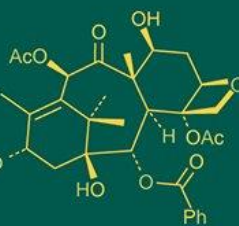
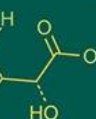
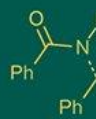


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Heat stress adaptation in goats: From physiological responses to genomic approaches

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Abstract

Climate change is currently being recognised as one of the important challenges that has been impacting the livestock production system across the globe. The rising temperatures, heat waves, changes in the precipitation pattern, and less availability of feed affect the well-being and productivity of livestock. Goats are known to be more adapted to difficult climatic conditions than other livestock due to the presence of a well-developed thermoregulation mechanism and effective utilisation of poor-quality feed sources. Nonetheless, the impact of heat stress may still affect feed intake, growth, reproduction, and productivity of animals. The response of livestock to thermal stress involves multiple mechanisms related to physiology, behaviour, biochemical, endocrine, and molecular responses. The respiratory rate, rectal temperature, heart rate, and skin temperature changes are the most frequently used physiological parameters for measuring heat stress in goats. In terms of molecular mechanisms, the heat stress triggers various cellular signalling cascades linked to heat shock, immunity, oxidative stress, apoptosis, and metabolism. Several candidate genes involved in protecting the cells and maintaining homeostasis under thermal stress include *HSPs*, *HSFs*, cytokines, antioxidants, and growth-related genes. Recent progress in molecular genetics and genomics has contributed significantly to the study of thermotolerance in goats. Some of these approaches include candidate gene studies, SNP association studies, selection signature studies, transcriptomics, and genome editing that have been employed in identifying molecular markers linked to heat tolerance. Indigenous goat breeds possessing superior adaptive ability may serve as valuable genetic resources for future climate-resilient breeding programmes. This review focuses on the effect of climate change on goat production as well as the molecular and genomic approaches associated with heat stress adaptation in goats.

Keywords: Climate Change; Candidate genes; GWAS; Heat stress adaptation

Introduction

Small ruminants are important for the livelihood of marginal and smallholder farmers in the arid and semi-arid regions of India. Their short gestation period, high prolificacy, rapid growth, efficient utilisation of low-quality forage, and better disease resistance make them suitable for low-input farming systems (Sejian, 2013) ^[54]. They also contribute significantly to the rural economy and food security by converting crop residues into meat, milk, fibre, skin, and manure (Kumar and Roy, 2013). Among small ruminants, goats are widely reared by resource-poor farmers because they require less labour, low investment, and simple management practices. Their early maturity and frequent kidding provide faster economic returns, making goat farming highly suitable in dryland and tropical regions (Kumar *et al.*, 2021) ^[30]. Goats are generally more tolerant to harsh environmental conditions than large ruminants (Kruger *et al.*, 2016) ^[29]. However, nutritional limitations and fluctuating feed resources in semi-arid regions continue to affect their performance (Sejian *et al.*, 2012a; Sejian *et al.*, 2012b) ^[52, 53]. Exposure to prolonged heat stress adversely affects feed intake, growth, reproduction, and milk production, thereby reducing the productive efficiency of animals (Kumar *et al.*, 2018) ^[31]. Heat stress has become an important concern under changing climatic conditions and rising global temperatures. Therefore, understanding the genetic and molecular mechanisms associated with heat adaptation is essential for improving thermotolerance and sustaining goat production.

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2. Climate change and heat stress in goats

2.1 Climate change

According to the Intergovernmental Panel on Climate Change (IPCC), climate change is defined as the changes in climate states that are usually noticed for decades or longer and are identified by variations in the mean and variability of its properties. Such changes may occur due to naturally internal processes or external factors, including human-made emissions and urbanisation. Human-induced climate stressors include ocean acidification, altered rainfall pattern, global warming, glacier depletion and frequent drought; all of which significantly affect global sectors (IPCC, 2007) [23]. The IPCC Special Report (2018) [24] projects that a temperature rise of 1.5 °C is likely to happen by 2030 to 2052 compared with pre-industrial levels. This emphasizes how critical it is to reduce carbon emissions in order to minimize the effects on the environment. Climate change has increased the occurrence of heat waves and extreme weather events, affecting both humans and livestock, particularly in tropical regions (UNFCCC, 2014). In India, climate change has also increased the risk of floods and extreme rainfall events, resulting in crop losses, reduced water storage capacity, and depletion of water resources (Ali *et al.*, 2019) [7]. Moreover, the frequency of heat waves has increased, while cold waves have declined. It is projected that by the end of the 21st century, the annual occurrence of warm days and nights may increase by 60-80% (Krishnan *et al.*, 2020) [28].

2.2 Effects of climate change on goat production

The effects of climate change on livestock production, including goats, can generally be classified into direct and indirect impacts (Collier *et al.*, 2019) [15].

2.2.1 Direct effects

The direct effects of climate change include physiological and performance-related responses to heat stress, caused by rising ambient temperatures. Among climate-induced stressors, heat stress is the most serious as it prevents livestock from realising their genetic potential for production (Gupta and Mondal, 2021). Dangi *et al.* (2015) [17], defined heat stress as the inability of an animal to dissipate enough heat to maintain thermal balance under prolonged exposure to high temperatures. Such stress reduces feed intake, growth, reproduction, meat and milk production, survival, and immune function (Gupta and Mondal, 2021), ultimately lowering productivity and profitability. Developing successful mitigation and adaptation methods requires an understanding of these consequences. Variations in ambient temperature impact the equilibrium between heat production and dissipation. This can alter the metabolic processes in livestock. Every animal has a thermal comfort zone called the thermoneutral zone (TNZ). It is the range of ambient temperatures within which physiological processes operate optimally without extra energy for thermoregulation. In goats, the TNZ ranges from 12 °C and 24 °C. Heat stress occurs when the ambient temperatures exceed 25 °C, especially at a RH above 50 per cent (Gupta and Mondal, 2021). Under severe heat stress, animals cannot reduce their metabolic heat production; instead, metabolic activity increases due to the Van't Hoff effect, with higher energy expenditure linked to increased respiratory activity (Dangi *et al.*, 2015) [17]. Susceptibility to thermal stress is influenced by the genetic potential of the animal, while, adaptive efficiency determines how effectively it responds to environmental stressors

(Silanikove and Koluman, 2015) [57].

One of the most direct effect of heat stress in goats is reduced growth rate, resulting from lower feed intake, digestive efficiency, and nutrient utilisation (Hirayama and Katoh, 2004). Since digestion adds to metabolic heat load, animals limit internal heat production by reducing feed intake (Gupta and Mondal, 2021). This decline in feed intake under heat stress has been reported by Bagath *et al.* (2016); and Shilja *et al.* (2016) [10, 56]. Pragna *et al.* (2018) [46] compared native goat breeds- Osmanabadi, Malabari, and Salem Black- during summer heat stress, and found reduced feed intake, body weight, and growth in all three breeds. However, Salem Black goats showed greater resilience, with significantly lower performance losses than Osmanabadi and Malabari. Heat stress further compromises meat quality. Changes in physicochemical and sensory characteristics have been reported in Black Bengal, Osmanabadi, and Salem Black breeds (Archana *et al.*, 2018; Hashem *et al.*, 2013) [9]. Lactation in dairy goats is also highly affected by heat stress. Lactating animals are more susceptible than the non-lactating ones, as increased metabolic heat production limits milk synthesis. Gupta and Mondal (2021) reported a strong correlation between heat load and productivity loss, particularly in high-yielding animals. Salama *et al.* (2014) [49] found feed intake and milk yield were decreased by 22-35% and 3-10%, respectively under heat stress, in goats. This condition also shortens the lactation period and reduces milk synthesis by impairing mobilisation of body reserves, especially when heat exposure occurs later in lactation. Reproductive efficiency in goats is also highly sensitive to elevated ambient temperatures. Adjassin *et al.* (2022) [4] reported reduced fertility, conception and prolificacy in Saanen × Red Maradi crossbreds under heat stress, with greater decline than in purebred Saanen goats. In female goats, heat exposure also suppressed follicular development and ovulation, likely due to downregulation of the luteinizing hormone receptor and impaired oestradiol synthesis (Ozawa *et al.*, 2005) [43]. Furthermore, the immune system is also compromised due to heat stress. El-Tarabany *et al.* (2017) [21] reported reduced total leukocyte count under severe heat conditions. This immunosuppression is likely linked to elevated cortisol levels, which inhibits cellular immune responses (Gupta and Mondal, 2021).

2.2.2 Indirect effects

Indirect effects of climate change include changes in rainfall pattern, reduced availability of feed and fodder, and alterations in forage composition due to increased atmospheric CO₂ levels. These changes negatively affect grazing lands by decreasing both forage quality and quantity, which ultimately affects livestock nutrition. Climate change also favours the emergence and re-emergence of pathogens and parasites, thereby increasing the occurrence of livestock diseases (Cheng *et al.*, 2022) [14]. Given these challenges, the ability of animals to adapt through behavioural, physiological, and molecular mechanisms becomes critical for maintaining survival and productivity under climate stress.

2.2.3 Adaptation of animals to heat stress

Adaptation refers to behavioural, physiological, biochemical, endocrine, and molecular mechanisms that help animals survive and perform under stressful environmental conditions. The ability to cope with stress depends largely on how effectively it can initiate physiological and behavioural adaptations (Silanikove and

Koluman, 2015)^[57]. Physiological adaptation is particularly important in goats which are often reared in hot and dry regions. Under heat stress, there will be a rise in rectal temperature, respiration rate, and pulse rate-the key indicators of thermal load. Even a 1 °C rise in rectal temperature can reduce performance of the animal (Marai *et al.*, 2007)^[34]. Increased respiration supports evaporative cooling, which helps the animal to lose excess body heat by panting (Salama *et al.*, 2014)^[49]. Higher pulse rate reflects circulatory adjustments for heat dissipation by transferring more blood to peripheral tissues (Shilja *et al.*, 2016)^[56]. The behavioural changes, such as reduced grazing, increased lying or standing in shade, and limited movement, also lower metabolic heat production (Alam *et al.*, 2011)^[5]. Heat stress alters biochemical and hormonal levels in goats, which cause changes in serum metabolites like glucose, total protein, albumin, and cholesterol. It also suppresses the pituitary hormones like luteinizing hormone, thyrotropin, somatotropin, and prolactin. Cortisol, in contrast, rises and is considered a reliable stress biomarker (Gupta and Mondal, 2021). Several studies have compared the thermotolerance of indigenous goat breeds of Kerala, Malabari and Attappady Black goats. Thomas *et al.* (2021) found similar rectal temperatures (RT) in Malabari and Attappady Black goats, but the latter showed lower pulse rates (PR), higher mean corpuscular volume (MCV), and better cardiovascular stability, suggesting superior adaptation to tropical thermal stress. Yamin *et al.* (2022)^[68] reported that, although respiration, RT, PR and skin temperature increased in all groups (Malabari, Attappady Black, and Malabari × Saanen), Attappady Black goats had lower cortisol and glucose levels with fewer hormonal and electrolyte shifts, indicating greater heat resilience and, hence, better suited under semi-intensive systems. Similarly, Lakshmi *et al.* (2025) found both breeds stressed during summer, but Attappady Black goats showed better thermoregulation, with decreased RT and adaptive increases in RR by day 30.

Since these adaptive responses are strongly influenced by external climatic conditions, it is essential to assess the role of temperature and humidity through indices such as the Temperature-Humidity Index (THI).

2.2.4 Climatic variables and temperature-humidity index

The main environmental factors influencing heat stress in livestock are ambient temperature (AT) and relative humidity (RH), though solar radiation, wind speed, and rainfall also play roles. High temperatures increase thermal load, while high humidity reduces the efficiency of evaporative cooling mechanisms such as sweating and panting. Together, they raise body temperature above the thermoneutral zone (Islam *et al.*, 2024)^[25]. Temperature-Humidity Index (THI) is a bioclimatic index, which combines AT and RH into a single value to quantify their effects on animals. It is widely used to assess heat stress in cattle, goats, sheep, and poultry (Islam *et al.*, 2024)^[25]. Higher THI values indicate hotter, more humid conditions and are associated with physiological stress, health risks, reduced productivity, and thermal discomfort.

In this study, THI was calculated using the Livestock-Poultry Heat Stress Index (LPHSI, 1990)^[33] formula

developed by Clemson University. THI values are classified as THI <72 = No heat stress; THI 72-78 = Mild to moderate stress; THI >78 = Severe stress (McDowell *et al.*, 1976)^[35]. Above 78, animals lose effective thermoregulation, showing signs such as elevated respiration and rectal temperatures, and reduced feed intake. As the impacts of temperature and humidity on livestock are evident from THI assessments, it becomes essential to explore strategies that can mitigate heat stress and sustain animal productivity.

3. Strategies to mitigate heat stress

Heat stress mitigation involves genetic, environmental, and nutritional approaches, including selection of heat-tolerant breeds, housing modifications, and dietary adjustments to sustain productivity under changing climates (Osei-Amponsah *et al.*, 2019)^[42]. Practical measures such as shade, fans, sprinklers, and rescheduling farm tasks like milking to cooler hours reduce thermal load. Nutritional strategies, including low-fibre, high-concentrate rations and slowly fermentable grains, also help minimise metabolic heat production (Vermunt and Tranter, 2011)^[62]. While such management and feeding interventions provide short-term relief, long-term resilience depends on adopting genetic strategies. While these management and feeding interventions are effective in the short term. However, long-term and sustainable resilience can only be ensured through the adoption of genetic strategies.

4. Genetic strategies for enhancing heat resilience in goats

Genetic diversity within and between breeds can be used to select animals with superior thermotolerance. Identifying genotypes inherently resilient to high temperatures is important for sustaining productivity in warm climates (Osei-Amponsah *et al.*, 2019)^[42]. McManus *et al.* (2022)^[37] noted that breeding programs should give emphasis to the selection of thermotolerant animals in hot and humid climates. Tropical and subtropical breeds generally show better adaptive traits than exotic ones (Gaughan *et al.*, 2019). For example, *Bos indicus* (Zebu) cattle tolerate heat better than *Bos taurus* of European origin due to lower metabolic rates and efficient heat dissipation (Osei-Amponsah *et al.*, 2019)^[42]. Morphological traits such as larger sweat glands (Pan, 1963)^[44] and improved peripheral circulation further enhance Zebu adaptability. In small ruminants, thermotolerance is influenced by phenotypic traits such as body size, coat type, and colour. Acharya *et al.* (1995)^[3] noted that goats with longer coats were more tolerant to radiant heat than those with shorter coats. Smaller-framed animals dissipate heat better due to a higher surface area-to-volume ratio as seen in the Morada Nova sheep which outperformed the larger Santa Ines under tropical stress (Seixas *et al.*, 2017)^[51]. Coat colour also affects heat tolerance, with lighter coats absorbing less solar radiation. Coarse carpet-type wool aids evaporative cooling (McManus *et al.*, 2022)^[37]. Among goats, Salem Black showed greater resilience than Osmanabadi and Malabari breeds, with physiological adjustments such as reduced skin and rectal temperatures and lower urinary water loss during summer (Pragna *et al.*, 2018; Aleena *et al.*, 2018)^[6, 46]. Heat tolerance is polygenic, with many genomic regions

identified. Rectal temperature under heat stress is heritable and can serve as a selection criterion (Dikmen *et al.*, 2012)^[20]. Genomic tools such as SNPs enable faster genetic gain. As a quantitative trait, heat tolerance is influenced by both genes and environment (Gaughan *et al.*, 2019). Indicators include physical traits (hair shedding, body surface area), physiological responses (body temperature, respiration rate), and biomarkers such as blood metabolites and molecular markers (Carabaño *et al.*, 2019)^[11]. Ravagnolo and Misztal (2000)^[48] suggested that production decline under heat stress can also indicate tolerance, with resilient animals showing slower reductions in output. Though not ideal, this remains a practical, cost-effective tool for selection. A large number of genomic regions associated with thermal tolerance have been identified, confirming that the trait is polygenic and involves multiple biological pathways. Since rectal temperature under heat stress is a heritable trait, it can serve as a useful selection criterion for heat-tolerant animals (Dikmen *et al.*, 2012)^[20]. The use of molecular markers, such as single-nucleotide polymorphisms (SNPs), can further accelerate selection for desirable traits and enhance genetic gain. Genetic strategies to enhance heat resilience in goats can be implemented through multiple approaches, ranging from conventional breeding methods to advanced molecular and genomic tools, which are outlined in the following subsections.

4.1 Conventional methods

Crossbreeding heat-susceptible livestock with heat-adapted breeds is a common strategy to improve thermotolerance. In the tropics, *Bos taurus* dairy breeds such as Holstein or Jersey were crossed with *Bos indicus* (Zebu) to combine milk yield with heat resilience (Osei-Amponsah *et al.*, 2019)^[42]. Another method was introgressing the 'slick hair' gene from Senepol into Holsteins to produce calves with shorter coats and better thermal tolerance (Olson *et al.*, 2003)^[40]. However, the productivity of these crosses often remained lower than purebred high-yielding breeds, affecting profitability McDowell *et al.*, 1996)^[36].

4.2 Selection based on candidate genes

In small ruminants, the candidate gene approach is appropriate to understand the genetic basis of traits related to growth, adaptation, immune response, and reproduction during heat stress.

4.2.1 Growth

Angel *et al.* (2018)^[8] reported significant downregulation of growth-related genes Growth hormone (GH), Growth hormone receptor (GHR), Insulin-like growth factor-1 (IGF1), Leptin (LEP), Leptin receptor (LEPR) and Thyroid hormone receptor (THR) in the liver of heat-stressed Malabari goats, which was interpreted as an adaptive mechanism to reduce metabolic heat. Bagath *et al.* (2016)^[10] observed reduced LEP expression in Osmanabadi goats, suggesting energy conservation and metabolic balance during heat stress. These genes regulate growth, nutrient partitioning, and energy metabolism; notably, IGF1 downregulation under high thermal stress impaired growth rates (Angel *et al.*, 2018)^[8]. Other genes such as Bone Morphogenetic Protein 2 (BMP2), Adenosine

monophosphate deaminase 1 (AMPD1), and gap junction proteins GJB2, GJB6, and GJA3 are also linked to growth traits and identified as potential candidates for selecting heat-resistant animals (Abioja *et al.*, 2023)^[1].

4.2.2 Immune response

Immune response is important for thermal resilience in goats, as heat stress can impair immune function. Several candidate genes related to immunity under high temperatures have been identified. In Osmanabadi goats, splenic expression of TLR1, TLR2, TLR3, TLR5, TLR6, TLR8, and TLR10 increased under heat, nutritional, and combined stress (Sophia *et al.*, 2016)^[59]. Chauhan *et al.* (2014)^[13] reported increased nuclear factor kappa B (NF- κ B) and tumour necrosis factor alpha (TNF- α) expression in the skeletal muscles of Merino $\times$ Poll Dorset ewes under thermal stress (28-40 °C), linking these genes in inflammation and stress response. In goats exposed to heat stress, Caroprese *et al.* (2017)^[12] showed increased IL-10 and HSP70 expression in PBMCs, suggesting a role for IL-10 in immune regulation. Other genes like BCL2L1, ERBB2 and IL12A have been associated with immune modulation in heat stress conditions (Onzima *et al.*, 2018)^[41].

4.2.3 Reproduction

Heat stress impairs reproductive performance in goats by altering expression of reproductive hormones and their receptors. In Shiba goats, chronic heat stress reduced Follicle-stimulating hormone receptor gene (FSHR) expression, with concurrent declines in follicle development, oestradiol levels, and expression of oestrus (Abioja *et al.*, 2023)^[1]. Luteinizing hormone receptor (LHR) expression was also significantly downregulated during thermal stress, which could be due to reduced ovarian steroidogenic function, which ultimately affects ovulation and fertility (Ozawa *et al.*, 2005)^[43].

4.2.4 Oxidative stress

Heat stress disrupts redox homeostasis through higher reactive oxygen species (ROS), leading to oxidative stress and cellular injury. Antioxidant enzymes and their genes use redox homeostasis to counteract this. *Superoxide Dismutase (SOD)*, *Catalase (CAT)*, and *Glutathione Peroxidase (GPx)*, *Nitric Oxide Synthase isoforms - eNOS, nNOS, and iNOS* are the primary genes involved in antioxidant defence during heat stress (McManus *et al.*, 2022)^[37]. Goats under summer heat stress showed elevated expression of *iNOS* and *eNOS*, highlighting their role in thermal adaptation (Yadav *et al.*, 2016)^[66]. *Ecto- NOX disulphide-thiol exchanger 2 (ENOX2)* is another important gene related to heat tolerance in animals. Vibhuti *et al.* (2022)^[63] found that during heat stress, *ENOX2* expression was higher in Attappady Black goats compared to Malabari goats, indicating the potential of *ENOX2* in imparting a higher thermotolerance.

4.2.5 Heat shock proteins and factors

To maintain homeostasis under heat stress, animals initiate adaptive responses at molecular, cellular, and tissue levels. *Heat shock proteins (HSPs)* are molecular chaperones that ensure proper protein folding and prevent aggregation of misfolded proteins. Their synthesis increases during heat

stress, protecting cells from damage (Abioja *et al.*, 2023) ^[1]. Based on molecular weight (kDa), *HSPs* are classified as *HSP110*, *HSP100*, *HSP90*, *HSP70*, *HSP60*, *HSP40*, *HSP20*, *HSP10*, and small *HSPs* (Gade *et al.*, 2010) ^[22]. Heat stress initiates activation of *heat shock factors (HSFs)*, elevated *HSP* production, increased glucose and amino acid oxidation, reduced fatty acid metabolism, and stimulation of immune and endocrine systems (Collier *et al.*, 2008) ^[16]. *Heat Shock Factor 1 (HSF1)* is the primary transcription factor regulating *HSP* expression during heat stress, while *HSF2* and *HSF4* have regulatory roles (Westerheide and Morimoto, 2005) ^[65]. In Barbari goats exposed to short-term heat stress (41–45 °C), rectal temperature and respiration rate increased significantly (Dangi *et al.*, 2014) ^[18]. They also found that only *HSP70* was consistently upregulated, suggesting its potential as an early biomarker of thermal stress. Other *HSPs* (*HSP60*, *HSP90*, *HSP105/110*) showed variable expression with THI, reflecting their specific roles in thermotolerance.

Singh *et al.* (2017) ^[58] found that the heat-tolerant Indian sheep breeds Magra and Madras Red had lower expression of genes *HSP90AA1*, *HSPA1A*, and *HSPA8* than other breeds. Sharma *et al.* (2013) ^[55] reported increased expression of several *HSP* families (*HSP27*, *HSP32*, *HSP40*, *HSP60*, *HSP70*, *HSP90*, and *HSP110*) during heat stress, supporting the central role of *HSPs* in cellular defence during thermal exposure.

5. Advanced genomic approaches

5.1 Selection based on snp association

Heat tolerance is controlled by multiple genes associated with different genomic regions. QTL studies give useful information on physiological and reproductive traits under heat stress. They also help identify genotypes with better thermotolerance (Salces-Ortiz *et al.*, 2013) ^[50].

Marker-assisted selection (MAS) enables breeders to indirectly select animals using genomic markers instead of phenotypic traits (Wakchaure *et al.*, 2015) ^[64]. Since complex traits like thermotolerance are difficult to measure directly, MAS gives breeders the ability to improve the accuracy of selection by using genomic markers such as SNPs. Single-nucleotide polymorphisms (SNPs) are widely used genetic markers in association studies. Several SNPs associated with thermoregulatory traits have been reported in different goat breeds (Nikbin *et al.*, 2014; Singh *et al.*, 2017; Yakubu *et al.*, 2017; Khan *et al.*, 2021) ^[27, 39, 58, 67]. Nikbin *et al.* (2014) ^[39] found two synonymous SNPs (74A>C and 191C>G) in exon 1 of *HSP70* in Boer goats. They also found that sperm concentration and sperm motility were significantly correlated with animals carrying the advantageous alleles.

Singh *et al.* (2017) ^[58] reported SNPs in *HSP90AA1*, *HSPA1A*, and *HSPA8* genes in four Indian sheep breeds and found that animals having certain SNP variants made them thermotolerant. Yakubu *et al.* (2017) ^[67] documented seven *MHC class II DRB* alleles in West African Dwarf, Red Sokoto, and Sahel goats linked to thermoregulatory traits. Khan *et al.* (2021) ^[27] identified three SNPs in the *SOD3* gene in Black Bengal, Ganjam, and Raighar goats and

concluded that the *SOD3* gene could be a possible genetic marker for heat resilience. Genomic variants linked to thermotolerance can be identified using GWAS. In a GWAS study, Zidi *et al.* (2014) ^[69] identified a significant SNP in *HSPBAP1* gene in Florida dairy goats, associated with *HSP27* interaction; goats carrying the less-favourable allele had higher mammary cell apoptosis under heat which indicated lower thermotolerance. Using 50K SNP genotyping, Aboul-Naga *et al.* (2025) ^[2] identified 90 SNPs across 47 genes, including *KDM6A*, *TRPM3*, *USP54*, and *RPS6KA5*, involved in epigenetic regulation, ion transport, and stress signalling, providing markers for selection of heat-resilient Egyptian desert goats. These results provided possible genetic markers to assist selection for heat-resilient goats in arid environments.

5.2 Selection signature analysis

Selection signature analysis identifies genomic regions under natural or artificial selection that contribute to environmental flexibility. Prashanthini (2023) ^[47] studied temperate breeds (Chegu, Changthangi, Gaddi) and tropical breeds (Beetal, Sirohi, Osmanabadi, Jamunapari) using whole-genome resequencing. They identified several candidate genes, including *DNAJC6*, *DNAJB14*, *NMNAT2*, and *GABRB2*, that were linked to thermotolerance. These genes were enriched in important stress-response pathways like MAPK, Ras, and HIF-1 signalling pathways, highlighting their role in climate adaptation and heat stress resilience.

5.3 Genome editing approach

Genome editing tools such as CRISPR/Cas9 provide new opportunities to improve climate resilience in goats. Gene editing has been shown to enhance thermotolerance through specific genes like *HSP70* without compromising productivity (Kaushik *et al.*, 2022) ^[26]. Approaches such as genome editing, selection signatures, and MAS offer practical options in breeding programmes to develop goats better adapted to harsh environments (Parsad *et al.*, 2025) ^[45].

5.4 Gene expression studies based on transcriptomics

Transcriptomic studies help to identify differentially expressed genes (DEGs) and pathways associated with heat resilience in goats. Velayudhan *et al.* (2023) compared Kanni Aadu and Kodi Aadu goats. Kanni Aadu showed stronger molecular responses with more DEGs and differentially methylated regions (DMRs), while Kodi Aadu appeared more resilient with fewer molecular perturbations. Dige *et al.* (2025) ^[19] used RNA-seq in Jamunapari goats grouped as heat-tolerant or heat-susceptible based on physiological traits under high heat load (THI > 92). They reported 734 DEGs (251 upregulated, 483 downregulated) in heat-tolerant goats. Many DEGs were linked to immune and stress pathways such as NF-κB, MAPK signalling, and cytokine-cytokine receptor interactions. Hub genes like *TOMM40* and *VCL* were associated with respiration rate and thermoregulatory efficiency.

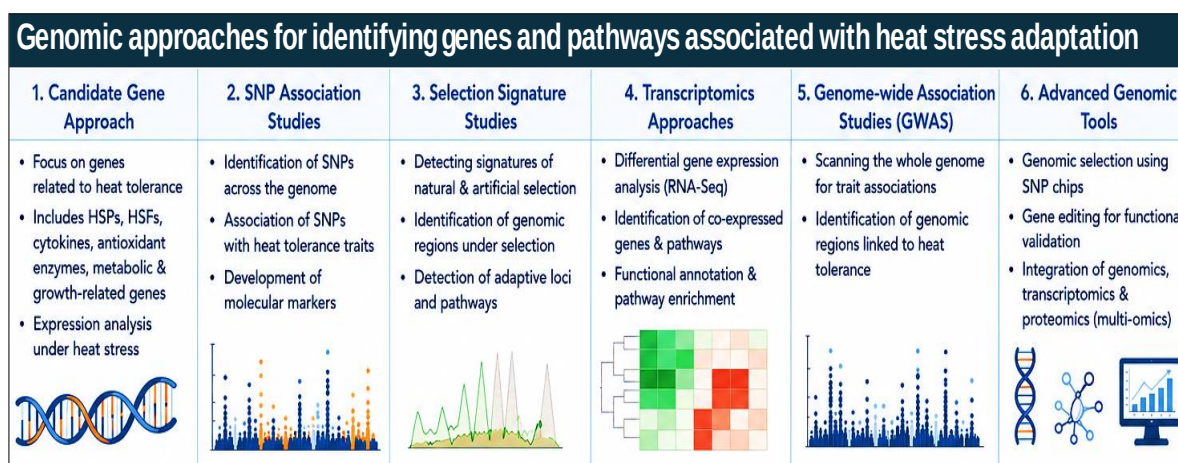


Fig 1: Genomic approaches for identifying genes and pathways associated with heat stress adaptation

6. Future perspectives

Enhancing heat resistance in goats has gained significance in light of the changing climatic conditions. The indigenous goats have valuable adaptive traits that can be used in future breeding programs. Recent advancements in molecular genetics, candidate gene analysis, SNP detection, transcriptomics, and genome editing techniques offer new avenues for identifying the genetic markers linked with heat tolerance. A combination of physiological, molecular, and genomic data could prove to be useful in developing new goat breeds capable of coping with climatic stresses. Nevertheless, additional validation in a larger population is needed before using the markers in breeding programs.

7. Conclusion

Heat stress is among the primary issues that affect goat productivity in the context of climate change. This has an adverse effect on growth, reproduction, lactation, immunity, and productivity. The goats are endowed with various physiological and molecular mechanisms for adaptation to the thermal stress environment. Studies on the candidate genes, molecular pathways, and genomics have enhanced knowledge about the thermotolerance of goats. The indigenous breeds with superior adaptive capacity can be used as an important genetic resource for sustainable livestock production in the hot environment. Thus, integrating conventional breeding with molecular and genomics could help in developing heat-resilient goat populations for future climate conditions.

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