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Review Article

Vulnerability and resilience capacity of livestock production system towards changing climatic scenario

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Abstract

The global livestock sector is undergoing rapid transformation driven by globalization, urbanization, increasing population, and improving standards of living. While these forces present new market opportunities, they simultaneously heighten the sector's exposure to climate-related risks, particularly extreme weather events. Climate change adversely affects livestock production systems through reduced milk yield, shortened lactation periods, impaired fertility, and increased vulnerability to parasites and diseases, with cascading consequences for rural livelihoods dependent on livestock rearing. Understanding the vulnerability, sensitivity, and resilience of livestock production systems is therefore critical for designing effective adaptation policies and interventions. This review systematically synthesizes published literature to examine how climate change affects livestock production systems across diverse agroecological zones, with a focus on vulnerability, sensitivity, resilience, and the adaptation and coping strategies employed by livestock-dependent communities. Key findings indicate that smallholder livestock producers in low-income countries face disproportionately high climate risk, that livelihood diversification and breed substitution are among the most widely adopted adaptation strategies, and that significant knowledge gaps persist regarding long-term resilience outcomes at the community level. By identifying these patterns and priority research needs, this review aims to guide policymakers, development practitioners, and researchers toward evidence-based strategies that support the sustainability of livestock-based livelihoods under a changing climate.

Keywords: Climate impact, Livestock biodiversity, Monogastric animals, Resilience, Sensitivity, Vulnerability

Highlights

- The interplay between vulnerability and resilience in livestock production systems under climate change was critically examined.
- Evidence-based policy frameworks are required to incentivize adoption of climate smart technologies.
- Breed-level resilience should be studied within native breeding tracts to assess adoptive potential.
- Climate change impacts on monogastric animals (chickens, pigs) remain underexplored and require focused research.

INTRODUCTION

Over the last three decades, consumption of meat, milk and eggs in low and middle-income countries has more than tripled (Food and Agriculture Organization of the United Nations [FAO], 2018). The global livestock sector is rapidly changing in response to globalization, urbanization, increasing population and improving living standard. This transformation offers business opportunities for many livestock producers but also introduces risks related to food and nutrition security, animal health and welfare and environmental sustainability. Livestock production systems contribute significantly to food security at multiple levels. At the household level, livestock provides nutritious diets and income. At the community level, the sector generates employment opportunities. At national and global levels, livestock ensures reliable supplies of affordable and safe animal-source foods, which currently account for 39% of protein and 18% of calorie intake worldwide (FAO, 2018). Classification systems for livestock production in developing countries (Thornton et al., 2009) provide useful stratification for modelling growth and off-take (FAO, 2007).

Climate-related extreme events account for nearly a quarter of global agricultural losses, with livestock second only to crops bearing a substantial share of damage (FAO, 2015). Projected scarcity of land and water under changing climatic scenarios will further challenge livestock production (Weindl et al., 2015). Climate change affects livestock both directly and

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indirectly. Direct impacts include reduced productivity due to heat stress and increased energy expenditure for maintaining homeostasis (Upadhyay et al., 2007; Morignat et al., 2014). Indirect impacts arise from reduced feed and forage quality, driven by changes in water-soluble carbohydrates and nitrogen concentrations (Kumar et al., 2015). Although livestock systems are often considered more resilient than crop-based systems (Prasad & Sejian, 2015), sector-specific data on the magnitude and nature of climate impacts remain essential for policy and practice formulation (Seo et al., 2009; Thornton & Gerber, 2010).

Resilience analysis offers a valuable perspective on how farming systems function under climate stress (Urruty et al., 2016) and can inform climate-smart management practices from global to local levels (Bullock et al., 2017). However, research on climate change impacts and adaptation in livestock systems remains fragmented, with limited attention to resilience capacity, particularly at the farmer level. This gap weakens the sector's ability to prepare for future climatic extremes. Studies have documented climate impacts such as droughts (Lacetera, 2018), floods (Lunt, 2012), heat stress (Upadhyay et al., 2012; Singh et al., 2013; Dash et al., 2016), and rainfall variability (Polley et al., 2013). While much of this research emphasizes physiological responses, fewer studies systematically address resilience capacity within livestock production systems. Recent work highlights variation in resilience across systems, species, and regions (Lamichhane et al., 2020), and empirical approaches to assessing vulnerability and resilience are gaining traction (Meuwissen et al., 2019). Therefore, this article synthesizes available knowledge on vulnerability, sensitivity, and resilience of livestock production systems under climate change, identifies research gaps, and highlights pathways for strengthening adaptive capacity.

Vulnerability of livestock production system against climate change

Livestock production systems face both biophysical and social vulnerability under climate change. Biophysical vulnerability arises from reduced feed quality, water scarcity, and increased disease outbreaks, while social vulnerability reflects the socioeconomic conditions, adaptive capacity, and access to resources among farming communities. Importantly, indigenous knowledge often enables farmers to cope with climate variability and risk, but systematic assessment of adaptation options remains necessary to reduce vulnerability and safeguard food security, incomes, and system resilience (Thornton et al., 2007). Several studies have attempted to quantify social vulnerability in livestock systems. For example, Maiti et al. (2014a) developed a "Social Vulnerability to Climate Change Index" for livestock rearers in eastern coastal India, finding that most households fell into medium vulnerability categories, with fewer in high or low categories. Similarly, Maiti et al. (2015) assessed pastoral nomads in Arunachal Pradesh using household-level indicators, showing that adaptive capacity strongly influenced vulnerability profiles. These findings highlight that vulnerability is not uniform but shaped by local socioeconomic and ecological contexts.

District-level analyses further illustrate variation in vulnerability. Using integrated approaches that combine exposure, sensitivity, and adaptive capacity, studies have mapped drought vulnerability in Tamil Nadu (Balaganesh et al., 2020), identifying districts such as Coimbatore as highly vulnerable, while others like Nagapattinam demonstrated stronger adaptive capacity. Such indices provide actionable insights for policymakers, suggesting targeted interventions such as water conservation, farm ponds, and livelihood diversification to reduce drought susceptibility. While these studies provide valuable evidence, the literature remains fragmented and heavily concentrated in specific regions and authorship. Broader incorporation of diverse case studies across species, production systems, and geographies is needed to strengthen understanding. Moreover, concepts such as exposure (degree of climate stress experienced), sensitivity (extent to which systems are affected), and adaptive capacity (ability to adjust and cope) should be consistently applied to ensure comparability across studies. Synthesizing these dimensions can guide the design of short- to medium-term adaptation strategies that enhance resilience of livestock systems under climate change.

Adaptation strategy of livestock production system towards climate change

Adaptation in livestock production is inherently local, shaped by traditional knowledge, scientific expertise, and the socioeconomic context of farmers. Farmers' decisions to adopt strategies in response to climate variability are influenced by social, economic, biophysical, and perceptual factors. Awareness is a critical prerequisite for adoption. For example, a study in India's eastern coastal region found that 37% of livestock rearers demonstrated high awareness of climate change, while 32% and 31% showed medium and low levels, respectively (Maiti et al., 2016).

The majority of respondents had an elevated degree of adoption in crop cultivation practices, next to livestock rearing as well as another farm practices, whereas they have had a modest rate of adoption in fish farming, according to a study on adoption of adaptation strategies among 4 mechanisms: livestock rearing, crop cultivation, fish farming, as well as other farming activities (Dutta et al., 2019). In the other research, researchers (Dutta et al., 2020) used the multi-criteria approach to decision-making capacity (Analytical Hierarchy Process) vis-à-vis adoption of distinct adaptation approaches between Indian Sundarbans' farming community. Among the different adaptation strategies, the more significant 1 has been found to be "Practicing of Integrated Farming System" according to the degree to which one adaptation method is more significant than another. A comprehensive climate change adaptation index for livestock rearers was created in a different study to track the relative significance of various adaptation tactics (Table 1).

Empirical studies illustrate varying adaptation levels. For instance, Dutta et al. (2019) reported higher adoption rates in crop cultivation compared to livestock rearing and fish farming, reflecting differences in perceived benefits and resource availability. Globally, similar patterns are observed: integrated farming and diversification are consistently identified as effective strategies in Africa and Southeast Asia (Thornton et al., 2009; Herrero et al., 2015).

Overall, adaptation strategies must integrate local knowledge with scientific innovation, while policy frameworks should incentivize adoption through financial and technical support. Categorizing strategies into farm-level, system-level, and policy-level approaches provides a clearer understanding of how livestock producers can strengthen resilience under climate change.

Resilience capacity of livestock production system towards climate change

Resilience in livestock production systems refers to the ability of animals and associated system

Table 1. Key adaptation strategies used by livestock farmers

S. No.	Practices	References
1	Farm management practices Feeding management (Dietary alteration, increase in concentration, supplementation of Vitamin E, fat etc., Use of climate resilient fodder variety, UMB etc,)Adjusting feeding regimes and water management to cope with heat stress and resource scarcity. Shed management Modifying housing and microclimate (e.g., improved cow sheds, shading, ventilation, Provision of fan/coolers/misting, Provision of shed during summer and rainy season, Paint the roof with radiating paints)	Deressa et al., 2008; Havlik et al., 2012; Maiti et al. 2014b;
2	Breeding management (Selection of breed according to local environment Use of Artificial Insemination)	Renaudeau et al., 2012 Gerber et al., 2008;
3	Practicing integrated farming systems that combine livestock, crops, and fisheries, which enhance resilience and resource efficiency Diversifying livestock species and breeds to reduce risk from climate variability.	ICF International, 2013
4	Adoption of climate-smart technologies, improved breeding practices, and disease surveillance systems. Access to extension services, credit, and insurance schemes to support adaptive capacity.	Dutta et al., 2020
5	Health management (Isolation of sick animals, Diseases testing programme Vaccination schedule, Deworming)	
6	Waste management (Utilize farm waste for biogas plant composting, Making dung cakes/ vermicomposting, Proper manure pit for storage and treatment of farm waste)	
7	Community and policy-level strategies Collective water conservation measures, such as farm ponds and rainwater harvesting. Development of regional adaptation policies tailored to local vulnerabilities.	Balaganesh et al., 2020

components to maintain essential functions and productivity under adverse climatic conditions. It encompasses both physiological traits of livestock and broader system-level attributes such as social capital, livelihood strategies, and access to resources. At the animal level, resilience indicators include body conformation, hair coat characteristics, sweating rate, tolerance to dehydration, reproductive efficiency, feed utilization, and metabolic stability. These traits determine the capacity of livestock to withstand heat stress, water scarcity, and nutritional fluctuations. At the system level, resilience can be assessed through components such as stability, income and food access, water availability, health services, socio-demographic status, assets, technology utilization, and access to basic services (Eeswaran et al., 2021; Dardonville et al., 2021; Dardonville et al., 2023).

Empirical studies have examined resilience across different production systems. For instance, Thorsoe et al. (2020) analyzed livestock systems, Lamichhane et al. (2020) studied intensive systems, Bell et al. (2021) assessed crop–livestock systems, and Li et al. (2019) focused on diversified systems. However, in situ resilience data remain limited due to the cost and complexity of long-term monitoring. Native livestock breeds are consistently identified as more resilient than exotic breeds because of their physiological and genetic adaptations to local environments (Rojas-Downing et al., 2017). For example, pastoral nomads in Arunachal Pradesh rely on yak and yak–cattle hybrids, adapting migration duration and pasture utilization practices to cope with shifting seasonal cycles (Maiti et al., 2014c). Similarly, drought adaptation indices developed in Bihar (Goswami et al., 2018; Madhusoodan et al., 2019) highlight coping mechanisms such as feeding crop residues, adjusting milking times, providing shade and water, reducing herd size, and selling animals when necessary. Herd size was found to be a critical determinant of coping capacity.

In coastal regions, farmers increasingly depend on resilient small ruminants such as Garole sheep and Black Bengal goats (Sejian et al., 2018). Dairy cows with higher production levels, however, are more vulnerable to heat stress due to greater metabolic heat output (Maiti, 2017). Breeding programs are therefore shifting towards climate-tolerant cattle, incorporating thermo tolerance traits such as rectal temperature and temperature–humidity index (THI) into selection indices (Angel et al., 2018; Rashamol & Sejian, 2018). Developing climate-resilient breeds requires balancing productivity, fertility, and disease resistance while maintaining animal welfare. Identifying genotypes suited to diverse agro-ecological zones and supporting their phenotypic expression is critical (Hoffmann, 2010). Broader resilience strategies also include diversification, crop–livestock integration, irrigation, and sustainable soil management, which collectively reduce production losses and enhance system sustainability (Pretty et al., 2010). Importantly, local and indigenous communities emphasize the need for context-specific strategies to secure livelihoods and build resilience, yet their experiences remain underrepresented in academic and policy discourse (Salick & Byg, 2007; Galloway et al., 2009; Zelalem et al., 2009).

Impact of climate change on livestock production system

Research on the effects of climate change on livestock production has gained increasing attention, though it has received comparatively less focus than studies on crop farming (Herrero et al., 2015). Key impact areas identified in the literature include livestock productivity, reproduction, feed and fodder availability, disease occurrence, soil and water resources, biodiversity, and farming system changes. The Temperature Humidity Index (THI) is a widely used composite measure for quantifying heat stress in livestock, and surpassing its threshold level has been associated with altered animal physiology and increased vulnerability to disease (Salama et al., 2014). The following subsections synthesize documented evidence under each major impact domain.

Impacts on productivity: Heat stress, mediated through elevated THI, is one of the most extensively documented drivers of reduced livestock productivity. Ravagnolo and Misztal (2000) estimated that each unit rise in THI above 72 is associated with a decline in milk yield of 0.2 kg per day. Nardone et al. (2010) further demonstrated that high-producing cattle kept in hot climatic zones exhibit increased metabolic heat production and respiratory rates, ultimately reducing milk output. Milk yield losses vary by lactation stage; losses are less pronounced during mid-lactation compared to early or late lactation. For Murrah buffaloes specifically, milk yield reductions of 10–30% have been recorded during the first lactation and 5–20% during the second and third lactation (Upadhyay et al., 2007). Beyond milk production, heat stress also impairs growth performance (Rhoads et al., 2009; Baumgard et al., 2012), meat production (Archana et al., 2018), and overall feed conversion

efficiency (Hristov et al., 2017). In hot semi-arid environments where livestock are raised extensively, animals face compounding stressors including physical stress from walking, feed and water scarcity, and heat exposure (Sejian et al., 2013). Research on Malpura rams demonstrated that simultaneous exposure to multiple stressors significantly decreases both body weight and body condition score (BCS) (Kumar et al., 2017), a finding corroborated in Malpura ewes by Sejian et al. (2013). Collectively, these findings indicate that the productivity impacts of climate change are multidimensional, operating through direct thermal effects as well as through associated resource scarcity.

Impacts on reproduction: Reproductive performance is profoundly sensitive to thermal stress, with consequences observed across multiple physiological pathways. Gwazdauskas et al. (1973) reported a 12.8% decrease in conception rate for every 0.5°C rise in uterine temperature above normal. Subsequent research has documented a broad spectrum of reproductive impairments under high environmental temperatures, including abnormal gametogenesis, folliculogenesis and ovulation; reduced sexual behavior in both sexes; increased embryonic and pregnancy losses; delayed postpartum recovery; longer calving intervals; and elevated perinatal mortality (Ghosh et al., 2015). In Indian buffaloes, low estradiol levels during estrus in summer have been associated with inadequate heat expression (Thornton et al., 2009).

Heat stress also negatively affects male fertility. Rahman et al. (2013) found that spermatozoa under heat stress showed significantly lower fertilization rates ($p<0.01$) compared to those under normal conditions. In females, heat stress inhibits oocyte growth and maturation (Singh et al., 2013) and elevates circulating prolactin levels, inducing acyclicity and infertility (Alamer, 2011). Notably, an estimated 80% of estrus events may go undetected during summer months (Rutledge, 2001), further compounding reproductive losses. High environmental temperatures additionally elevate the incidence of anestrous and silent heat, while simultaneously shortening and intensifying estrus (Kadokawa et al., 2012; Singh et al., 2013). In Nepal, climate change has been associated with increased infertility and reduced lactation length, with external parasite incidence (43.3%) ranked as the primary livestock health concern in warm temperate zones (Dhakal et al., 2013). Temperature increases exceeding 2°C have also been linked to low or desynchronized endocrine activity along the pineal-hypothalamo-hypophyseal-gonadal axis in unvaccinated buffaloes, further impairing reproductive efficiency (Upadhyay et al., 2012).

Impacts on feed and fodder resources: Both the quantity and quality of feed and fodder are substantially affected by changing climatic conditions. Rising temperatures are directly linked to increased lignification of plant tissues, which reduces the digestibility of forage (Giridhar & Samireddypalle, 2015). This occurs alongside broader shifts in grassland species composition, with potential consequences for biodiversity and animal genetic resources (Thornton et al., 2009). Extreme drought events have further diminished the diversity and availability of palatable grass and fodder species in pasture systems (Digambar, 2011). In arid and semi-arid grazing systems, livestock face year-round fluctuations in water and forage availability, which are among the most visible manifestations of global warming impacts (Rojas-Downing et al., 2017). Water intake in *Bos indicus* cattle has been shown to increase sharply with ambient temperature from approximately 3 kg per kg DM intake at 10°C to around 10 kg at 35°C (Hoffman & Vogel, 2008), placing additional physiological demand on animals already experiencing thermal stress. Taken together, reduced fodder quality, diminished diversity of forage species, and increased water requirements constitute compounding feed-related risks that threaten livestock production under a changing climate.

Impacts on disease occurrence and distribution: Climate change influences animal disease dynamics through both direct and indirect pathways. Direct effects include increased exposure to pathogens and weakened host immunity resulting from heat stress, as well as elevated disease incidence during extreme weather events such as droughts, floods, and cyclones, all of which raise rates of morbidity and mortality in livestock (Joshi et al., 2013; Bett et al., 2017). Indirect effects operate through changes in host resistance, the severity of zoonotic diseases, and the expanded geographic range and abundance of disease vectors and parasites (Gethings et al., 2015).

Documented climate-driven disease events include nematode infections in cattle (Verschave et al., 2016), helminthological infections in ruminants (Van Dijk et al., 2010), and increased incidence of clinical mastitis in dairy cows (West, 2003). Rainfall, temperature, and humidity together accounted for 52% and 84% of the seasonality of Foot and Mouth Disease (FMD) in cattle

in the hyper-endemic region of Andhra Pradesh and the meso-endemic area of Maharashtra, respectively (Ramarao, 1988). Similarly, hot and humid weather conditions have been found to exacerbate tick infestations including *Boophilus microplus*, *Haemaphysalis bispinosa*, and *Hyalomma anatolicum* in cattle (Basu & Bandyopadhyay, 2004). These findings collectively indicate that the disease burden on livestock is likely to intensify and shift geographically as climatic conditions continue to change.

Impacts on biodiversity and genetic resources: Climate change poses significant threats to livestock genetic diversity. FAO (2007) reported that of 3,831 breeds of pig, horse, sheep, cattle, goat, ass, and water buffalo documented in the 20th century, at least 618 had become extinct by its close, while approximately 20% of remaining breeds were considered at risk, with 475 classified as rare. High-yielding livestock breeds in tropical climates are considered the most vulnerable to climate change impacts due to their limited physiological capacity to cope with high temperatures and relative humidity (Gaughan et al., 2008; Martello et al., 2010). In pastoral systems, climate-related disasters such as droughts, floods, and disease outbreaks have led to severe livestock losses, with direct consequences for rural livelihoods. In Yabelo, Borana Zone of southern Ethiopia, households experienced a mean reduction of approximately 80% in livestock holdings over the preceding decade, attributed largely to climate change (Stark et al., 2011). Pastoral communities have been identified as among the most exposed to these disaster risks (Aklilu et al., 2013). In response, rural agrarian populations have developed a wide range of adaptation and coping strategies, drawing on indigenous knowledge accumulated over generations (Mongi et al., 2010).

Morphological adaptations of livestock to thermal stress

Morphological traits play a critical role in determining how effectively livestock exchange heat with their environment through radiation, evaporation, and cutaneous convection (McManus et al., 2009). Coat color is among the most important of these traits: animals with light or white coats can reflect 50–60% more direct solar radiation than those with dark coats, conferring an adaptive advantage under heat stress conditions (McManus et al., 2009). Indigenous breeds such as Tharparkar cattle possess inherent adaptability across thermal seasons; their highly pigmented skin acts as a barrier to direct ultraviolet radiation by blocking its penetration into deeper tissues (Maibam et al., 2014). Additionally, coat length, thickness, and follicle density influence adaptability animals with thin skin, short hair, and fewer hair follicles per unit area are more closely associated with improved heat tolerance in tropical climates (Hoffmann, 2010). These morphological features underscore the value of conserving locally adapted breeds as a biological strategy for sustaining livestock production under future climate scenarios.

Future research directions

Climate change exerts its most profound and wide-ranging effects on livestock production systems through alterations in feed and fodder resources, water availability, and disease dynamics. Rising temperatures reduce both the quantity and quality of forage by increasing lignification of plant tissues and decreasing digestibility and degradation rates. These changes are accompanied by losses in livestock biodiversity, which erode the capacity of communities, particularly those in marginal environments, to adapt to shifting climatic conditions. Animals that are genetically suited to specific or harsh environments are inherently more resilient and productive under such pressures. Consequently, maintaining the genetic diversity of livestock breeds must serve as a foundation for future conservation and improvement initiatives. Strategies addressing climate change, disaster risks, and emergencies should be formulated with this principle as a guiding priority. A review of the existing literature reveals several critical gaps that warrant focused research attention, as outlined below.

Species-specific sensitivity studies in livestock

The majority of published studies on climate change sensitivity have concentrated on crop-based farming systems, with relatively limited representation of livestock and minimal focus on specific species such as cattle, buffalo, sheep, and goat. This is a critical gap, given that livelihoods in developing countries depend substantially on these species. Sector-wise and species-specific analyses of sensitivity and resilience to climate change would facilitate the identification of appropriate indicators for technology intervention and inform the formulation of evidence-based policies tailored to the needs of vulnerable livestock-dependent communities.

Climate resilience in mixed crop–livestock systems

Articles reviewed in the existing literature focus predominantly on crop-based production systems. There is a need for dedicated research on the sensitivity and resilience of mixed crop–livestock production systems to climate change impacts. This integrated production system supports the livelihoods of the majority of rural households in developing regions (Tarawali et al., 2011). Investigations in this domain are likely to have significant implications both for sustaining farmers' livelihoods under changing climatic conditions and for ensuring the long-term sustainability of mixed farming systems.

Bridging the research gap on monogastric livestock

An analysis of reviewed publications reveals that approximately 87% focus on ruminant livestock, with monogastric animals, particularly chickens and pigs, receiving disproportionately little research attention. This gap is significant because pigs and poultry play a critical role for many smallholder farmers in developing nations and regions, as they can be integrated into diverse agricultural systems through mixed and integrated farming approaches. Moreover, local breeds of chicken and pig are characterized by a comparatively higher capacity for climate adaptation, owing to their inherited resilience traits (Kantanen et al., 2015). While the individual economic contribution of monogastric animals may be lower than that of ruminants, their collective importance to household food security and income in developing regions justifies substantially greater research investment.

Breed-level resilience assessment in native agro-climatic zones

Assessing the resilience capacity of a livestock breed within its native breeding tract provides a critical baseline for understanding the adaptive traits that have evolved under specific agro-climatic conditions. This approach is particularly important for climate adaptation research because it enables systematic evaluation of whether superior or improved breeds, when introduced into different agro-climatic zones, retain their productive efficiency or experience reduced performance. This approach is particularly important for climate adaptation research: understanding which breeds maintain productivity, health, and reproductive performance under climatic stress is essential for guiding breed selection, conservation priorities, and the design of climate-resilient livestock improvement programs.

Strengthening conservation of livestock genetic diversity under climate change

The adoption of the Convention on Biological Diversity (CBD) in 1993 represents a foundational global commitment to protecting biodiversity, including the genetic diversity of livestock. However, a survey of threats to cattle genetic diversity (FAO, 2008) found that climate change was identified by stakeholders as only a minor factor within the broader context of land-based production systems. Critically, a large proportion of the stakeholders surveyed did not yet recognize climate change as a significant concern for livestock biodiversity management and conservation. Subsequent research has since confirmed that climate change does pose substantial risks to livestock biodiversity. In light of this evidence, dedicated and urgent efforts are needed to conserve livestock genetic diversity within the context of changing climatic scenarios, including through targeted breed conservation programs, the establishment of gene banks, and the integration of climate risk considerations into national and international animal genetic resource strategies.

Conclusion

This review demonstrates that livestock production systems face compounding and interrelated vulnerabilities under a changing climate. The primary drivers of this vulnerability are thermal stress mediated through elevated Temperature Humidity Index (THI), degradation of feed and fodder resources through reduced forage quality and digestibility, increasing water scarcity, and the expanding range and intensity of disease vectors and pathogens. These stressors do not operate in isolation; their simultaneous occurrence substantially amplifies productivity losses across key performance parameters including milk yield, growth rate, reproductive efficiency, and overall animal health. High-yielding breeds and livestock in tropical and semi-arid regions are disproportionately exposed, while indigenous and locally adapted breeds demonstrate comparatively greater inherent resilience. The erosion of livestock biodiversity further diminishes the biological capital available to communities for long-term adaptation. Resilience assessment is of utmost importance for the strategic design and adoption of climate-resilient livestock systems. Effective adaptation requires a combination of interventions operating at multiple levels: the adoption of climate-smart management practices such as improved housing and modified feeding regimes; the conservation and selective utilization of locally

adapted breeds with demonstrated thermal tolerance; diversification of livestock species to distribute production risk; and the integration of mixed crop–livestock systems to enhance resource efficiency and household income stability. Advances in genomics and breeding technologies offer additional opportunities to accelerate the development of heat-and disease-tolerant breeds, particularly for species and production systems that remain underrepresented in current research, including monogastric livestock and smallholder-oriented systems in developing regions.

Translating these adaptation strategies into practice requires robust policy frameworks and coordinated institutional action. Governments and international organizations must prioritize the integration of climate risk into livestock sector policies, including the mainstreaming of animal genetic resource conservation into national biodiversity and agricultural adaptation plans. Financial and technical support mechanisms should be directed toward the most vulnerable farming communities, with emphasis on improving access to climate information, early warning systems, and extension services. A multi-stakeholder approach engaging farmers, researchers, policymakers, and development organizations is essential for the co-development and dissemination of climate-resilient practices. Addressing the identified research gaps, particularly in species-specific sensitivity analysis, mixed farming systems, and livestock biodiversity conservation, will be critical for generating the evidence base necessary to inform effective and equitable policy responses.

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Author's contribution: RY: Data compilation, data analysis, draft manuscript preparation; SM: Conceptualized the research, data analysis, final manuscript preparation; SG: Reviewed the final manuscript; MKV: Wrote the discussion part of the paper; MB: Conceptualized and reviewed of the final manuscript; GS: Reviewed the final manuscript.

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