strengthening management strategies that combine (i) seasonal feed planning (including strategic supplementation), (ii) preventive health protocols and integrated parasite control, and (iii) basic reproductive management and record-keeping, is a key leverage point for boosting productivity and resilience without increasing pressure on the natural resource base.

Finally, these management improvements rely on service delivery and learning pathways. The CA2007 questionnaire structure also records whether production units received technical assistance and related support, allowing analysis of management constraints within broader “services and adoption” bottlenecks (INEGI, 2009). This is especially important in drylands, where timely advisory support, such as drought early actions, ration formulation, and herd health calendars, can decrease losses and enhance decision-making under climate condition variability.

#### **Economic and value-chain constraints**

Economic viability is a central sustainability bottleneck for goat systems in Zacatecas because dryland conditions translate biophysical stress into higher and more variable costs, while market and service constraints limit producers’ ability to capture value. Feed supplementation during recurrent dry seasons is a dominant cost driver in smallholder herds, and it can quickly erode margins when forage availability declines and producers must purchase concentrates or roughage (Herrero *et al.*, 2009; Dida, 2021). Limited access to credit and investment further constrains adaptation, reducing the capacity of producers to improve water infrastructure, housing, herd health management, and feeding strategies that would stabilize productivity under climatic variability (Negrete, 2014).

Value-chain limitations also restrict income opportunities. In smallholder settings, weak aggregation, cold chain, processing capacity, and transport infrastructure reduce market access and limit value addition in dairy and meat products, reinforcing dependence on local sales and intermediated marketing channels (Hemme and Otte, 2010). Value-chain analyses in Mexican dryland goat dairy systems similarly highlight the central role of intermediaries and the potential of coordinated upgrading (e.g., collective action, quality control, and targeted infrastructure) to improve profitability and market outcomes for producers (Gómez-Ruiz *et al.*, 2012).

#### **Social, labor, and demographic constraints**

Social and demographic conditions in Zacatecas create structural constraints that can limit the continuity, adaptive capacity, and innovation uptake of goat production systems. Official results from the INEGI Agricultural Census 2022 show an aging producer profile in the state: most producers are older than 45 years, including a substantial share aged 65 years or older, which can reduce labor availability, weaken

generational succession, and constrain the adoption of new practices without strong extension support (INEGI, 2023). In addition, census-based profiles report basic educational constraints (with primary schooling predominating), which can further slow the diffusion of innovations and the implementation of more complex management responses to drought and market risk (INEGI, 2023).

The lack of generational succession is a major social constraint for the long-term viability of goat production systems in Zacatecas. Rural outmigration can reduce the availability of young labor and weaken intergenerational knowledge transfer, leaving herds increasingly dependent on older producers and limiting the capacity to adopt improved practices and technologies. INEGI demographic statistics indicate population outflows from Zacatecas during 2015–2020, reflecting broader livelihood pressures that can undermine continuity in agricultural activities (INEGI, 2024). In goat systems, this demographic shift can translate into lower management intensity and slower innovation uptake, increasing vulnerability to climatic shocks and market volatility. Strengthening entry pathways for youth (training, access to productive assets, and profitability-oriented upgrading) is therefore a priority to sustain the sector over the medium term.

Gender dynamics are relevant for sustainability in Zacatecas' goat systems because women often contribute to smallholder livestock activities, yet they are underrepresented in formal decision-making roles within production units. Agricultural Census 2022 profiles for Zacatecas indicate that women constitute a minority among producers/responsible persons, which can limit access to training, veterinary services, and finance and reduce participation in upgrading and value addition (INEGI, 2023). At the same time, rural evidence consistently describes women's key roles in milking, artisanal dairy processing, and local marketing, activities that directly support household income and food security (FAO, 2011; Garay-Rodríguez *et al.*, 2022). Strengthening gender-responsive extension and improving access to services and resources are therefore relevant not only for equity, but also for expanding adoption capacity and improving the economic viability of smallholder goat systems (FAO, 2011; Unay-Gailhard and Bojnec, 2021).

Local knowledge about herd management, grazing patterns, and seasonal cycles remains an important asset for goat production in semi-arid regions. In drylands, pastoral mobility (including seasonal movements of herds) can function as an adaptive strategy to track spatial and temporal variability in forage and water availability, helping reduce localized grazing pressure and buffer climatic uncertainty (Dong, 2016; Manzano and Casas, 2010). In Zacatecas, local reports suggest that these practices are becoming harder to sustain as herding labor declines and shepherds age, which can reduce flexibility in grazing management and increase the risk of concentrating animals near settlements and water points (Hatfield and Davies, 2006). Preserving and adapting traditional knowledge, combined with practical innovations such as grazing planning, water-point management, and community-based coordination, may therefore contribute to resilience under recurrent drought in the state's goat systems (Dong, 2016).

### **Governance and services (organization/extension)**

Governance conditions, particularly producer organization, access to extension, and service delivery, are key determinants of sustainability in Zacatecas' goat systems because they shape producers' capacity to manage risk, adopt improved practices, and coordinate along the value chain. The INEGI Agricultural Census 2007 includes items that capture whether production units are organized and what types of support or services are obtained through organizations (e.g., technical assistance, input purchasing, financing, commercialization, and training), indicating that these enabling conditions are measurable and policy-relevant components of production systems (INEGI, 2009). Evidence from small-scale livestock value chains indicates that, when organization and extension are limited, smallholders tend to face higher transaction costs, fragmented marketing channels, and weaker access to reliable information, technologies, and services, factors that can constrain upgrading, investment, and resilience (FAO, 2012). Participatory training approaches such as Farmer Field Schools have been implemented in Zacatecas and provide a relevant platform to strengthen technical and organizational capacities, which are often identified as limiting factors for sustainable performance in mixed systems (Luna-Coronel *et al.*, 2025).

In dryland contexts, extension is especially important because management decisions must be adaptive to rainfall variability and drought. Timely advisory services, such as seasonal feed planning, forage conservation, herd health calendars, and grazing management guidance, can support decision-making under uncertainty and reduce avoidable losses. However, limited coverage of technical assistance and uneven access to veterinary and organizational support are frequently reported constraints in small-ruminant systems, restricting the adoption of preventive health practices, improved feeding strategies, and value addition. Consequently, strengthening governance and services through (i) scalable producer organization, (ii) bundled extension and animal-health support, and (iii) coordinated market access strategies emerge as a cross-cutting leverage point to improve the sustainability of goat production systems in Zacatecas (FAO, 2012; INEGI, 2009).

### **INTEGRATED SYNTHESIS: TRADE-OFFS, SYNERGIES, AND EVIDENCE GAPS**

Across the evidence synthesized in this review, sustainability in Zacatecas' goat systems emerges as the outcome of interacting trade-offs and synergies among the environmental resource base, household livelihoods, and value-chain conditions. A central trade-off is that drought-driven feed and water scarcity often leads producers to adopt short-term coping strategies (greater reliance on purchased feed, reduced grazing mobility, herd downsizing), which can stabilize production temporarily but increase cash costs and financial vulnerability in smallholder contexts (FAO, 2012; Thornton *et al.*, 2015). At the same time, responses aimed at raising productivity, such as supplementation, preventive health protocols, and improved reproductive

management, can improve outputs but may increase dependence on external inputs if not supported by coordinated services and reliable market access (INEGI, 2009; FAO, 2012).

These patterns suggest that sustainability is shaped not by a single constraint but by how constraints cascade through the system, from climate variability to feed and water shortages to costs, market participation, and reinvestment capacity (Table 2). Recent cross-sectional assessments in Zacatecas provide useful snapshots of sustainability levels, but they also underscore the need for longitudinal evaluation to track how technical assistance and training translate into sustained improvements over time (Luna-Coronel *et al.*, 2025).

**Table 2.** Integrated sustainability diagnosis matrix for goat production systems in Zacatecas: constraints, mechanisms, evidence and leverage points.

Sustainability dimension	Key constraint (Zacatecas)	Mechanism (what it affects)	Evidence in Zacatecas (official/context)	Sustainability implication	Leverage point (priority)
Environmental	Rainfall variability and recurrent drought	Reduced forage growth and water availability; increased reliance on supplementation	INEGI territorial/climate context; state rainfall records (e.g., SMN/CONAGUA) (Medina <i>et al.</i> , 2023)	Higher costs and lower productivity; increased pressure on grazing lands	Drought preparedness: forage conservation, strategic supplementation, and water harvesting and storage
Environmental	Risk of rangeland degradation and overgrazing	Loss of vegetation cover, increased erosion risk, reduced carrying capacity	INEGI land cover (xerophytic shrubland and grassland) and rangeland condition evidence (Aguirre-Rivera <i>et al.</i> , 2023)	Long-term decline of the feed resource base	Adaptive grazing management: recovery periods, mobility where feasible, and restoration practices
Production and health	Seasonal feed deficits	Lower body condition, reduced reproductive performance, higher disease susceptibility	Census/literature anchors on production and feeding in drylands; evidence on seasonal protein/energy gaps (Luna-Coronel <i>et al.</i> , 2026)	Lower kid survival and reduced output	Seasonal feed planning and low-cost supplementation aligned with dry-season constraints
Production and health	Limited preventive herd health services	Higher parasite and disease burden, reduced efficiency, higher mortality risk	Evidence on gastrointestinal nematodes and anthelmintic resistance in goats (Hoste <i>et al.</i> , 2002, 2005; Reyes-Guerrero <i>et al.</i> , 2021)	Productivity losses and animal welfare risks	Veterinary extension and preventive health packages (health calendars, integrated parasite control, targeted treatments)

**Table 2.** Continued.

Sustainability dimension	Key constraint (Zacatecas)	Mechanism (what it affects)	Evidence in Zacatecas (official/context)	Sustainability implication	Leverage point (priority)
Economic and value chain	Price volatility and limited bargaining power	Income instability and reduced investment capacity	SIAP production/value time series (context indicators)	Low profitability and potential exit from activity	Collective marketing, improved market information, and feasible local value addition
Economic and value chain	Weak infrastructure for collection, processing, and transport	Quality losses and restricted market access	Evidence from Mexican dryland dairy value chains (Gómez-Ruiz <i>et al.</i> , 2012), institutional and technical reports	Limited value capture	Scalable infrastructure through producer groups and local institutional support
Social and demographic	Aging producers and weak generational succession	Labor constraints and slower innovation uptake	CA2022 producer age structure; migration context (INEGI, 2023, 2024b)	Continuity risk for production systems	Youth inclusion via training, entry pathways, and improved profitability conditions
Social and gender	Underrepresentation of women in formal decision-making roles	Reduced access to decision-making, training, and finance; lower participation in upgrading	CA2022 producer profile (women as a minority among producers and responsible persons) and contextual literature (FAO, 2011)	Missed opportunities for productivity and household welfare gains	Gender-responsive extension, training, and improved access to services and finance
Governance and services	Low organization and limited service coordination	Higher transaction costs and reduced adoption of improved practices	Census instruments and value-chain evidence indicating the role of organization or extension (INEGI, 2009; FAO, 2012); local FFS experience (Luna-Coronel <i>et al.</i> , 2025)	Fragmented value chain and low innovation uptake	Strengthening producer groups and bundling extension, animal health, and market services

Note: “Evidence in Zacatecas” refers to official sources used as contextual anchors (INEGI, 2007, 2023; CONEVAL, 2020; Medina *et al.*, 2023; SIAP, 2023) and is complemented by peer-reviewed literature for mechanistic interpretation.

Important synergies are also evident. Grazing management and rangeland restoration can support both environmental and economic sustainability by stabilizing forage supply and reducing land degradation risk under variable rainfall; evidence syntheses on adaptive grazing emphasize the role of recovery time and flexibility in maintaining grazing land function (Teague *et al.*, 2017). Complementary synergies arise when soil-

water conservation improves infiltration and plant-available water, buffering drought impacts and supporting more stable forage production in semi-arid settings (Lal, 2001).

At the production level, integrated packages that combine seasonal feed planning with preventive animal health and parasite control can improve kid survival and reproductive outcomes, enhancing efficiency without necessarily increasing pressure on the natural resource base, provided that access to services, inputs, and knowledge is reliable (Hoste *et al.*, 2005). Finally, governance and market synergies occur when producer organization enables collective purchasing and marketing, reduces transaction costs, and facilitates value addition, improving price realization and strengthening incentives for adopting better management practices (FAO, 2012).

The review also identifies clear evidence gaps that limit a comprehensive sustainability assessment in Zacatecas. First, while census and official statistics provide robust structural baselines (inventories, production units, demographic context), state-specific studies that quantify sustainability outcomes (e.g., profitability, productivity under drought, animal health burdens, rangeland condition metrics, and adoption impacts) remain scarce, requiring cautious inference from comparable semi-arid systems. Second, there is limited peer-reviewed evidence on value-chain performance and governance in Zacatecas specifically (e.g., margins, market power, quality standards, transaction costs, and the effectiveness of collective action). Third, few studies integrate environment-health-economics in a single analytical framework, which constrains the identification of optimal intervention bundles and the assessment of trade-offs (e.g., supplementation costs vs. productivity gains; grazing intensity vs. rangeland recovery). These gaps reinforce the need for targeted research linking official datasets with field-based measurements and system-level indicators, and for evaluation of integrated strategies that combine drought preparedness, animal health, and market upgrading. These findings inform the priorities outlined in the Conclusions section.

## STRATEGIC PRIORITIES FOR ACTION AND RESEARCH

### Priorities for action (short-term to medium-term)

Based on the integrated diagnosis, five priorities emerge as the most actionable leverage points for improving sustainability in Zacatecas' goat systems:

**Drought preparedness and feed planning.** Priority actions include strengthening seasonal feed budgets, forage conservation (hay/silage where feasible), and strategic supplementation aligned with rainfall seasonality to reduce crisis-driven losses and stabilize outputs (Thornton *et al.*, 2015). These priorities, including drought preparedness, grazing timing, and forage diversification (native grasses and shrubs), are consistent with evidence syntheses for Mexican drylands that translate resilience into operational rules and monitoring needs (Luna-Coronel *et al.*, 2026).

**Water access and low-cost infrastructure.** Priority options include water harvesting, storage, and context-appropriate distribution solutions for smallholders and grazing settings to reduce time and cost burdens associated with water scarcity (Pretty, 2008; Doreau *et al.*, 2012).

**Preventive herd health and parasite management.** Scaling basic health calendars (vaccination and targeted parasite control) and improving access to veterinary support are priority measures to reduce avoidable productivity losses and welfare risks (Hoste *et al.*, 2005).

**Producer organization and bundled services.** Strengthening local producer groups can facilitate collective purchasing, coordinated extension/veterinary services, and collective marketing, reducing transaction costs and improving adoption capacity (FAO, 2012).

**Value addition and market access.** Feasible upgrading pathways, including aggregation, basic quality control, simple processing, and cold-chain solutions where relevant, can improve price realization and reduce income variability, particularly for dairy products and kids for meat markets (FAO, 2012).

#### **Priorities for research and monitoring**

To address the evidence gaps identified, future work should prioritize: (i) state-specific quantification of productivity, profitability, and drought-related risk across system types; (ii) integrated assessments linking rangeland condition, feed–water strategies, animal health burdens, and economic outcomes; (iii) value-chain studies in Zacatecas documenting margins, governance, and performance of organizational models; and (iv) evaluation of bundled interventions (drought preparedness + health + market upgrading) using transparent designs and measurable indicators to identify scalable pathways for sustainability.

#### **CONCLUSION**

Goat production in Zacatecas remains a relevant livelihood activity in Mexico's drylands; however, comparisons across agricultural census rounds indicate a structural contraction of the sector over time, alongside a producer base characterized by demographic vulnerability. Within this context, sustainability constraints arise from the interaction of (i) recurrent drought and rainfall variability that limit forage and water availability, (ii) management bottlenecks in feeding, herd health, and reproduction that reduce productivity and resilience, and (iii) value-chain limitations, including weak coordination, limited infrastructure, and price volatility, that restrict producers' ability to capture value and reinvest. These constraints are compounded by gaps in service coverage and organizational capacity, which can limit adoption of

preventive health practices, drought preparedness measures, and feasible upgrading options.

Overall, the review indicates that sustainability in Zacatecas' goat production systems is not constrained by a single limiting factor but by the cumulative and interacting effects of environmental variability, technical inefficiencies, and institutional and market limitations. Addressing these challenges therefore requires integrated strategies that simultaneously protect the natural resource base, improve herd-level productivity, and strengthen value-chain participation, rather than isolated interventions targeting individual constraints.

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