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Resilience in a Warming World: A Scoping Review of the Adaptive Mechanisms of East African Indigenous Goats

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Abstract

Climate change and increasingly erratic weather patterns pose a severe threat to livestock production, particularly in East Africa. While exotic breeds often struggle under environmental stress, indigenous goats, specifically the Small East African (SEA) breeds, exhibit remarkable resilience. Goats exhibit a range of morphological, physiological, behavioural and genetic adaptations that enable their survival under harsh climatic conditions. However, for indigenous goats in East Africa, these specific mechanisms and genetic drivers of this adaptability remain poorly synthesized. This scoping review aims to map the existing evidence regarding the environmental resilience, adaptive traits (phenotypic and genetic), and socio-economic significance of indigenous goats in East Africa in the context of climate change. A structured search was used to query relevant articles across multiple databases following the PRISMA-ScR guidelines. Studies focusing on morphological, physiological, behavioral, and genetic adaptations of East African goats were included. The scoping review identified a multi-dimensional adaptive strategy in indigenous goats with studies describing both phenotypic and genetic adaptations. Phenotypic adaptations included the high surface-area-to-volume ratios for heat dissipation, superior water conservation (desiccated feces and concentrated urine), and dietary flexibility. Genetic adaptations are linked to key biomarkers that ensure innate hardiness and survival through disease resistance (*FGF*9 and *MAPK*3), thermo-tolerance (*HSPA*2 and *HSP*70) and metabolic signaling (*ADCY*4). Despite these findings, a significant "characterization gap" exists: while phenotypic traits are well-documented across breed categories, high-

resolution genomic data specific to East African populations is sparse. Socio-economically, these goats function as a flexible, self-renewing asset for smallholder farmers, requiring low inputs while maintaining reproductive success under stress. Indigenous goats thus allow farmers to recover from economic shocks by providing a source of capital that can be quickly liquidated. Therefore, indigenous East African goats possess a genetic footprint that is critical for sustainable livestock production in a warming world. To fully leverage this potential, future research must transition from descriptive studies to functional genomics and marker-assisted selection. Integrating these resilient breeds into national climate adaptation policies is a critical step toward ensuring long-term food security.

Keywords

Indigenous Goats, Climate Change Resilience, Genetic Characterization, Phenotypic Adaptation

1. Background

African goats, often referred to as the "poor man's cow", play a central role in the economies and livelihoods of many African nations, particularly within rural and resource-poor agricultural systems of the East African region [1]. Goats provide essential animal protein, income, and socio-cultural value to millions of smallholder farmers, especially in harsh and variable environments [2]. Their relatively low body mass and metabolic requirements enable lower maintenance needs and reduced water consumption, making them well suited to marginal production systems [3]. Despite their importance, climate change is increasing the vulnerability of goat production systems through more frequent and prolonged droughts, altered disease dynamics, and progressive degradation of natural resources [4]. Conventional livestock development strategies in the region have historically emphasized the introduction of high-yielding exotic breeds such as Boer, Red Kalahari, and Savannah goats [5]. However, these breeds often perform poorly under low-input management conditions characterized by inadequate nutrition, water scarcity, and limited access to veterinary services [6]. In contrast, indigenous goat populations, although generally characterized by slower growth rates and lower mature body weights (approximately 30 - 40 kg), demonstrate remarkable resilience, reproductive efficiency, and adaptability, often producing multiple offspring per kidding under challenging conditions [7]. These attributes highlight the value of indigenous goats as a critical genetic reservoir for climate change adaptation and the development of resilient and sustainable production systems. A clear understanding of the environmental and economic advantages conferred by indigenous goat genetic diversity is essential to inform evidence-based conservation, utilization, and breeding strategies. This scoping review therefore examines current knowledge on the phenotypic and genetic diversity of indigenous goat popula-

tions in East Africa and assesses how these attributes contribute to environmental and economic sustainability under climate change. Uganda, Kenya and Tanzania indigenous goats were included in this review, as these are countries that commonly share climatic conditions across their different regions in East Africa and hold the largest proportion of Small East African goats in the region. Specifically, the review aims to: 1) evaluate evidence on adaptive traits of these indigenous goats, 2) assess their environmental and economic viability within smallholder production systems, 3) identify key knowledge gaps, and (iv) propose future research and policy directions.

2. Methods

This scoping review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) [8] to ensure methodological rigor and transparency.

2.1. Protocol and Registration

No formal review protocol was registered for this scoping review. However, the authors followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines to systematically develop and implement the review methodology guidelines

2.2. Eligibility Criteria

Studies were eligible for inclusion if they met the following criteria: (i) peer-reviewed articles published in the English language; (ii) studies focusing on phenotypic and/or genetic characteristics of goat populations with relevance to resilience and adaptation to tropical climatic challenges; (iii) studies characterizing indigenous goat populations across diverse agro-ecological environments of East Africa; (iv) research explicitly addressing environmental sustainability and/or economic viability of indigenous goat breeds; and (v) original research articles, review papers, and case studies. The review focused on the adaptive traits of goat breeds in Uganda, Kenya and Tanzania, which are the specific physical, genetic, and behavioural characteristics that allow these indigenous goats to survive and reproduce in the harsh, changing environments of the region where other breeds would fail. In that context, they exhibit environmental resilience through the innate potential to maintain physiological homeostasis, good health and productivity while facing severe environmental stressors such as prolonged drought, intense heat, and high disease burdens. In the end adapted goat breeds support economic viability of goat production in East Africa, defined as the goat breed's ability to generate sustainable net profit and provide financial security for smallholder farmers under low-input conditions. Studies were excluded if they: (i) focused primarily on goat characteristics not relevant to tropical production systems; (ii) examined exclusively exotic goat breeds; or (iii) were not available in English or lacked full-text access, including abstracts only and conference pro-

ceedings.

2.3. Information Sources

Relevant studies were identified through comprehensive searches of major academic databases covering the period from 2000 to 2025. The databases searched included web of science, Google Scholar, Research Gate, and Science Direct. Searches were conducted using combinations of keywords and Boolean operators, including: ("indigenous goats" OR "local goats" OR "native goats") AND ("East Africa" OR Kenya OR Tanzania OR Uganda) AND ("genetic diversity" OR "genetic characterization" OR "adaptive traits") AND ("sustainability" OR "economic viability" OR "environmental impact" OR "resilience").

2.4. Search Strategy

The search strategy was developed collaboratively by the authors, reviewed for relevance and completeness, and finalized prior to implementation. All retrieved records were exported to Mendeley Desktop reference management software, where duplicate records were identified and removed. A search strategy used under Google scholar has been attached as **Appendix 1**.

2.5. Selection of Sources of Evidence

All records retrieved from the database searches were screened for eligibility using a two-stage process. In the first stage, titles and abstracts were screened to assess relevance to the review objectives. In the second stage, full-text articles of potentially relevant studies were assessed against the predefined inclusion and exclusion criteria (**Figure 1**). Screening and selection were conducted by the authors, with discrepancies resolved through discussion and consensus.

2.6. Data Charting Process

Data from the included studies were extracted using a standardized data charting form. Extracted information included study characteristics (author, year of publication, country/location), research objectives, indigenous goat breed(s) studied, phenotypic and genetic traits assessed, key findings related to environmental resilience and economic sustainability, and identified research gaps. The data charting process was iterative, and done independently among three of the authors while other authors reviewed and guided the process, with the form refined as familiarity with the literature increased. Original research articles, review papers and case studies were all integrated into the findings of this review based on their contribution to specific adaptive mechanisms of these indigenous goats (morphological, physiological, behavioral, and genetic). A total of 24 original research articles, 6 review papers and 2 case studies were included in the review. Original research articles formed the basis of the information and were used as the data sources to build the core evidence on indigenous goats in East Africa, review papers and case studies helped to give an overview of the identified evidence to

deepen understanding of scenarios as well as clarifying on the identified research gaps.

2.7. Data Items

Data were sought based on the following items (**Appendix 2**):

Publication year: the year in which the article was published; articles published from 2000 to 2025 were selected.

Journal: The journal which published the article; articles from peer-reviewed journals were considered.

Language: This is the language in which the article was published; only English language publications were selected.

Study type: This referred to the information generated in the different studies. Characterization studies with a focus on climate resilience and economic sustainability traits were considered. Other studies were those which helped in the understanding of the environment where the indigenous goats in East Africa survive and the mechanisms behind the different observable traits exhibited.

Aim of the study: This is the intention for which the study was conducted.

Livestock type: The species of livestock studied; studies focusing on goats were included.

Adaptation type: This is the mechanism that enables the indigenous goats to survive in the stressing environment yet other goat types struggle through or even fail to survive. These were either phenotypic or genetic adaptations.

Type of observation: This is the actual characteristic observed among the goats in the stressing environmental condition in East Africa.

Analysis and interpretation: This is the explanation of how the observed characteristic helps the goats in the adaptation process.

Relevance to climate resilience: This is the value that the observed characteristic presents relative to the climate change characteristics observed in East Africa. This review focused on characteristics that ensured environmental sustainability and economic viability.

2.8. Synthesis of Results

The extracted evidence was synthesized qualitatively using a thematic approach. Findings were grouped into themes related to environmental sustainability, including disease resistance, feed efficiency, and heat tolerance, and economic sustainability, including input costs, productivity, profitability, and market value. Information on inherent adaptive characteristics of indigenous goats was distinguished from reported performance outcomes and interpreted in relation to prevailing and projected climatic conditions under climate change scenarios.

3. Results

3.1. Selection of Sources of Evidence

The literature review revealed compelling evidence for the unique value of indig-

enous East African goats across several key areas.

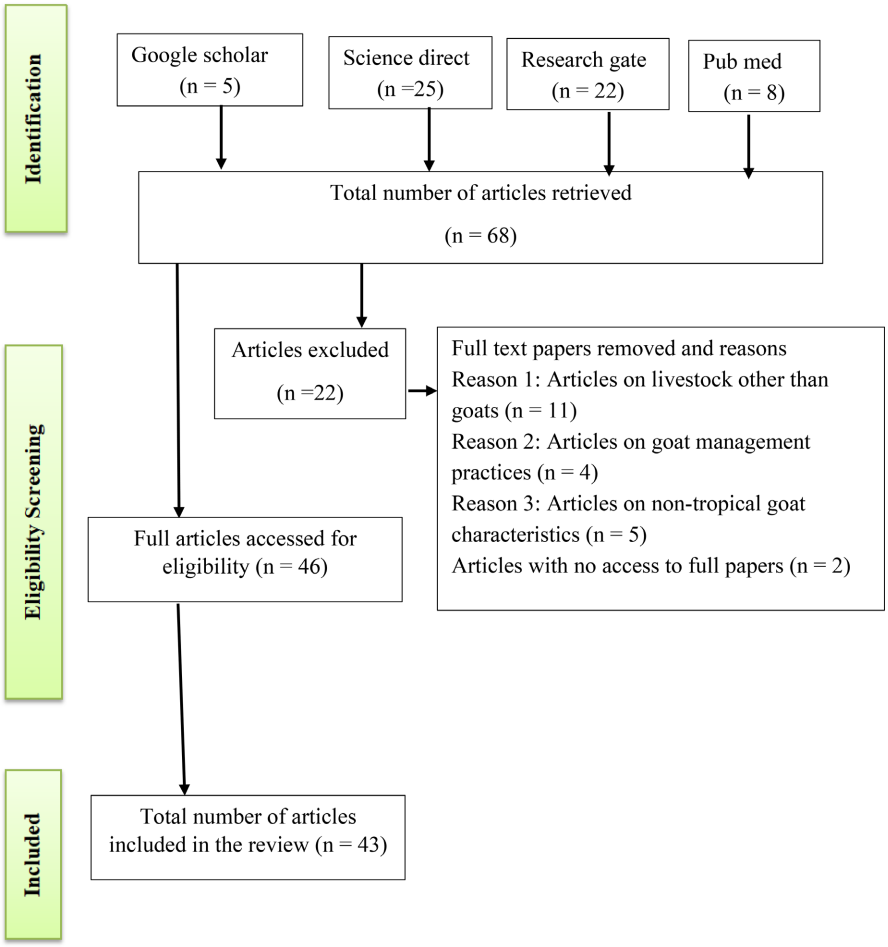

Figure 1. The PRISMA flow diagram showing the inclusion/exclusion steps for articles used in the study.

3.2. Environmental Resilience and Adaptive Traits

Goats have higher adaptability to wider range of environmental conditions as compared to all other livestock species [9], which underscores their tremendous potential to be projected as the "Future Animal" in the era of climate change. Indigenous goats in East Africa have high agility and thus adapt easily to changes in their environment even under varied ecological conditions to sustain productivity [10]-[12]. The goats survive with diverse communities in varying agro-ecological zones (**Table 1**) where management systems range from small scale mixed crop-livestock systems with few animals on limited land resources, to extensive pastoral systems with large numbers of animals raised on large tracts of land [13]. The selection, adaptation and environmental characteristics has shaped the goats' phenotypic and genetic diversity (**Table 2**).

Climate change poses a significant global threat to ecosystems through increasingly abnormal weather patterns [14], with grazing livestock particularly affected by thermal stress, declining pasture quality and quantity, and increased prevalence

Table 1. Environmental characteristics of different agro-ecological zones in Uganda, Kenya and Tanzania and the commonest indigenous goat breeds within them.

Country	Agro-ecological zone (AEZ)	AEZ characteristics	Commonest indigenous goat ecotype(s)	Information sources
Uganda	Northeastern dry lands	Hot and dry, with thorny bushes, cammiphora woodlands, occasional small trees, and patches of grassland.	Small East African breed	[7] [27]
Uganda	Northeastern savannah grasslands	Hot and dry, with thick savannah grassland and Thorny bushes	Small East African	[7] [27]
Uganda	Northwestern savannah grasslands	Hot and humid, Savanna vegetation with open mixtures of trees and shrubs standing within tall grass	Small East African	[7] [27]
Uganda	Para-savannah	Hot and dry, with savannah Mosaic and savanna grasses	Small East African, Mubende	[7] [27]
Uganda	Kyoga plains	Hot and humid, with predominantly savanna mosaics, isolated forest remnants and colonizing savannah trees integrated with grasses and shrubs	Small East African, Mubende	[7] [27]
Uganda	Lake Victoria Crescent	Warm and humid, with forest/savanna mosaic with patches of dense forest in the south and scattered trees in shrubs and grassland of the north.	Mubende, Small East African	[7] [27]
Uganda	Western Savannah grasslands	Warm and dry, with rainforest and rich natural savanna grassland	Mubende, Small East African	[7] [27]
Uganda	Pastoral rangelands	Hot and humid, with forests, Savanna mosaic and grass savanna	Mubende, Small East African Kigezi	[7] [27]
Uganda	Southwestern farmlands	Warm and humid with natural equatorial forest vegetation	Mubende	[7] [27]
Uganda	Highland ranges	Cool/warm and moist with high altitude forest, Savannah Mosaic at high altitudes montane forest and high open moorland	Mubende, Kigezi	[7] [27]
Tanzania	Plateau	A semi-arid climate with moderate rainfall and temperatures.	Sukuma	[11] [28]
Tanzania	Southern and western highlands	A cooler climate than the rest of the country, with higher rainfall and cooler temperatures.	Songwe, Fipa Ujiji	[11] [28]
Tanzania	Northern highlands	A warm climate, with higher rainfall and warm temperatures.	Pare	[11] [28]
Tanzania	Semi-arid and Arid	Low rainfall and high temperatures, making them prone to drought and desertification	Masaai, Gogo	[11] [28]
Tanzania	Coastal	Hot and humid conditions, with high rainfall and temperatures.	Tanga, Lindi, Pwani, Newala	[11] [28]
Kenya	Semi-Arid zone	Characterized by semi-arid climate.	Small East African Galla goats	[2] [28]
Kenya	Arid zone	Characterized by arid climate.	Small East African Galla goats	[2] [29]

Table 2. Characteristics of different indigenous goat breeds in the studied East African countries.

Breed/ ecotype	Country	Phenotypic characteristics	Genetic characteristics	Information source
Mubende	Uganda	Short, fine, shiny coat, predominantly black or black and white; mature weight 35 - 45 kg for males and 30 - 35 for females; dished facial profile; short backward sweeping horns; primarily meat goats-high quality meat and skin; ~30% twinning rate; adapted to hot, sub-humid tropical savanna conditions; tolerant to tick borne diseases	Ugandan indigenous goats possess -Heat tolerance genes PPP1R36 and HSPA2 (Heat Shock Protein A2); -Immune response genes related to disease tolerance like IL10RB and IL23A; -Adaptation genes like MAPK3 gene aids cell growth and metabolism for survival under poor feed quality -Moderate to high genetic diversity -Mubende is highly admixed population with Kigezi and Small East African	[7] [30]
Kigezi	Uganda	Thick hair coat with long hair especially on hind quarters. Mainly in black, grey or brown coat colors; Mature weight is between 25 - 30 kg; adapted to high altitude, cool and steep environments		
Small East African	Uganda, Kenya, Tanzania	Short fine hair coat, mostly brown, speckled and black. Mature weight of 25 - 30 kg for females and 30 - 40 kg for males; Small-bodied and compact, height of 50 - 65 cm tall; short, straight and backward curving horns with sharp tips		
Galla	Kenya	Tall with long legs, a long back (slightly dipped), and a white coat, with black spots on the skin, nose, and feet; Mature weight up to 70 kg for males and 45 to 50 kg for females; Highly prolific with good milk production;	Higher genetic diversity than Small East African goats -Possess genes for heat tolerance and disease resistance	[1] [24]
Sukuma	Tanzania	Small size goats; mature weight is 21 kg, withers height; high resistance to disease and drought; pied black and white spotted coat; slow growth rate; low twinning rate	Microsatellite marker analysis places Sukuma goats in their own separate genetic group, distinguishing them from other regional strains like the **Gogo**, **Sonjo**, and **Pare**, which are more closely related to one another.	[1] [32] [33]
Masaai	Kenya	Mature weight of about 30 kg, short erect ears; concave facial profile, straight back and wattles present; adapted to arid to hyper-arid areas; dual purpose for meat and milk; ~8.7% twinning rate; Reproductive maturity at 11months for males and 16.7 months for females; kidding interval 7.7 months	-Maasai goats belong mainly to haplogroup A, with a smaller representation of haplogroup G -Exhibit high genetic variation	[1]

of pests and diseases [15]. In contrast to many exotic goat breeds that do not survive easily under these conditions, indigenous East African goats demonstrate a superior capacity to survive and function under these harsh climatic conditions and on scarce, low-quality feed resources [10] [16]. This resilience is underpinned by integrated phenotypic, physiological, behavioral, and genetic adaptations [17]. While these adaptive strategies often result in lower growth rates and reduced milk and meat yields, they prioritize survival and reproductive success under environmental stress [14] [17].

Phenotypic adaptations: Goats display a wide range of physical traits to cope with climate change including morphological, physiological, and behavioral traits

as well as superior water and feed utilization characteristics [18] in addition to variations in coat color which impacts heat absorption [19].

- **Morphological adaptations:** Small East African goats have short smooth hair coats, mostly in light or reflective colors which helps to reflect solar radiation thus reducing heat absorption [18]. The small to medium body size and conformation (longer legs) of Small East African goats [7] [20] assures them of a greater surface area to volume ratio to allow faster heat exchange to the environment for body cooling [1].
- **Physiological adaptation:** Goats have high respiration rates with a preference for panting than sweating to enhance evaporative cooling through the lungs thus thermoregulation [20]. In addition, indigenous goats have a superior ability for water conservation including high tolerance to water restriction intermittent water regimes without severe impact on production. The goats desiccate the feces and concentrate urine to reduce on water loss [17].
- **Behavioral traits:** Indigenous goats are endowed with dietary flexibility and nutritional adaptability [14] [18]. They are intermediate feeders and utilize a wide spectrum of plants, including tough, woody vegetation and crop residues including those that are unusable by larger ruminants [21]. This non-competitive feeding behavior makes them ideal for mixed-species grazing systems. The goats' digestive system can efficiently digest dry matter and recycle nitrogen [15], thus allowing them to thrive in environments where forage quality and availability fluctuate due to drought [10].
- **Heat Tolerance and Drought Adaptation:** Through their efficient thermoregulation and lower water requirements indigenous goats are able to thrive in high-temperature, arid environments [17] [22]. This inherent adaptation is highly pronounced among the Small East African goats [2] [10] [11] and makes them crucial for maintaining productivity in the face of increasing climate variability and extreme weather events [9].
- **Disease and Parasite Resistance:** Small East African goat breeds have known resistance to common endemic diseases and parasites, such as trypanosomiasis [30] and gastrointestinal nematodes [31]. This natural resilience significantly reduces the reliance on costly and potentially environmentally impactful veterinary treatments thus environmental sustainability.
- **Efficient Resource Utilization:** Indigenous breeds exhibit remarkable feed efficiency, thriving on low-quality forage, shrubs, and agricultural byproducts that other livestock often ignore [32]. This enables the effective use of marginal lands, minimizing competition for higher-quality pastures and enhancing overall ecosystem stability through nutrient cycling [33].

Genetic adaptations

Although indigenous goats have low productivity (slow growth, small body size), they possess the genetic signature to survive under challenging conditions, making them a crucial resource for sustainable, low-input farming in East Africa. The goat populations' geographical distribution [34] and environmental adapta-

bility reflect a rich genetic diversity allowing them to survive in unique environments [35]. These genetic attributes include: Innate hardiness and survival genes; indigenous goats have evolved specific genomic regions related to environmental adaptation. For example, studies have identified genes like HSPA2 (heat tolerance), and IL10RB and IL23A (immune response) in Ugandan goats, which allow them to manage metabolic and physiological stress in high-temperature situations and areas with low-quality feed.

- Disease Resistance: Indigenous goats have a high, inherited tolerance to endemic diseases such as heartwater, worms, and mange, which often kill exotic or non-native breeds.
- High Genetic Diversity: The genomes of these populations generally show high genetic diversity and low levels of inbreeding compared to commercial breeds (like the Boer goat), providing a robust genetic reserve for adapting to future climate changes.
- "Hidden" Selection Signatures: The "pre-adaptation" is often characterized by complex, polygenic traits (many genes acting together) rather than single-gene changes. These are sometimes called "signatures of selection" that have accumulated over time.
- Minimalist Requirements: Their genome is optimized for survival in low-input systems where they must walk long distances for water, browse on diverse plant species, and survive in dry, arid conditions.

The goat genome contains various genes associated with environmental adaptation including HS70, ACTHR, FGF12, SLC2A1, EPAS1, and UCP1[36]. These genes play vital regulatory roles exhibiting the different selection pressures which goats under different geographical and climatic conditions experienced, leading to the diversity of goat breeds.

Indigenous goat populations in Uganda possess unique genetic variations that enable adaptation to harsh, hot, and often resource-limited environments. Studies on the genome-wide characterization of these goats have identified specific genes—HSPA2 for heat tolerance, and IL10RB and IL23A for immune response—as key components of their resilience.

HSPA2 and Heat Tolerance

- Role: The HSPA2 (Heat Shock Protein Family A Member 2) gene is critical for cellular thermoregulation. Variations in this gene are linked to improved heat tolerance in indigenous goats, enabling them to maintain homeostasis and productivity under high-temperature conditions.
- Mechanism: HSPA2 acts as a molecular chaperone, assisting in protein folding and preventing denaturation during heat stress, which is essential for survival during frequent droughts in East Africa.
- Context: While HSP70 and HSP90 are also heavily involved in the heat shock response (protecting tissues like the testes and mitigating cellular stress), HSPA2 specifically has been identified in Ugandan breeds as a key adaptive marker.

IL10RB, IL23A, and Immune Response

- Significance: The IL10RB (Interleukin 10 Receptor Subunit Beta) and IL23A (Interleukin 23 Subunit Alpha) genes are associated with the immune system.
- Environmental Adaptation: These genes were identified within "runs of homozygosity" (ROH) islands, indicating they are under strong selection pressure to aid in disease resistance, which is vital for survival in areas with limited veterinary services.
- Pathogen Resistance: These immune genes, alongside others like FGF9 and MAPK3, contribute to the overall resilience of indigenous breeds against parasites and diseases endemic to the region.

Under heat exposure, which is common due to climate change and global warming, HSP70 is the genetic biomarker for thermo tolerance in goats through its central role in protein folding and cellular protection under elevated temperatures while ACTHR is vital in stress hormone signaling [35] [36]. Although indigenous goats are known to tolerate harsh weather including heat, detailed genetic characterization to explain their expression of genes related to environmental adaptation is lacking. There is need for further exploration of the genomes of indigenous goats in East Africa to understand their genetic footprint for environmental adaptation, which is so vital for selection in the process of climate change adaptation for sustainable livestock production.

Molecular and cellular means to maintain homeothermy. Genetic regulation for environmental adaptation highly enhances the survivability of a breed in an environment [17]. Genes involved in the oxytocin signaling development, fat metabolism, and ion homeostasis include ROCK1 (Rho-associated protein kinase 1), ACNA1C (calcium voltage-gated channel sub unit alpha1C), and OXTR (oxytocin receptor). These help to regulate several physiological processes including reproduction, body weight and social behavior [36]. Additionally, SLC24A4 (sodium/potassium/calcium exchanger4) gene located in the classical HIF-1 (hypoxia-induced factors) pathway is central in regulation of hypoxia-related cellular responses. Genes associated with cashmere fiber traits include the LHX2, FGF9 (fibro blast growth factor 9) and WNT2 [36] [37]. Fine cashmere fibers help goats to combat heat loss in cold and dry environments [38]. In addition, ADCY4 (adenylyl cyclase4) gene, regulates insulin secretion, adrenergic signaling in cardiomyocytes, rap1signalling pathway, cGMP-PKG signaling pathway, and oxytocin signaling pathway [14] [36]. Recognition of particular genetic mechanisms that regulate gene expressions and phenotypes relevant in climate resilience is vital in selection of breeds or goats for climate change adaptation. Inadequate genetic characterization of local African breeds denies the opportunity to identify and exploit desirable climate resilient traits among them [39]. Genetic characterization of indigenous African goats deserves prioritization in the process of climate change adaptation and mitigation given the resilient phenotypic potential exhibited in harsh environments where the goats survive. In-depth genetic characterization to uncover the genes controlling the various phenotypic traits will urgently assist to understand the appropriate breeds for selection and optimal utilization based on the inherent

characteristics for survival and production under harsh environmental conditions.

3.3. Economic Viability and Livelihoods

Indigenous goats in East Africa have great socio-economic relevance where they act as assets for quick cash, food security (meat/milk), and insurance against crop failure [10] [11]. They require low investment, have high prolificacy, early maturity period, yet thriving on marginal land and are easier to market, thus empowering women, reducing poverty, and building community resilience through tangible income and intangible social benefits [25]. This contribution is a result of several factors including:

Low Input Production Systems: Goats need low startup as well as maintenance costs, use marginal lands, and thrive in harsh conditions, making them ideal for smallholders [28]. They have a lower need for specialized feed and veterinary inputs, which directly translates to lower operational costs [40]. This low-input model aligns perfectly with the resource constraints of smallholder producers, making goat farming a highly accessible and economically viable enterprise.

Multiple Income Streams and Market Value: Beyond meat and milk, goats provide consistent income through the sale of live animals, skins and manure [25] [41]. Given their small size, goats are easier to liquidate unlike cattle thus act as a form of "living savings account," they offer a reliable source of immediate cash for emergencies or specific household needs [25]. Local markets often prefer the meat from indigenous goat breeds due to traditional preferences for flavour and leanness, sometimes commanding premium prices [42]. The high market value of goat meat relative to beef [40] in East Africa assures high returns on capital invested in goat enterprises [25] compared to other livestock types, yet the input costs for production are even lower hence significantly contributing to household income and poverty reduction

Contribution to household nutrition and food security: The role of goat meat and milk in household nutrition and food security is immense. Goat milk is homogenous, less allergenic, is better digested and absorbed than the cow milk yet it has got an excellent buffering action [43]. There is higher relevance of using goat milk in feeding infants and the elderly since it forms softer curds and has smaller fat granules, making it easier to digest relative to cow milk. Goat meat is a lean protein source relative to beef, pork, or chicken, with more iron and it contains less total fat, saturated fat, and cholesterol, which are harmful to the human health system [43]. Aside from nutrition, the income from sales of various enterprise generated products increases resilience of families to financial shocks while the manure helps to improve soil fertility. The result in diversified diets, socio stability and sufficient nourishment for households hence food secure communities [28].

4. Discussion

4.1. Summary of Evidence and Landscape of Resilience

This scoping review mapped the multifaceted resilience of indigenous East Afri-

can goats, revealing a complex synergy between phenotypic plasticity and genetic potential. The evidence underscores that these breeds, most notably the Small East African goat, do not rely on a single mechanism for survival. Instead, they employ an integrated strategy involving morphological traits (e.g., high surface-area-to-volume ratios and reflective coat colors), physiological efficiency (e.g., superior water conservation and nitrogen recycling), and behavioral flexibility.

Our findings confirm that while these adaptations often come at the "cost" of lower absolute yields in milk and meat, they represent an evolutionary prioritization of reproductive success and survivability over raw productivity. In the context of escalating climate variability, this trade-off is increasingly recognized as an economic asset rather than a limitation, positioning indigenous goats as a cornerstone of food security and "living insurance" for smallholder farmers.

The "Genetic Characterization" Gap

The Gap between Phenotype and Genotype

A significant finding of this review is the disconnect between **observed resilience** and **genetic documentation**. While the phenotypic resilience of Small East African goats is well-documented, their underlying genetic architecture remains under-explored. The literature reveals a stark lack of detailed genetic characterization specific to East African indigenous populations. Most of the existing molecular research remains general or focused on exotic breeds. There is a critical "knowledge lacuna" regarding the specific genetic footprints that allow East African goats to thrive in unique local micro-climates. Although the literature identifies several candidate genes associated with environmental stress, few studies provide a high-resolution "genetic footprint" specific to East African populations.

Key genetic biomarkers identified in the broader literature, such as HSP70 (Heat Shock Protein 70), serve as essential regulators of thermo-tolerance by maintaining protein folding during thermal stress. Others, like ACTHR, FGF12, and UCP1, are implicated in stress signaling and thermogenesis. However, the lack of localized genomic data for indigenous breeds prevents the integration of these markers into marker-assisted selection (MAS) programs. Without precise mapping of these loci, the inherent "climate-smart" potential of these goats remains an untapped resource for sustainable livestock production.

Molecular Regulation of Homeothermy

The review highlights that maintenance of homeothermy under environmental pressure is governed by complex molecular pathways. This includes:

- **Ion Homeostasis and Social Behavior:** Genes such as ROCK1 (Rho-associated protein kinase 1) and OXTR (Oxytocin receptor) regulate not just physiological processes like body weight, but also the behavioral adaptations necessary for survival in communal grazing systems.
- **Hypoxia and Cold Adaptation:** The SLC24A4 gene, situated within the classical HIF-1 (Hypoxia-induced factor) pathway, suggests a specialized cellular response to high-altitude or low-oxygen environments. Similarly, the presence

of genes like LHX2 and WNT2-associated with fine cashmere fiber, indicates a genetic mechanism for combating heat loss in arid, fluctuating climates.

- **Metabolic Signaling:** The ADCY4 (Adenylyl cyclase 4) gene appears central to various systemic responses, including:
  - The Rap1signaling pathway.
  - The cGMP-PKG signaling pathway.
  - Insulin secretion and adrenergic signaling in cardiomyocytes.

Implications for Climate Resilience

The synthesis of these molecular findings suggests that indigenous goats possess a "pre-adapted" genome. However, the current literature is largely descriptive. There is an urgent need to transition from identifying these genes in general populations to performing functional genomic studies specifically on East African breeds. Identifying the specific alleles that drive the expression of resilient phenotypes is a prerequisite for any meaningful climate change mitigation strategy. Without this data, the "desirable traits" identified in this review remain underutilized in formal breeding programs. The absence of this characterization represents a missed opportunity for the strategic selection of breeds that could lead the climate change adaptation agenda in sub-Saharan Africa.

4.2. Economic and Sustainability Implications

The literature suggests that the economic viability of these goats is inextricably linked to their low-input requirements. By thriving on marginal lands and utilizing poor-quality forage that other livestock ignore, these goats minimize competition for human food sources and high-quality pastures. This makes them a naturally environmentally sustainable livestock option. Furthermore, their innate resistance to endemic diseases like trypanosomiasis reduces the financial and environmental burden of veterinary interventions, further enhancing their value to resource-constrained households.

4.3. Limitations of the Scoping Process

While this review provides a broad overview, it is limited by the prevalence of older studies in certain geographical areas and a lack of longitudinal data regarding how these goats' adaptive traits hold up under *extreme* (rather than just "harsh") weather events. Additionally, much of the evidence regarding "economic viability" is qualitative, lacking recent standardized econometric modeling to fully quantify the goats' value in a changing market.

5. Conclusion

This scoping review highlights that East African indigenous goat are not merely livestock, but a vital biological and socio-economic buffer against climate change. Their resilience is the result of a sophisticated integration of phenotypic plasticity, such as efficient thermoregulation and dietary flexibility, and a complex genetic architecture designed for survival in marginal environments. However, a signifi-

cant "translation gap" exists: while their resilient traits are observable in the field, the specific genetic drivers behind these traits remain poorly characterized compared to exotic breeds. As climate variability intensifies, the survival of smallholder farming systems in East Africa may depend on the formal recognition, protection, and genomic exploitation of these indigenous genetic resources.

6. Recommendations for Future Research and Policy

The following table links the evidence gaps identified in this review to specific, actionable recommendations.

Focus Area	Identified Gap	Recommended Action
Genomics	Lack of high-resolution mapping for East African breeds (HSP70, ADCY4).	Conduct whole-genome sequencing (WGS) and functional genomic studies to identify unique climate-resilient alleles.
Productivity	Limited data on the "yield vs. resilience" trade-off under extreme stress.	Perform longitudinal studies to quantify production thresholds (meat/milk) during prolonged drought cycles.
Methodology	Scarcity of standardized "resilience indices" for indigenous goats.	Develop a multi-metric "Resilience Score" combining phenotypic, physiological, and genetic markers.
Economics	Absence of recent econometric data on the value of goats as "insurance."	Conduct cost-benefit analyses comparing indigenous low-input systems vs. exotic high-input systems under climate stress.
Policy	Indigenous goats are often undervalued in national agricultural agendas.	Integrate indigenous breed conservation into National Climate Change Adaptation Plans (CCAPs) and livestock policies.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix 1. Search Strategy

Google scholar: (assessment OR survey OR questionnaire OR scale) AND ("indigenous goats" OR "small East African goats") AND ("climatic resilience" OR "adaptation to climate change" OR "heat tolerance" OR "environmental adaptations" OR "disease resistance" OR "genetic adaptations") AND (breeds OR ecotypes).

Appendix 2. Data Extraction Form

Scoping review title: Resilience in a Warming World: A Scoping Review of the Adaptive Mechanisms of East African Indigenous Goats.

Review question: How are indigenous goats, especially in East Africa, adapted to survive through extreme heat conditions?

S/N	Publication year	Country	Title	Journal	Language	Study type	Aim of study	Livestock type	Adaptation type	Type of observation	Analysis and interpretation	Relevance to climate resilience