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Genetic and phenotypic basis of goat adaptability across agro-ecological zones: Implications for breeding and conservation

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SUMMARY

Goats are among the most adaptable livestock species that can survive in varied agro-ecological zones globally. This resilience is shaped by the interactions between genetic and phenotypic traits. This review assesses the available information on morphology, physiology, and molecular characteristics that enable them to adapt and their implication for breeding and conservation. Phenotypic characteristics, including variation in coat color, the type and density of hair, body size, skin color, and thermoregulation behavior, were observed to be measures of adaptation to heat, cold, and feed scarcity. The review also observed some key candidate genes at the molecular level, including HSP70, EPAS1, FGF5, and MC1R, among others, with pathways that are responsible for heat tolerance, hypoxia response, and metabolic efficiency. The link between environmental pressures and phenotypic variation is examined as a driver for genetic differentiation among local goat populations. Incorporating these phenotypic and genetic insights forms a basis for breeding strategies that are climate-resilient and for safeguarding adaptive genetic resources. This will ensure that goats stay productive and diverse over time, thereby contributing to food security and the current climate change.

Keywords: *goat adaptability; genetic diversity; agro-ecological zones; indigenous goats; signature selection*

INTRODUCTION

Goats are among the first domesticated species in the Fertile Crescent of southwest Asia and neighboring countries (Daly et al., 2018). Archaeological evidence suggests the presence of wild goat (bezoar) across various regions about 10,000 years before the present (BP), with the first domestic goats phenotypes observed in the Anatolian region (Zheng et al., 2020). These goats were deemed valuable for their contribution towards food, income, and social status security in many livelihoods through the supply of meat, milk, fiber, skin, and other products like organic manure, especially in areas with restricted resources (Lu, 2023; FAO, 2020b) and to date, they play an important role in global agriculture. Following their domestication, human migration helped in dispersal of these goats to various regions of the world where they adapted to withstand varied climates and environments conditions, including rocky, plain lands, drought areas, and highlands, among others.

These adaptive mechanisms were contributed by environmental conditions exposed to, as well as the husbandry levels they were subjected in (Zheng et al., 2020). These adaptive features allowed them to withstand varied conditions, therefore, it is hypothesized that these goats contain unique genetic and phenotypic features that make them produce and reproduce across several agro-ecological regions without stress, These places them among the promising enterprises to consider, especially in the challenging environmental conditions as well as the rural communities. Adaptability is therefore defined as the ability of a species to maintain or change its performance, including growth, reproduction, and survival performance in different environmental conditions. These changes allow the species to live, reproduce, and become useful even when production conditions are not favorable (Fodor et al., 2023).

Adaptability is most important, especially in the varied agro-ecological conditions, such as changes in climate variables like temperatures, humidity, pasture, forage, and feed resource availability, altitude, and disease outbreaks, as farmers are able to select suitable breeds that can survive in a given environments (Aboul-Naga et al., 2025).This is achieved through selecting those traits which can be altered or modified thereby developing a more resilient breeding programs that manages the effects of climate change in livestock. Therefore, understanding adaptive mechanisms in goat breeds not only helps them survive and produce but also makes farming more environmentally friendly, especially in the current global climate change era.

Several molecular markers have been used to study the genetics and genomics of goat’s adaptations, including single-nucleotide polymorphisms (SNPs), genome-wide association studies (GWAS), microsatellites, mitochondrial DNA, and transcriptomics, among others. The findings from these studies report important genes responsible for adaptation to harsh environments, including high altitude, arid and semi-arid regions, and cold conditions, for example (Song et al., 2016; Wang et al., 2025; Kichamu et al., 2025). These adaptive mechanisms are not only from genetic composition, but are coupled with the phenotypic manipulation of a species. Phenotypic manipulation here is defined as the ability of a species to change its physiological,

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morphological, and behavioral mechanisms in response to changes in the environmental conditions exposed to. These changes are important for the survival of a species (Fontanari et al., 2023). These phenotypic characteristics include variation in coat and skin color, different hair types, body size, reproductive success, and metabolic efficiency, all of which present themselves as observable indicators of environmental adaptation. For example, goats produced in drought-infested areas tend to have light coat with a small body size. These bright colors help them reflect heat and retain more water in the body, thus playing a role in thermoregulation. Besides, those that are produced in colder regions tend to contain a thick coat with lots of fat deposits underneath the skin which help them maintain body warmth (Liu et al., 2022; da Silva et al., 2025).

Therefore, understanding both genetic and phenotypic information is important in developing sustainable breeding and management programs, as it provides an idea of how different goat genotypes react environmental changes. Previous studies have reported on goat adaptability as a complex trait that is influenced by both genetic composition and phenotypic expression. For example, studies presented by Kim et al. (2016) on indigenous goats and sheep noted the presence of important genes in the studied population which were linked to thermo tolerance, disease resistance, and reproductive efficiency, These genes facilitated their survival to extreme climate stressors. Besides, Chokoe et al. (2020) also demonstrated how phenotypic traits, including the coat color, body size, and growth performance, changed depending on the ecological regions, a finding showcasing that animals usually adapt to different levels of heat, humidity, and altitude. Results from studies provides an insight into the importance of incorporating both the genetic and phenotypic basis of adaptability across various ecological zones. Unlike previous studies that focus on single aspects of goat adaptation, this review integrates genetic, phenotypic, and ecological mechanisms to provide a holistic understanding of adaptive strategies across agro-ecological zones. This remarkable adaptability in goats makes them an important resource for sustaining many livelihood and food security under diverse and changing global climates. This review explores the genetic and phenotypic basis of goat adaptability across diverse ecological zones, basing on the existing literature with the aim of understanding their adaptive mechanisms. Through the synthesis of available knowledge, the review aims to guide practical decisions in breeding, conservation, and management programs, thereby supporting development of resilient and productive goat breeds under climate change conditions.

Various agro-ecological zones and their environmental challenges

Goats are produced in various production systems and in a wide range of agro-ecological zones (AEZs) globally. Each of these zones is characterized by distinct climatic conditions, vegetation type and composition, geographical features, and the resources available (Meza-Herrera et al., 2024). These agro ecological zones can influence the species' adaptive responses and productivity. There are various AEZs suitable for goat production (*Table 1*). The most common ones include arid and semi-arid regions, humid and sub-humid tropics, temperate highlands, and dry subtropical environments (FAO, 2020a). The arid and semi-arid zones are those with low and erratic rainfall, with few and sparse vegetation mostly dominated by shrubs and xerophytic tree species. In these regions, goats have developed browsing behaviors with mechanisms that enable efficient metabolism of water with tolerance to heatwaves and nutritional stress (Kaliber et al., 2016).

In contrast, the humid and sub-humid tropical zones are characterized by high rainfall and humidity, high quantities of pasture and forages, but the region is susceptible to parasites and diseases. Goats produced in these zones must have well-developed mechanisms to cope with high infestation of gastrointestinal parasite loads and seasonal declines in forage quality during the dry season (Mpofu et al., 2020). The temperate and mountainous regions are characterized by fluctuating temperatures with seasonal feed availability. Here, goats need to possess a mechanism that withstands cold, such as having a highly dense hair coat with the capability to efficiently regulate temperatures (Nocelli et al., 2020). The hot and dry subtropical regions, including the desert and steppe ecosystems, this zones experience extreme heat, solar radiation, and a long period of water scarcity. Goats in these regions contain some physiological and behavioral adaptation mechanisms for them to survive (Silanikove, 2000).

Different environmental factors work hand in hand to influence the adaptation of goats to their surroundings or regions. One of the most serious factors in heat stress which affects the animal feed intake, growth, milk yield, reproduction, and immunity function (Aboul-Naga et al., 2025). Therefore, goats should have a mechanism that can withstand these effects of heat stress, including Physiological mechanisms like increased respiratory rate, skin vasodilation, and the expression of heat shock proteins to help them maintain thermal homeostasis under high temperatures (Aboul-Naga et al., 2023). Besides, the scarcity of water and recurrent droughts may affect the hydration and biomass of the forage, which forces goats to browse on low-quality shrubs or move for long distances in search of feed and water (Silanikove, 2000). Seasonal fluctuation in feed, pastures, and forage leads to nutritional stress, which is a constant factor in most constraints across agro-ecological zones. During the dry periods, crude protein and energy levels in forages and pastures reduce, thus affecting the animals' productivity and reproductive performance (Nguyen et al., 2023). Disease and parasite infections, especially in warm and humid regions, further influence the performance; for instance, the presence of gastrointestinal nematodes, tick infestations, and vector-borne diseases tends to weaken the health of the animal and productivity (Nguyen et al., 2023).

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Indigenous goat breeds, which are shaped by long-term natural and human selection within their native agro-ecological zones, often exhibit some of the discussed adaptive features that enable them to outperform the international breeds, especially under harsh conditions (Rahimiet al., 2022). Therefore, understanding these environmental challenges and their interactions with genotype performance can help in designing effective breeding, management, and conservation strategies geared towards improving goat productivity and resilience under climatic variability.

Table 1. **Various agro ecological zones where goat production is practiced**

Agro-Ecological Zone	Features	Mean Annual Rainfall (mm)	Mean annual Temperature (°C)	Vegetation type	References
Arid Zone	The region experiences very low and seasonal erratic rainfall with high evaporation rates and solar radiation, frequent droughts, and extreme scarcity of water and pastures	< 400	25–45	Sparsely distributed desert shrubs, seasonal grasses, and succulent trees like cactus	FAO, 2020a; IPCC, 2021
Semi-Arid Zone	Diverse wet and dry seasons with different types of vegetation, and sometimes the presence of moderate droughts	400–1,000	20–35	Grasses are of a savannah-type, thorny bushes, with scattered acacia trees	FAO, 2020a; Kassam & van Velthuizen, 2011
Humid and Sub-Humid Tropics	High levels of humidity with alternating wet and dry seasons, especially in sub-humid regions with deep weathered soils	>1,000–4,000	> 18	presence of open woodlands, tall grasses, with mixed savanna, dense evergreen, or moist tropical rainforest	FAO, 2020a; UNEP, 2016
Temperate Humid and Sub-Humid Zone	Moderate to high rainfall with clearly marked seasons, experiences mild to cool winters and warm summers.	700–2,000	8–18	Deciduous forests with grasslands and pastures	FAO, 2020a; IPCC, 2021
Tropical Highland and Mountain Zone	Cooler temperatures and variation in rainfall with some slopes	600–1,500	5–20	Presence of Montane forests with alpine grasslands and shrubs	FAO, 2020a; Kassam & van Velthuizen, 2011
Mediterranean Zone	Hot, dry summers and cool, wet winters, seasonal water deficit with moderate temperatures	300–900	10–25	Evergreen shrubs, olive and oak trees, and drought-tolerant vegetation	FAO, 2020a; UNEP, 2016

Genetic basis of adaptability in goats

The domestication process, which proceeded to the formation of different breeds, then selection for traits of economic importance by human beings, further produced breeds that are adapted to a range of environmental conditions with specific traits. Besides, the varied geographic features, such as rocky, mountainous, and valley, coupled with selection pressures, both natural and artificial, also contributed to specific changes in genomic regions that can control particular traits, including body conformation, productivity, adaptability to harsh conditions, and disease resistance (Saravanan et al., 2021). The ever-changing climate variables pose a significant threat to global food systems. The projections that global temperatures will rise by 1.5 to 2 °C by 2050 (Klimenko et al., 2025), these changes will come along with risks and uncertainties that will affect livestock productivity and survival rates due to increased heat stress and the spread or outbreak of different diseases. Indigenous goats, which have evolved through natural selection, have developed adaptive mechanisms to withstand these extreme environmental conditions, thus making them a climate-resilient breed (Kichamu et al., 2025).

The advances in genomics have revealed important signature selection associated with Thermo tolerance (*PPP1R36, A2(HSPA2*, *MST1*, *PCK HOXC12, HOXC13)* which controls and protects the cells during the extream heat stress, Immunity (*ERBB2*, *ENO1*, *HYAL1*, *HYAL3*) which helps that animals to withstand the prevalence of any pathogens and diseases, metabolic adaptation (*PPP4R3B, UGT2A2)*, that are responsible for enabling the animals to respond to the changing environmental conditions and coat color modulation and adaptation to cold (*Table 2*).

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Table 2. **Candidate gene for adaptation and immune response in some indigenous goats**

Breed	Country	Method	Candidate gene	Function	References
Mubende SEA	Uganda	Illumina GoatSNP50 Bead Chip	*PPP1R36, A2(HSPA2)* *ERBB2 & ENO1*	Responsible for Heat shock protein and Heat stress Immunity regulation	Onzima et al., 2018
Galla	Kenya	Illumina GoatSNP50 Bead Chip	*HYAL1, HYAL3, MST1, PCK*	Immunity regulation, Adaptation	Waineina et al., 2021; Kamidi et al., 2023
Sebei	Uganda	Illumina GoatSNP50 Bead Chip	*HOXC12, HOXC13*	Thermoregulation	Onzima et al., 2018
Karamoja	Uganda	Illumina GoatSNP50 Bead Chip	*KPNA4 (CHI1), MTOR*	Heat shock	Onzima et al., 2018
Kigezi	Uganda	Illumina GoatSNP50 Bead Chip	*IL10RB & IFNLR1*	Immunity Regulation	Onzima et al., 2018
Galla	Kenya	mtDNA D-loop and *HSP70* gene	*HSP70*	Thermoregulatory role in testes (spermatogenesis)	Masila et al., 2024
Begiat	Ethiopia	Whole-Genome Sequencing	Multiple genes *(SLC6A2, SLC7A11,* etc.*)*	Immune response and adaptation	Gebreselase et al., 2024
Barki	Egypt	Caprine and ovine 50K SNP Beadchip	Multiple genes *(FGF2, GNAI3, PLCB1,* etc.*)*	Thermotolerant, Energy and digestive metabolism, Nervous and autoimmune response	Aboul-naga et al., 2025
Aberegalle	Ethiopia	Whole-Genome Sequencing	*PPP4R3B, UGT2A2*	Regulate lipid metabolism and energy homeostasis	Berihulay et al., 2019
51 indigenous breeds	Various climatic regions		Various genes *(ASIP, DENND1A, DLG1,* etc.*)*	Coat color, feed intake, immune response, and heat tolerance	Peng et al., 2024
Tibetan cashmere goat	High altitude area in China	Caprine and ovine 50K SNP Beadchip	*EPAS1* *PAPSS2*	high-altitude adaptation	Song et al., 2016 Li et al., 2022
Nepalese goat	Nepal	PCR-RFLP	*FGF5, EPAS1*	Hair follicle growth for High altitude adaptation	Sasazaki et al., 2021
Egyptian goats	hot, dry environment of Egypt		KDM6A, TRPM3, USP54	Heat stress adaptation	Aboul-Naga et al., 2025

Phenotypic basis of adaptability in goats

Phenotypic adaptation in goats involves all those physical features that enable them to survive, produce, and reproduce in varied conditions. This includes morphological, physiological, and behavioral characteristics. These phenotypic traits are those that are observable with our naked eyes and have been manipulated by factors such as natural selection, artificial breeding, and environmental pressures. Goats have therefore exhibited high levels of adaptation due to their history of surviving in various climatic regions, including hot arid deserts to high-altitude plateaus (Mwacharo et al., 2017) (*Table 3*). Morphological Adaptations play an important role in the environmental fitness of an animal. Some of the morphological features include the coat color, the outer covering of an animal, length, and density of the coat. Animals with light coat color are known to reflect heat. This makes them thrive well in arid and semi-arid regions, for example, the white coat color seen in the Kenyan Galla goats *Figure 1* raised in pastoral drought arid and semi-arid regions, helps them to reduce body heat absorption and facilitate thermoregulation (Mutindi et al., 2022).

In contrast, goats raised in high-altitude and cold regions normally have a thick coat and long fiber, which keeps them warm. For example, the Chinese Tibetan cashmere *Figure 2* and Nepalese mountain goats *Figure 3* have observable dense undercoats of fine cashmere fibers that act as insulators to the cold regions (Sasazaki et al., 2021; Li et al., 2022). Apart from coat color, body conformation also plays an important role in environmental adaptation. Those animals with compact and small body size are capable of dispelling heat more efficiently in hot regions, while the large and heavy-bodied animals tend to conserve heat, making them suitable for colder regions. Other features like ear length, horn shape, and skin color also contribute to the adaptability of this breed. For example, animals with dark skin are well protected from the ultraviolet radiation. These morphological differences highlight the plasticity of the species in adapting to thermal, solar, and topographic variability.

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Table 3. **Phenotypic traits associated with environmental adaptability in goats across agro-ecological zones**

Agro-ecological zone	Representative region / breed	Phenotypic trait	Adaptive significance	References
Hot arid or desert	Egypt- Barki and Baladi goats	Light coat color, mostly white or cream, with short and glossy hair	Reflects solar radiation and minimizes heat absorption, helping in improving thermoregulation in desert climates	El-Sherbiny et al., 2023
	Saudi Arabia – Ardi & Harri goats	Increased respiration and heart beat rate with stable rectal temperature	Promotes evaporative cooling and homoeothermic under extreme heat stress	Al-Samawi et al., 2014
	India – Osmanabadi & Malabari goats	High water intake, frequent panting, reduced feed intake	Reduces metabolic heat production and assists in heat tolerance	Aleena et al., 2018
	Kenya-Galla goats	White coat color	minimizes the absorption of heat in arid conditions	Mutindi et al., 2022
Semi-arid/savannah	Kenya and Tanzania - East African indigenous goats	Small body size with short hair, high mobility	Low metabolic heat production and efficient foraging in a small boy during drought	Berihulay et al., 2019
Humid tropical / sub-humid	Nigeria-WestAfrican Dwarf goats	Compact body with short legs and dark pigmentation	Facilitates movement in dense vegetation and protects against UV and parasites	Daramola & Adeloye, 2009
Cold mountainous/high altitude	China-Tibetan cashmere goats	Dense undercoat (cashmere fiber)	Provides insulation and absorbs solar radiation for warmth under cold hypoxic conditions	Zhao et al., 2022
	Nepal-Chyangra goats, mountain goats	Thick hair growth with higher hemoglobin levels	Enhances insulation and oxygen transport efficiency in high-altitude environments	Gorkhali et al., 2023
	Mongolia-Inner Mongolian Cashmere goats	Thick double coat with seasonal molting	Maintains thermal insulation during cold seasons; adapts coat with climate variation	Gong et al., 2022
Multi-zone (global)	Global-Local goat populations across regions	Variation in coat color (light in hot areas, dark in cold zones)	Optimizes solar heat reflection or absorption to match environmental temperature	Arenas-Báez et al., 2023

Figure 1. **The Kenyan Galla goat is adapted to arid and semi-arid regions**

(Photo taken by Nelly Kichamu)

Figure 2. **Chinese Tibetan goat with dense fiber adapted to cold regions** (Song et al., 2016)

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Figure 3. **Nepalese mountain goats with dense fiber adapted to cold regions** (NABGRC, 2021)

Physiological responses also play a role in animals' adaptation by enabling them to maintain their homeostasis processes to reduce the impact of stress. For example, those goats that are tolerant to heat stress normally have a stable rectal temperature, lower respiration rates, and efficient sweating mechanisms during the heat stress periods (El-Sherbiny et al., 2023). In hot environments, goats adjust their water metabolism, electrolyte balance, and feed conversion efficiency to be able to maintain their productivity. While those in high altitude or cold regions normally contain increased levels of hemoglobin concentration, packed cell volume, and oxygen-binding capacity, this allows for enough supply of oxygen under hypoxic conditions. Behavioral adaptations are closely linked to morphological and physiological mechanisms. In some conditions, goats may modify their daily activities to lessen some of the environmental extremes. For example, some may rest under the shade or go for grazing during the cooler times, like very early in the morning or late in the evening. Others include social behaviors like grazing or browsing in a group (Devendra, 2012). All these mechanisms contribute significantly to the overall adaptability of goats.

CONCLUSIONS

Adaptation of goats to various agro ecological regions is facilitated by complex interaction between genetic and phenotypic mechanisms. The differences in climatic conditions, vegetation, topography, and altitudes exert pressure forcing them to develop survival mechanisms. Phenotypic features, including hair type and coat color, act as an important mechanism for these goats to survive environmental stresses like heat, cold, and drought. These features do not work alone but are complemented by the genetic mechanisms known as signature selections, for instance, the presence of (*HSP70*, *EPAS1*, *MC1R*, *FGF5*) genes in some goats regulates cellular responses to stress, oxygen metabolism, and coat development. Together, these genetic and phenotypic adaptations support the resilience and productivity of indigenous goat breeds in their present local environments. Therefore incorporating these adaptive traits through genomic and phenotypic selection can improve goat breeding under climate change. Selection programs can prioritize those animals with high combination of productivity and environmnetal resilience to develope a more robust and sustainable breeding program as the future of goat production will highly depend on locally adapted and genetically diverse populations, especially in regions vulnerable to climate variability. Despite the progress, there are still some existing knowledge gaps including limitation in functional validation of adaptive gene, scacity of long-term genotype–environment–phenotype data, and incorporation of genomic findings into practical breeding programs and decisions is still weak. These gaps can be effectively addressed through participatory breeding programs, incorporating the genomic with ecological and phenotypic data to strengthen strategies for adaptive breeding and sustainable conservation thereby safeguarding genetic resources and ensuring the long-term sustainability and resilience of the goat sector.

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REFERENCES

Aboul-Naga, A.M.; Alsamman, A.M.; Melak, S.; Nassar, A.E.; Abdelsabour, T.H.; Gamal, L.; Adley, M.; Elshafie, M.H. (2025): Genomic analysis association of tolerance to heat stress in subtropical Egyptian goats raised in hot dry environment. *BMC genomics*, *26*(1), 568. https://doi.org/10.1186/s12864-025-11748-x

Aboul-Naga, A.M.; Khalil, M.; El-Sherbiny, H.M. (2023): Phenotypic and physiological responses of Egyptian goats to heat stress in arid environments. *BMC Veterinary Research, 19*(1), 128. https://doi.org/10.1186/s12917-023-03653-w

Aleena, J.; Sejian, V.; Bagath, M.; Krishnan, G.; Beena, V.; Bhatta, R. (2018): Resilience of three indigenous goat breeds to heat stress based on phenotypic traits and PBMC HSP70 expression. *International Journal of Biometeorology*, *62*(11), 1995–2005. https://doi.org/10.1007/s00484-018-1604-

Al-Samawi, K.A.; Al-Hassan, M.J.; Swelum, A.A. (2014): Thermoregulation of female Aardi goats exposed to environmental heat stress in Saudi Arabia. *Indian Journal of Animal Research, 48*(4), 344–349. https://doi.org/10.5958/0976-0555.2014.00453.1

Arenas-Báez, P.; Torres-Hernández, G.; Castillo-Hernández, G.; Hernández-Rodríguez, M.; Sánchez-Gutiérrez, R.A.; Vargas-López, S.; González-Maldonado, J.; Domínguez-Martínez, P.A.; Granados-Rivera, L.D.; Maldonado-Jáquez, J.A. (2023): Coat

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DOI: 10.34101/ACTAAGRAR/1/16371

colour in local goats: Influence on environmental adaptation and productivity, and use as a selection criterion. *Biology, 12*(7), 929. https://doi.org/10.3390/biology12070929

Berihulay, H.; Liu, X.; Jiang, L.; Ma, Y.; Liu, W. (2019): Adaptation mechanisms of small ruminants to environmental heat stress. *Animals, 9*(3), 75. https://doi.org/10.3390/ani9030075

Chokoe, T.C.; Matelele, T.C.; Maqhashu, A.; Ramukhithi, F.V.; Mphahlele, T.D.; Mpofu, T.J.; Nephawe, K.A.; Mtileni, B. (2020): Phenotypic diversity of South African indigenous goat populations in selected rural areas. *American Journal of Animal and Veterinary Sciences*, *15*(1), 59–66. https://doi.org/10.3844/ajavsp.2020.59.66

da Silva, W.S.T.; Silveira, R.M.F.; da Silva, W.E.; Leite, J.H.G.M.; Bermejo, L.A.; McManus, C.M.; Krupij, A.T.; Façanha, D.A.E. (2025): Coat traits, skin evaporation, and milk production of Majorera and Palmera goats in a temperate region. *International Journal of Biometeorology*. Advance online publication. https://doi.org/10.1007/s00484-025-03016-0

Daly, K.G.; Maisano Delser, P.; Mullin, V.E.; Scheu, A.; Mattiangeli, V.; Teasdale, M.D.; Hare, A.J.; Burger, J.; Pereira Verdugo, M.; Collins, M.J.; Kehati, R.; Erek, C.M.; Bar-Oz, G.; Pompanon, F.; Cumer, T.; Çakırlar, C.; Mohaseb, A.F.; Decruyenaere, D.; Davoudi, H.; … Bradley, D.G. (2018): Ancient goat genomes eveal mosaic domestication in the Fertile Crescent. *Science, 361*(6397), 85–88. https://doi.org/10.1126/science.aas9411

Daramola, J.O.; Adeloye, A. A. (2009): Physiological adaptation to the humid tropics with special reference to the West African Dwarf (WAD) goat. *Tropical Animal Health and Production*, *41*(7), 1005–1016. https://doi.org/10.1007/s11250-008-9267-6

El-Sherbiny, H.R.; Hashem, N.M.; Abdelnaby, E.A. (2023): Coat color affects the resilience against heat stress impacts on testicular hemodynamics, reproductive hormones, and semen quality in Baladi goats. *BMC Veterinary Research*, *19*, 107. https://doi.org/10.1186/s12917-023-03653-w

Fodor, I.; Tőzsér, J.; Bíró, O.; Farkas, B.; Gáspárdy, A.; Komlósi, I. (2023): A systematic review of genotype-by-climate interaction for production, fertility, and health traits in cattle, swine, and poultry. *Frontiers in Animal Science, 4*, 1324830. https://doi.org/10.3389/fanim.2023.1324830

Fontanari, J.F.; Matos, M.; Santos, M. (2023): Local adaptation, phenotypic plasticity, and species coexistence. *Ecology and Evolution.* Advance online publication. https://doi.org/10.3389/fevo.2023.1077374

Food and Agriculture Organization of the United Nations (FAO) (2020a): Global Agro-Ecological Zones (GAEZ v4): Model documentation. *Rome: FAO.* https://gaez.fao.org

Food and Agriculture Organization of the United Nations (FAO) (2020b): The State of Food and Agriculture 2020: Overcoming water challenges in agriculture. *Rome: FAO.* https://doi.org/10.4060/cb1447en

Gebreselase, H.B.; Nigussie, H.; Wang, C.; Luo, C. (2024): Genetic Diversity, Population Structure, and Selection Signature in Begait Goats Revealed by Whole-Genome Sequencing. *Animals (Basel), 14*(2). https://doi.org/10.3390/ani14020307

Gong, G.; Li, J.; Wang, D.; Li, C.; Zhang, H.; Li, J. (2022): Identification of genes related to hair follicle cycle development in Inner Mongolia cashmere goat by WGCNA. *Frontiers in Veterinary Science, 9,* 894380. https://doi.org/10.3389/fvets.2022.894380

Gorkhali, N.A.; Paudel, B.; Basnet, K.; Bhandari, S.; Pokhrel, B.R.; Sharma, S.B.; Sapkota, S. (2023): Qualitative characteristics of cashmere fiber of Chyangra goat of Nepal. *Journal of Nepal Agricultural Research Council*, *9*(1), 114–125. https://doi.org/10.3126/jnarc.v9i1.61604

Intergovernmental Panel on Climate Change (IPCC) (2021): Climate Change 2021: The Physical Science Basis. *Cambridge University Press.* https://doi.org/10.1017/9781009157896

Kaliber, M.; Koluman, N.; Silanikove, N. (2016): Physiological and behavioral basis for the successful adaptation of goats to severe water restriction under hot environmental conditions. *Animal: an international journal of animal bioscience*, *10*(1), 82–88. https://doi.org/10.1017/S1751731115001652

Kassam, A.H.; van Velthuizen, H.T. (2011): Spatial analysis of agro-ecological zones and their applications in the global assessment of agricultural resources. *Agricultural Systems, 104*(2), 98–111. https://doi.org/10.1016/j.agsy.2010.09.002

Kichamu, N.; Wanjala, G.; Dossybayev, K.; Bagi, Z.; Bekmanov, B.; Kusza, S. (2025): Genome-wide analysis provides insight into the genetic diversity and adaptability of Kazakhstan local goats. *Scientific Reports, 15*, 19327. https://doi.org/10.1038/s41598-025-02427-8

Kim, E.S.; Elbeltagy, A.R.; Aboul-Naga, A.M.; Rischkowsky, B.; Sayre, B.; Mwacharo, J.M.; Rothschild, M.F. (2016): Multiple genomic signatures of selection in goats and sheep indigenous to a hot arid environment. *Heredity, 116*(3), 255–264. https://doi.org/10.1038/hdy.2015.94

Klimenko, V.V., Tereshin, A.G.; Mikushina, O.V. (2025): Bumpy road to climate neutrality: Why the 1.5 °C threshold is close and why the temperature overshoot will be long. *Journal of Globalization Studies*, *16*(1), 3–24. https://doi.org/10.30884/jogs/2025.01.01

Li, C.; Wu, Y.; Chen, B.; Cai, Y.; Guo, J.; Leonard, A.S.; Kalds, P.; Zhou, S.; Zhang, J.; Zhou, P.; Gan, S.; Jia, T.; Pu, T.; Suo, L.; Li, Y.; Zhang, K.; Li, L.; Purevdorj, M.; Wang, X.; Li, M.; Wang, Y.; Liu, Y.; Huang, S.; Sonstegard, T.; Wang, M.-S.; Kemp, S.; Pausch, H.; Chen, Y.; Han, J.-L.; Jiang, Y.; Wang, X. (2022): Markhor-derived introgression of a genomic region encompassing *PAPSS2* confers high-altitude adaptability in Tibetan goats. *Molecular Biology and Evolution, 39*(12), msac253. https://doi.org/10.1093/molbev/msac253

Liu, X.; Tang, J.; Zhang, R.; Zhan, S.; Zhong, T.; Guo, J.; Wang, Y.; Cao, J.; Li, L.; Zhang, H.; Wang, L. (2022): Cold exposure induces lipid dynamics and thermogenesis in brown adipose tissue of goats. *BMC Genomics, 23*, 528. https://doi.org/10.1186/s12864-022-08765-5

Lu, C.D. (2023): The role of goats in the world: Society, science, and sustainability. *Small Ruminant Research, 227*, Article 107056. https://doi.org/10.1016/j.smallrumres.2023.107056

Masila, E.M.; Ogada, S.O.; Ogali, I.N.; Kennedy, G.M.; Too, E.K.; Ommeh, C.S. (2024): Mitochondrial DNA D-Loop Polymorphisms among the Galla Goats Reveals Multiple Maternal Origins with Implication on the Functional Diversity of the HSP70 Gene. *Genetics Research*, *2024*(1), 5564596. https://doi.org/10.1155/2024/5564596.

Mutindi, E.; Ogali, I.; Kuria, S.; Moraa, G.; Too, E.; Kingoo, J.; Ommeh, S. (2022): Assessment of phenotypes, physiological and behavioural responses associated with heat tolerance among Galla goats in North Eastern Kenya. *Journal of Agriculture, Science and Technology*, *21*(1), 4–17. https://doi.org/10.4314/jagst.v21i1.2

Mpofu, T.J.; Nephawe, K.A.; Mtileni, B. (2020): Gastrointestinal parasite infection intensity and hematological parameters in South African communal indigenous goats in relation to

DOI: 10.34101/ACTAAGRAR/1/16371

anemia. *Veterinary world*, *13*(10), 2226–2233. https://doi.org/10.14202/vetworld.2020.2226-2233

National Animal Breeding and Genetics Research Center (NABGRC) (2021): *Indigenous livestock breeds of Nepal* (2nd ed.). Kathmandu, Nepal: Government of Nepal, Nepal Agricultural Research Council.

Nguyen, V.D.; Hoang, T.T.H.; Pham, K.T.; Do, N.T. (2023): Goat production, supply chains, challenges, and opportunities for development in Vietnam: A review. *Animals*, *13*(15), 2546. https://doi.org/10.3390/ani13152546

Nocelli, C.; Cappelli, K.; Capomaccio, S.; Pascucci, L.; Mercati, F.; Pazzaglia, I.; Mecocci, S.; Antonini, M.; Renieri, C. (2020): Shedding light on cashmere goat hair follicle biology: from morphology analyses to transcriptomic landscape. *BMC genomics*, *21*(1), 458. https://doi.org/10.1186/s12864-020-06870-x

Onzima, R.B.; Upadhyay, M.R.; Doekes, H.P.; Brito, L.F.; Bosse, M.; Kanis, E.; Groenen, M.A.M.; Crooijmans, R. (2018): Genome-Wide Characterization of Selection Signatures and Runs of Homozygosity in Ugandan Goat Breeds. *Front Genet*, *9*, 318. https://doi.org/10.3389/fgene.2018.00318

Peng, W.; Zhang, Y.; Gao, L.; Wang, S.; Liu, M.;Sun, E.; Lu, K.; Zhang, Y.; Li, B.; Li, G.; Cao, J.; Yang, M. (2024): Examination of homozygosity runs and selection signatures in native goat breeds of Henan, China. *BMC Genomics*, *25*(1), 1184. https://doi.org/10.1186/s12864-024-11098-0

Rahimi, J.; Mutua, J.Y.; Notenbaert, A.M.; Marshall, K.; Butterbach-Bahl, K.; & others (2021): Heat stress will detrimentally impact future livestock production in East Africa. *Nature Food*, *2*(2), 88–96. https://doi.org/10.1038/s43016-021-00226-8

Saravanan, K.A.; Panigrahi, M.; Kumar, H.; Parida, S.; Bhushan, B.; Gaur, G.K.; Dutt, T.; Mishra, B.P.; Singh, R.K. (2021): Genomic scans for selection signatures revealed candidate genes for adaptation and production traits in a variety of cattle breeds. *Genomics*, *113*(3), 955–963. https://doi.org/10.1016/j.ygeno.2021.02.009

Sasazaki, S.; Tomita, K.; Nomura, Y.; Kawaguchi, F.; Kunieda, T.; Shah, M.K.; Mannen, H. (2021): FGF5 and EPAS1 gene polymorphisms are associated with high-altitude adaptation in Nepalese goat breeds. *Animal Science Journal*, *92*(1), e13640. https://doi.org/10.1111/asj.13640

Silanikove, N. (2000): The physiological basis of adaptation in goats to harsh environments. *Small Ruminant Research*, *35*(3), 181–193. https://doi.org/10.1016/S0921-4488(99)00096-6

Song, S.; Ma, Y.; Fang, C.; Jiang, F.; Liu, J.; Li, Q.; Zhang, X.; Zhang, W. (2016): Exome sequencing reveals genetic differentiation due to high-altitude adaptation in the Tibetan cashmere goat (*Capra hircus*). *BMC Genomics*, *17*(1), 122. https://doi.org/10.1186/s12864-016-2449-0

United Nations Environment Program (UNEP) (2016): Global Environment Outlook: Regional Assessments. *Nairobi*: *UNEP*. https://wedocs.unep.org/20.500.11822/7673

Waineina, R.W.; Ngeno, K.; Okeno, T.O.; Ilatsia, E.D. (2021): Genetic diversity and population structure among indigenous and imported goat breeds in Kenya. *Genetic Resources*, *2*(3), 25–35. https://doi.org/10.46265/genresj.EQFQ1540

Wang, X.; Li, J.; Zhang, Y.; Liu, H.; Zhao, Q.; Sun, X.; Chen, Y.; Wang, W. (2025): Integrating SNP data to reveal the adaptive selection features of goats in different extreme environments. *BMC Genomics, 26*, Article 11743. https://doi.org/10.1186/s12864-025-11743-2

Zhao, B.; Wu, C.; Sammad, A.; Ma, Z.; Suo, L.; Wu, Y.; Pu, Y.; He, X.; Guan, W.; Yang, N.; Ma, Y.; Fu, X. (2022): The fiber-diameter traits of Tibetan cashmere goats are governed by inherent differences in stress, hypoxic, and metabolic adaptations*: An integrative study of proteome and transcriptome. BMC Genomics*, *23*(1), 191. https://doi.org/10.1186/s12864-022-08422-x

Zheng, Z.; Wang, X.; Li, M.; Li, Y.; Yang, Z.; Wang, S.; Sun, H.; Kang, X.; Wang, X.; Pan, X.; Liu, H.; Zhao, Q.; Wang, C.; Hu, X.; Li, Y.; Yang, J.; Wang, W. (2020): The origin of domestication genes in goats. *Science Advances*, *6*(6), eaaz5216. https://doi.org/10.1126/sciadv.aaz5216