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EDITED BY
Fisayo Oretomiloye,
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REVIEWED BY
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University of the Gambia, Gambia
Bessy Kathambi,
University of Nairobi, Kenya

*CORRESPONDENCE
Hameed Akande Bashiru
✉ hbashiru@oauife.edu.ng

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Simplified climate change adaptation strategies for livestock development in low-and middle-income countries

Hameed Akande Bashiru* and Saidu Oyarekhua Oseni

Department of Animal Sciences, Faculty of Agriculture, Obafemi Awolowo University, Ile-Ife, Nigeria

Climate change, characterized by the increased frequency and intensity of extreme weather events, is the greatest environmental challenge threatening global food systems. Its impacts are particularly severe for livestock production systems in developing countries. In low-and middle-income countries (LMICs), livestock production provides critical livelihoods for millions of vulnerable people and plays a significant role in food security. However, the sector is highly susceptible to the adverse effects of climate change. Climate change in LMICs is associated with erratic rainfall, rising temperatures, flooding, drought, desertification, and a higher frequency of extreme weather events. In particular, when temperatures exceed the thresholds projected by the Intergovernmental Panel on Climate Change (IPCC), livestock are subjected to heat stress, which reduces productivity, lowers conception rates, and can be life-threatening for many species. In response, various climate adaptation strategies have been implemented to enhance resilience in livestock production systems. This review evaluates existing adaptation strategies including their effectiveness in LMICs and proposes simplified and targeted adaptation strategies to build resilience in livestock production systems. Key adaptation measures include genetic improvement and diversification of livestock species, early warning systems, precision livestock farming technologies, climate-smart strategies, institutional and policy frameworks and capacity-building initiatives. Further, key factors influencing adaptation strategies outcomes such as governance, financial investment, community engagement, and technological infrastructure were highlighted. While some strategies such as breeding programs for heat-tolerant livestock and early warning systems have yielded positive results, challenges including limited financial resources, weak institutional frameworks, and resistance to change hinder their widespread adoption. The review also provides recommendations for improving adaptation strategies, including enhanced investment in data-enabled innovations, integration of climate adaptation policies into national development plans, and increased participatory approaches involving local livestock farmers. In conclusion, this study provides a roadmap for building climate-resilient livestock production systems in LMICs to ensure sustainable food production and improved livelihoods under changing climate.

KEYWORDS

climate change, livestock production, adaptation strategies, resilience, food security, indigenous breeds, precision livestock farming

1 Introduction

According to FAO (2006) and the World Bank (2020), the global livestock sector contributes 40% of the world's agricultural gross domestic product, employing one to three billion people and providing a livelihood base for about one billion individuals living in poverty. Livestock serves as a critical resource for low-income populations, including pastoralists who rely entirely on livestock, agro-pastoralists who raise crops and livestock, and smallholder farmers who primarily depend on crops but also keep livestock. These groups represent key players in complex and interconnected livestock value chains globally. Further, livestock products are also vital to global food security, contributing 17% of global kilocalorie consumption and 33% of global protein consumption (Rosegrant et al., 2009; Godde et al., 2021; Erdaw, 2023). Despite its substantial contribution to global economic development as highlighted, the livestock sector faces numerous challenges, with climate change being one of the most significant (Rojas-Downing et al., 2017; Cheng et al., 2022). Climate change is characterized by the increased frequency and intensity of extreme weather events, representing the greatest environmental challenge and a global threat to food systems especially in low and middle-income countries (LMICs). LMICs, as of 2024, are classified by the World Bank as nations with a gross national income (GNI) per capita of $4,465 or less (World Bank, 2024). These countries are primarily located in Africa, Asia, Latin America, and parts of the Pacific. They are disproportionately affected by climate change due to high dependence on climate-sensitive sectors, such as agriculture and livestock farming. They are also characterized by limited financial and technological resources to implement large-scale adaptation measures to climate change.

Extreme weather events such as droughts, rising temperatures, heat stress, unpredictable rainfall, and increased flooding are likely to adversely affect livestock production both in the short-term and long-term (Godde et al., 2021; Thornton and Gerber, 2010). For example, during the 2011–2012 period, Mexico experienced its most severe drought in 70 years, leading to substantial declines in livestock populations. Specifically, cattle and goat stocks decreased by approximately 3% across the country (Murray-Tortarolo and Jaramillo, 2019). Further, Mongolia's livestock industry has been recurrently affected by dzud—a climatic phenomenon characterized by harsh winters following dry summers. During the 2009–2010 Dzud crisis, approximately 9,000 families lost all their livestock, with an estimated 17% of the country's livestock perishing (Otani et al., 2015). Further, climate change poses a significant environmental threat not only to crops and animals but also to the entire human race (Thornton, 2010; Abbass et al., 2022). Its effects have serious implications for agriculture, livestock production, ecosystems, water resources, human health, soil quality, and the atmosphere. In many LMICs in the tropics and subtropics, the impacts of climate change are already evident. Weather-related disasters have become increasingly frequent over the past four decades, a trend that is predicted to deteriorate further (Thomas and López, 2015).

In terms of vulnerability, the agricultural sector, particularly the livestock sub-sector, is highly vulnerable to climate variability and extreme weather (Godde et al., 2021; Cervigini et al., 2013; Ayanlade et al., 2022). Depending on the region, climate change can manifest as fewer wet days, heavier rainfall, flooding, rising surface air temperatures, sea-level rise, and accelerated soil erosion. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007) identified many LMICs especially those in sub-Saharan Africa as being most vulnerable to climate change. Associated threats include food and nutrition insecurity, environmental degradation, and exacerbated poverty levels. The report further predicted that the frequency of extreme weather events will continue to aggravate their socio-economic conditions. Projections indicate that global average surface temperatures could rise by 1.8 to 4.0°C by 2,100—significantly higher than temperature increases observed in the last century. These challenges are expected to result in increased mortality and morbidity, further worsening poverty levels among millions of households. For instance, the Horn of Africa experienced an unprecedented multi-year drought from 2020 to 2023 which severely affected many livestock-dependent communities. In particular, the drought led to significant livestock deaths, with reports indicating that approximately 13.2 million livestock perished across Somalia, Ethiopia, and Kenya (Henchiri et al., 2024; Odongo et al., 2025). To mitigate the impacts of climate change on critical livelihood assets such as livestock, a variety of adaptation strategies must be implemented. This review presents a novel synthesis of climate change adaptation strategies specifically tailored for livestock production systems in low-and middle-income countries (LMICs). Unlike previous reviews that primarily discuss general adaptation measures, this study integrates emerging innovations such as precision livestock farming, data-enabled decision-making, and climate-smart genetic improvement programs. Additionally, it critically evaluates the effectiveness of existing strategies by incorporating recent case studies and empirical evidence from LMICs, an area that remains underexplored in climate adaptation literature. A key research gap addressed is the lack of region-specific, practical adaptation frameworks that consider the socio-economic and infrastructural constraints faced by livestock farmers in resource-limited settings. These strategies are intended for implementation by key stakeholders, including government agencies, non-governmental organizations (NGOs), livestock keepers, and other actors in the livestock sector, to mitigate the impacts of climate change on livestock productivity. In this narrative review, we synthesized existing knowledge on climate adaptation strategies for livestock production through qualitative comparison, with a focus on low-and middle-income countries (LMICs). Literature was selected from reputable databases, including Google Scholar, Scopus, Web of Science, and institutional reports from FAO, IPCC, and the World Bank. A thematic analysis approach was used to categorize adaptation strategies into key areas and key findings were presented in tabular format to facilitate structured analysis of adaptation measures, their benefits, challenges, and implementation feasibility.

2 Livestock production and climate change

Climate change can result from both natural and human (anthropogenic) influences (IPCC, 2013; Zheng et al., 2021). Among these, the production of greenhouse gases such as methane, carbon dioxide, water vapor, and nitrous oxide stands out as a major anthropogenic driver. According to IPCC (2013), the primary sources of these gases are the burning of fossil fuels and agricultural activities, including livestock production. The FAO (2006) report highlighted the significant role of the livestock production sector, identifying it as a major threat to environmental sustainability and biodiversity. The sector contributes up to 18% of anthropogenic greenhouse gas emissions—a figure reported to exceed emissions from the entire transport sector (Rojas-Downing et al., 2017). However, this claim has been disputed with estimates lower than this (Kristiansen et al., 2020; Twine, 2021; Scoones, 2022). Regardless of these debates, the livestock sector remains both a contributor to and a victim of climate change.

More than 60 billion land animals are reared and slaughtered annually for human consumption worldwide (FAO, 2020). Furthermore, livestock inventories are expected to double by 2050, with the majority of this growth occurring in developing countries (Steinfeld et al., 2006). As livestock numbers rise to meet increasing demand for meat, milk, and eggs, greenhouse gas emissions from the sector are likely to escalate, further exacerbating climate change and its adverse effects on livestock production, human health, and environmental sustainability. In addition to livestock production, other significant sources of greenhouse gas emissions include fossil fuel combustion, land use changes such as deforestation and desertification, and agricultural practices such as bush burning and fertilizer application (Rojas-Downing et al., 2017).

3 Impact of climate change on livestock production

Climate change has both direct and indirect impacts on livelihoods and livestock production systems in LMICs. Direct impacts include heat stress, flooding, and other extreme weather events that affect livestock assets and food systems (Godde et al., 2021). Indirect impacts extend to the economy, food security, and infrastructure. Valtorta (2009) highlighted four primary pathways through which climate change impacts animal production in tropical regions. Firstly, it reduces the availability of livestock feed-grains, leading to increased prices. Secondly, climate change causes declines in both the production and quality of pastures and forage crops, which are essential for livestock nutrition. Thirdly, it alters the distribution of livestock diseases and pests, potentially exposing animals to new threats. Lastly, extreme weather events directly affect animal health, growth, reproduction, and overall performance, further compounding the challenges faced by livestock producers. These impacts can result in significant adverse consequences for livestock production and yields, which in turn affect human livelihoods. Impaired performance and productivity, high mortality rates, and the loss of animals lead to reduced revenues, increased poverty, and hunger for individuals and communities. Rising global temperatures exacerbate these issues, especially for livestock production. Heat stress impairs livestock performance, reduces productivity, lowers conception rates, and can even be life-threatening (Thornton et al., 2022). Additionally, rising sea levels could flood pastures with saltwater, raising salinity levels and negatively affecting livestock feeds, fodders, forages, and grazing fields. Further, temperature changes may introduce vector-borne diseases, parasite infestations, and the transmission of diseases to new areas previously unaffected by these stressors (Thornton and Herrero, 2008). Addressing these challenges is critical to safeguarding livestock production and the livelihoods dependent on it. Detailed case studies of the impact of climate change on livestock production in LMICs are presented in Table 1.

4 Climate change adaptation strategies for the livestock sector development in LMICs

Adaptation to climate change, as defined by the IPCC (2001), involves adjustments in natural or human systems to actual or anticipated climatic stimuli and their effects, to mitigate harm or capitalize on beneficial opportunities. Adaptive capacity refers to a system's ability to adjust to climate change, including variability and extremes, to reduce potential damages, exploit opportunities, or cope with its consequences. The extent to which agricultural systems including the livestock sector are affected by climate change depends significantly on their adaptive capacity (Thornton and Herrero, 2008). Further, the impacts of climate change vary across regions, with some areas more severely affected than others. Climate change "hotspots" are regions where the effects are expected to be most pronounced. Using the Regional Climate Change Index (RCCI), Giorgi (2006) identified Sub-Saharan and Southern Equatorial Africa as primary hotspots in Africa. The RCCI evaluates regional responses to climate change by considering factors such as changes in mean precipitation, mean surface air temperature, and variability in these elements over time.

Africa's agricultural vulnerability to climate change largely stems from its reliance on rain-fed and underdeveloped farming systems. Most African farmers operate on a small scale, with limited financial resources, inadequate infrastructure, and inconsistent access to information (Thornton et al., 2009). Despite these challenges, the inherent diversity, context specificity, and traditional knowledge within African agricultural systems offer significant resilience to climate change (Thornton et al., 2014). Addressing the threats posed by climate change requires strategies to reduce vulnerabilities and enhance resilience. These adaptation strategies are essential for maintaining or improving livestock productivity in a rapidly changing climate (Herrero et al., 2008). These practices enable individuals and communities to cope with or adjust to climate change impacts (Nyong et al., 2007). In the livestock sector, adaptation measures focus on improving livestock tolerance to heat and their ability to thrive, grow, and reproduce under conditions of poor nutrition, parasites, and diseases exacerbated by climate change (Hoffman and Vogel, 2008). Such strategies are critical for ensuring food and livelihood security for livestock producers. Community-based interventions, like those documented by Oseni and Bebe (2010) in Kenya, have proven effective in building resilience among pastoral communities. Commonly adopted adaptation strategies include the use of emergency fodder during droughts, diversification of herd composition, improved breeding practices, de-stocking to manage heat stress, provision of shade, and supplementary feeding. These measures play a vital role in safeguarding the livelihoods of livestock-dependent communities in the face of evolving climatic conditions.

Adaptation strategies in livestock production systems can be categorized into different levels: herd, communal, national, and regional. At the herd level, strategies are tailored to small-scale livestock keepers and include measures such as documenting and selecting for heat-tolerant breeds, providing shade, and improving feed availability. At the communal level, collective approaches such as shared grazing

TABLE 1 Case studies on the impact of climate change on livestock production in low-and middle-income countries (LMICs).

Country/ Region	Climate change event	Direct impact on livestock	Indirect impact on livelihoods	Affected livestock system	Quantitative data	References
East Africa (Ethiopia, Kenya, Somalia)	Prolonged drought (2020–2023)	Significant livestock mortality due to starvation and dehydration	Increased food insecurity, loss of income, displacement of pastoral communities	Pastoral systems	Approximately 13.2 million livestock deaths across the region	Henchiri et al. (2024) and Odongo et al. (2025)
Sahel Region (Niger, Mali, Burkina Faso)	Recurrent droughts (2018–2022)	Reduced livestock productivity due to inadequate feed and water	Migration of pastoralists to urban areas, increased conflict over resources	Transhumant pastoralism	Decrease in herd sizes by up to 50% in some areas	Igbatayo et al. (2022) and Coly et al. (2023)
Bangladesh	Increased frequency of cyclones (2019–2021)	Livestock injuries and deaths, reduced milk production	Loss of assets, increased vulnerability to poverty	Small-scale dairy farming	Economic losses estimated at $1.5 billion in the agricultural sector	Rahman et al. (2023), Naim et al. (2023), and Islam (2025)
Andean Region (Peru, Bolivia)	Glacier melt and altered precipitation patterns (2015–2020)	Increased incidence of livestock diseases, reduced pasture availability	Decline in traditional livelihoods, food insecurity	High-altitude pastoralism	Reduction in alpaca populations by 30%	Pabón-Caicedo et al. (2020) and Liberman (2021)
Nigeria	Projected climate change impacts	Declining livestock productivity	Long-term GDP decline up to 4.5%, increased food imports, worsened food security	Mixed crop-livestock systems, pastoralism	Projected 20–30% reduction in crop yields long-term GDP decline of up to 4.5%.	Cervigini et al. (2013)
Mexico	Severe drought (2011–2012)	Decrease in cattle and goat populations	Income loss for livestock farmers, increased rural poverty	Extensive livestock farming	Approximately 3% decrease in cattle and goat stocks	Murray-Tortarolo and Jaramillo (2019) and Pérez and Jerez-Ramírez (2023)
Mongolia	Dzud (harsh winter following dry summer) (2009–2010)	Massive livestock mortality	Loss of livelihoods for nomadic herders, increased poverty	Nomadic pastoralism	Approximately 17% of the country's livestock perished; around 9,000 families lost all their livestock	Otani et al. (2015) and Rao et al. (2015)
Brazil (Amazon Region)	Deforestation linked to cattle ranching	Loss of biodiversity, soil degradation affecting livestock forage	Displacement of indigenous communities, conflicts over land use	Extensive cattle ranching	Significant increase in deforestation rates correlating with cattle ranching expansion	Alston et al. (2000) and Skidmore et al. (2021)
India (Rajasthan)	Heatwaves and water scarcity (2010–2015)	Heat stress reducing livestock productivity, increased disease incidence	Decline in household income, increased indebtedness among farmers	Smallholder dairy farming	Milk yield reductions of up to 15% during peak summer months	Ravindra et al. (2024) and Kulhari et al. (2024)
Peru (Andean Region)	Glacier retreat affecting water availability (2000–2010)	Reduced pasture availability leading to lower livestock productivity	Loss of traditional livelihoods, increased migration to urban areas	High-altitude pastoralism	Significant reduction in available grazing land due to shrinking glaciers	Chevallier et al. (2010) and Buytaert et al. (2017)

areas and community breeding programs are emphasized. At the national and regional levels, governments and organizations can implement policies and programs to support sustainable livestock practices and promote resilience to climate change. By employing these simplified strategies, livestock producers can build resilience, increase adaptive capacity, and reduce the impacts of climate change on livestock production systems. These efforts are crucial for ensuring sustainable livelihoods and food security in vulnerable regions. A detailed critical evaluation of these climate change adaptation strategies for livestock production including their benefits, challenges, implementation feasibility, cost implications, stakeholders involved, and scalability are presented in Table 2.

TABLE 2 Critical evaluation of climate change adaptation strategies for livestock production.

Adaptation strategy	Benefits	Challenges	Implementation feasibility	Cost implications	Stakeholders involved	Scalability
Resilience building and diversification of livestock species and breeds	Increases adaptability to climate stress, improves food security, enhances biodiversity	Resistance to change, need for extensive knowledge of suitable breeds, potential market limitations	High feasibility in mixed farming systems	Low to Medium - Costs involve acquiring diverse livestock species and farming systems, but can be offset by improved productivity and resilience	Livestock farmers, breeders, researchers, government agencies	High - Can be scaled across various agro-ecological zones and farm sizes
Early warning systems	Helps mitigate disaster impacts, reduces livestock losses, allows for timely interventions	Requires technological infrastructure, accessibility issues for rural farmers	Moderate feasibility in areas with good network coverage	Medium - Requires investment in meteorological data collection, communication infrastructure, and dissemination systems	Government agencies, meteorological departments, NGOs, local communities	High - Can be expanded to cover large geographic areas, but rural connectivity remains a limitation
Breeding strategies	Develops heat and disease-resistant livestock, enhances productivity and sustainability	Requires long-term investment, limited access to superior genetics in some regions	Moderate feasibility depending on genetic resource availability	Medium to High - Costs vary depending on whether traditional selection or advanced genomic approaches are used	Researchers, breeding organizations, government, farmers	Medium to High - Can be scaled with investments in breeding programs and farmer adoption
Application of science, technology, and innovation in building resilience and adaptation	Enhances efficiency, improves monitoring, and reduces resource wastage	High cost, limited technical expertise, potential lack of infrastructure in rural areas	Moderate to high feasibility with investment in R&D	High - Requires significant investment in research, infrastructure, and technology adoption	Universities, research institutions, private sector, government	High - Can be widely adopted but requires continuous investment in education and infrastructure
Capacity building for livestock keepers	Improves knowledge, enhances adoption of climate-smart practices, empowers local communities	Requires consistent training, potential resistance to new practices, language barriers	High feasibility with proper training programs	Medium - Costs include training materials, expert facilitation, and outreach programs	Government agencies, NGOs, universities, extension workers	High - Can be implemented in various communities with proper stakeholder involvement
Institutional policies for climate-smart livestock systems	Provides regulatory support, enhances sector-wide resilience, ensures long-term sustainability	Bureaucratic hurdles, policy inconsistency, limited enforcement capacity	Moderate to high feasibility with political will	Medium to High - Costs depend on policy development, implementation, and enforcement structures	Government, policymakers, international organizations	High - Policies can be adapted across national and regional levels
Precision livestock farming and data-enabled innovations for climate change adaptation	Real-time monitoring, data-driven decision-making, improves livestock management efficiency	High initial costs, requires technical knowledge, dependence on stable internet infrastructure	Moderate feasibility in rural areas, high feasibility in developed regions	High - Requires investment in IoT devices, software, and digital infrastructure	Private sector, research institutions, tech companies, large-scale farmers	Medium to High - More feasible for commercial farms but can be adapted for small-scale farmers with supportive policies

4.1 Short-term adaptation measures

Short-term adaptation measures are immediate, reactive interventions aimed at reducing the negative impacts of climate variability and extreme weather events on livestock production. These strategies are cost-effective, require minimal infrastructure investment, and are critical for preventing sudden losses in productivity and livestock mortality. The following short-term measures can help livestock farmers mitigate climate-induced stress and maintain productivity.

4.1.1 Resilience building and diversification of livestock species and breeds

To enhance resilience and mitigate the impacts of climate change, livestock farming systems in LMICs must adopt alternative options and strategic adjustments. One effective approach that could be adopted is the introduction of mixed farming systems, where farmers integrate crop and livestock production. Mixed farming systems often yield higher overall productivity due to complementary resource use (Sujatha and Bhat, 2015; Low and Meuwissen, 2023). Farmers also benefit from multiple income streams, which improve financial stability and food security. Furthermore, mixed species systems contribute to ecosystem health by maintaining ecological balance and enhancing biodiversity. Mixed farming also promotes nutrient cycling, as crop residues can be used as livestock feed, and livestock manure can enhance soil fertility. Additionally, providing shaded areas can reduce heat stress impacts on livestock, thereby improving their productivity and welfare. Moreover, enhancing livestock management through improved feeding regimes, effective disease control, and better reproductive management is essential for maintaining productivity under stressful conditions. Further, adjusting stocking rates helps prevent overgrazing by modifying the number of animals per unit area, ensuring sustainable pasture use. Implementing rotational grazing systems also allows pastures to recover, maintaining both the availability and quality of forage all-year. At the national level, coordinated guidelines for livestock production adjustments should be established. These standards should reflect the vulnerability and adaptive capacity of each community, ensuring that interventions are context-specific and sustainable. In addition, the development and implementation of climate-smart feed strategies are essential for enhancing feed efficiency and reducing greenhouse gas (GHG) emissions. These strategies include the use of specific feed additives and formulations. Additives such as tannins (Cardoso-Gutiérrez et al., 2021), seaweed extracts (McGurrin et al., 2023), and essential oils (Benetel et al., 2022; Jiménez-Ocampo et al., 2022) have been shown to mitigate methane emissions from ruminants. Precision feeding techniques also play a crucial role by optimizing nutrient intake, thereby reducing waste and environmental impact (Llorens et al., 2024). Additionally, utilizing locally available feed resources, such as crop residues and agro-industrial by-products, can decrease reliance on imported feed, lowering both costs and emissions. Effective manure management techniques through anaerobic digestion and compositing are also vital for reducing emissions and recycling nutrients (Chadwick et al., 2020; Dadrasnia et al., 2021). Anaerobic digestion captures methane from manure and convert it into biogas for energy production (Jameel et al., 2024). Composting, when properly managed, stabilizes nutrients, reduces methane emissions, and produces organic fertilizer. Biogas production systems not only help in emission reduction but also provide renewable energy for farm operations. Incorporating renewable energy into livestock farming systems could potentially reduce the carbon footprint. Solar-powered water pumps, for instance, offer a reliable water source for livestock in remote areas while reducing dependence on fossil fuels. Wind energy systems, through small-scale wind turbines, can power essential farm equipment, supporting sustainable operations. Additionally, bioenergy production from livestock manure and other organic waste helps reduce waste and provides clean, renewable energy.

Diversification of livestock species and breeds is an essential adaptation strategy to mitigate the impacts of climate change on livestock production systems. By keeping more than one species of livestock, farmers can generate a wider variety of livestock products and make better use of available forage in different seasons even in times of crisis. Diversification also mitigates risk by reducing the likelihood of total production failure, as species respond differently to climatic shocks. Examples of diversification practices include multi-species grazing systems, where cattle, sheep, and goats are integrated to optimize forage use and enhance productivity (Tohiran et al., 2023; Slayi and Jaja, 2024). Another practice involves integrating poultry farming with aquaculture, where chicken manure is used to enhance pond productivity (Njoku and Ejiogu, 1999; Shoko et al., 2019). A summary of proposed production adjustments in various livestock systems for climate change adaptation is presented in Table 3.

4.1.2 Early warning systems

Swift responses to perceived threats to livestock are crucial in building resilience and reducing their vulnerability (LEGS, 2014). Prompt interventions, such as relocating animals from affected areas during emergencies like floods and droughts, can significantly help in preserving key livestock assets. The specific intervention required depends on the nature of the emergency, the local context, and the phase of the emergency—whether it is ongoing, in the immediate aftermath, or during recovery or rehabilitation phases (FAO, 2016). The Livestock Emergency Guidelines and Standards (LEGS, 2014) offer comprehensive guidelines aimed at protecting and rebuilding the livestock assets of crisis-affected communities. These guidelines are designed with a focus on livelihoods objectives, providing rapid assistance to support communities in distress. LEGS is particularly valuable for a wide range of stakeholders, including donors, program managers, technical experts, NGOs, policy and decision-makers, educational institutions, and community-based organizations. It helps in identifying the most appropriate livestock interventions during disasters. Typical livestock interventions include the provision of animal health services, emergency feeding and water supplies, and shelter. Additionally, strategies such as destocking help manage livestock numbers during crises, while restocking efforts aim to rebuild herds post-crisis (FAO, 2016). It is crucial to prioritize adaptation efforts in communities where vulnerabilities are highest and the need for resilience is greatest. By focusing resources and efforts on these communities, interventions can be more effective in mitigating the impacts of emergencies and fostering long-term resilience.

4.2 Long-term adaptation measures

Long-term adaptation measures focus on sustainable, proactive strategies that enhance the resilience and productivity of livestock systems in the face of climate change. Unlike short-term interventions, these strategies require systematic planning, investment, and policy support but provide lasting benefits by reducing vulnerability, increasing efficiency, and ensuring food security. The key long-term adaptation measures include the following.

TABLE 3 Proposed production adjustments in various livestock systems for climate change adaptation.

Type of adjustment	Target livestock	Adjustment details	Objective	Possible outcomes/ Impact	Reference (s)
Rotational Grazing	Ruminant animals including cattle, sheep, and goats	Planned grazing schedules to allow pasture recovery and reduce overgrazing.	Ensure sustainable pasture use and reduce degradation.	Improved forage availability, increased livestock productivity, reduced soil erosion.	DeLonge and Basche (2017) and Henry et al. (2018)
Herd reduction	Pastoral livestock systems	Reduced herd sizes during prolonged droughts to match resource availability.	Minimize livestock mortality during resource scarcity.	Reduced herd losses, improved remaining livestock health and productivity.	Speranza (2010)
Shade provision	Ruminant animals	Constructed artificial shade structures and planted trees around grazing areas.	Mitigate heat stress in dairy cattle.	Increased milk yield, improved welfare, and reduced heat-related mortality.	Sullivan et al. (2011) and Masters et al. (2023)
Mixed farming systems	Smallholder farms (crops and goats)	Integrated goat farming with crop production; used crop residues as feed and manure as fertilizer.	Diversify income sources and optimize resource use.	Improved household income, enhanced soil fertility, and reduced feed costs.	Herrero et al. (2010), Thornton and Herrero (2014), and Thornton and Herrero (2015)
Intensive pasture management	Cattle	Introduced rotational grazing and reseeding of degraded pastures.	Enhance pasture productivity and mitigate overgrazing impacts.	Increased pasture biomass, improved livestock productivity, and carbon sequestration.	Rust (2018)
Agroforestry integration	Beef cattle	Incorporated trees into pasturelands to create silvopastoral systems.	Improve microclimates for livestock and enhance carbon storage.	Reduced heat stress, increased weight gain, and higher carbon sequestration rates.	Matocha et al. (2012) and Quandt et al. (2023)
Stocking rate adjustment	Sheep and goats grazing systems	Reduced stocking rates during drought to balance grazing pressure with pasture regrowth.	Prevent overgrazing and maintain pasture quality.	Improved pasture recovery and sustained livestock productivity.	Savian et al. (2021)
Renewable energy integration	Livestock farms	Installed solar panels to power ventilation and lighting systems in livestock houses.	Reduce reliance on fossil fuels and lower carbon footprint.	Lower energy costs, reduced GHG emissions, and improved energy efficiency.	Aroonsrimorakot et al. (2021)
Nutritional modification	Poultry	Inclusion of vitamin C and E in feed and water to ameliorate heat stress.	Enhance the antioxidant defense system to reduce oxidative stress caused by heat stress and improve physiological adaptation to high environmental temperatures.	Improved antioxidant status, better thermoregulation, improved performance, increased survival rates and economic benefits.	Abidin and Khatoon (2013) and Wasti et al. (2020)
Housing system change	Poultry	Transition from battery cages to enriched cage systems with perches, nesting boxes, and scratching areas.	Improve bird welfare and comply with animal welfare regulations.	Improved bird welfare, increased egg production quality, and consumer acceptance; potential for higher production costs.	Tactacan et al. (2009) and Renaudeau et al. (2012)
Alternative feed resources	Poultry	Use of insect-based protein (e.g., black soldier fly larvae) as a replacement for soybean meal in diets.	Reduce feed costs and dependency on conventional feed resources.	Improved sustainability, reduced feed costs, and comparable production performance to conventional feeds.	Khan (2018) and Belhadj-Slimen et al. (2023)

4.2.1 Breeding strategies

Breeding strategies play a pivotal role in enhancing the resilience and productivity of livestock under the increasing pressures of climate change. Significant differences in adaptation exist between livestock breeds and even within breeds, enabling targeted selection and improvement to meet specific environmental challenges. Indigenous livestock breeds are typically more adapted to changing climates (Ahlawat et al., 2015; Mathew and Mathew, 2023). They also have lower feed requirements and can efficiently utilize low-quality pasture and feeds (Ateş et al., 2014). Thus, identifying and strengthening local breeds that have adapted to local climatic stress and feed sources is key to breeding for resilience and adaptation to extreme climatic conditions (Rojas-Downing et al., 2017). For example, breeds such as the Red Maasai sheep (Radeny et al., 2022) and East African shorthorn zebu (Ayalew et al., 2023) demonstrate inherent resilience to harsh climates and diseases. These traits make them invaluable in breeding programs aimed at enhancing climate resilience. Breeding strategies that focus on resilience to heat stress and diseases are especially crucial to adapt to climate change. For example, the development of heat-tolerant cattle breeds, such as the Bonsmara in South Africa (Fedrigo et al., 2021), has shown success in improving resilience to high temperatures and disease resistance. Therefore, designing breeding programs that incorporate adaptation as a major breeding goal could potentially lead to progenies that are hardy, suitable, and well adapted to climate variability. Vulnerable stocks can also be improved through cross-breeding with more adapted breeds. At the herd level, breeding strategies could involve documenting and identifying stocks that have adapted to changing climates and whose performance and productivity are least affected by climate change impacts for breeding purposes. At the communal level, options for nucleus or community-based breeding programmes (CBBPs) should be explored. CBBPs have been utilized over the years under low-input systems in developing countries with considerable success for improving productivity and adaptation (Olaniyan et al., 2024). For instance, the productivity of the indigenous Djallonke sheep was improved in an open nucleus breeding scheme in Ivory Coast (Yapi-Gnaore et al., 1997a; Yapi-Gnaore et al., 1997b). Similarly, Abdel-Salam et al. (2010) reported high genetic gain in milk production of Egyptian Buffalo in open nucleus breeding scheme. Similarly, CBBPs for smallholder farmers in Liberia have resulted in genetic improvements for Liberian goats (Karnuah and Dunga, 2018). These models can be replicated in other regions to enhance climate resilience. Further, these showed that nucleus or community breeding schemes represent unique opportunities for genetic improvement of livestock at the communal level for adaptation to climate change impacts (Shrivastava et al., 2018). At the national and regional levels, investment and collaborative efforts are needed to design and implement breeding programs that incorporate adaptation as a major goal. Additionally, there should be investment in biodiversity conservation. Developing regional gene banks for animal genetic resource conservation can improve breeding programs and serve as an insurance policy against the erosion of valuable indigenous genetic resources. A summary of case studies of how indigenous livestock breeds could enhance resilience and adaptation to climate change is presented in Table 4.

4.2.2 Application of science, technology, and innovation in building resilience and adaptation

The Federal, State, and Local Governments in LMICs must make investments in scientific research and development for climate change adaptation. Advancing science and technology is a fundamental requirement for developing effective management strategies to cope with the anticipated impacts of climate change. Both basic and applied research in areas such as breeding and genetics, biotechnology, molecular biology, animal nutrition, pasture and range management, and animal health are essential. These fields will enhance our understanding of the expected impacts of climate change on livestock systems and help devise strategies to reduce their vulnerability. For instance, Oseni (2018) highlighted significant gaps in the application of science, technology, and innovations (STI) in the management of indigenous livestock resources across Eastern, Southern, and Western Africa through the EU-funded iLinova program. One notable area is the development of alternative livestock production systems, such as pasture-based systems, which reduce feed costs by incorporating natural supplements like insects and grasses (Sanusi and Oseni, 2020; Oseni and Bashiru, 2022). Additionally, the use of unconventional feedstuffs and kitchen waste as alternative feed sources has been shown to sustain livestock productivity without adverse effects. The program also emphasized the importance of regional collaboration for the institutionalization of STI in managing indigenous livestock. Such collaborations foster knowledge sharing, resource pooling, and the development of region-specific solutions to common challenges. By prioritizing research and innovation in these areas, a more resilient livestock sector that is better equipped to withstand the pressures of climate change could be attained in LMICs. This will not only protect livelihoods but also contribute to food security and sustainable agricultural development.

Government-led investments in science, technology, and innovation have been demonstrated as effective strategies for enhancing climate adaptation in LMICs. For example, in Bangladesh, the government has implemented the Bangladesh Climate Change Strategy and Action Plan (BCCSAP) to address the increasing threats of flooding and cyclones (Reid et al., 2012; Islam et al., 2013; Akon and Mia, 2024). Further, in Kenya, the Kenya Climate Smart Agriculture Strategy (KCSAS) promotes drought-resistant crop varieties and water-efficient irrigation technologies to mitigate erratic rainfall and prolonged droughts (Kenya Climate Smart Agriculture Strategy, 2025; Waaswa et al., 2024). In Ethiopia, the Sustainable Land Management Program (SLMP) has focused on soil and water conservation, reforestation, and agroforestry to combat land degradation and drought (World Bank, 2020; Schmidt and Tadesse, 2019). Detailed case studies of these investments including their impacts are presented in Table 5.

4.2.3 Capacity building for livestock keepers

There is an urgent need to enhance the capacity of livestock keepers and herders to understand and address the impacts of climate change on livestock production. Mobilizing various local and agrarian communities for climate change adaptation actions is critical to mitigating the adverse effects on key sectors and vulnerable populations. This mobilization should focus on implementing practical strategies and interventions that directly address the challenges posed by climate change. One crucial area for improvement is providing adequate training in heat stress management and fodder production. These skills are essential for ensuring a consistent supply of animal feed, which helps reduce malnutrition and mortality in herds. By equipping livestock producers with the knowledge and tools to manage heat stress and maintain fodder supplies, the resilience of livestock systems can be significantly improved. Strengthening the existing capacities of local authorities, civil society organizations, and the private sector is equally important. This capacity-building effort lays the groundwork for robust climate risk management and facilitates the rapid scaling up of adaptation measures through community-based risk reduction and effective local governance (Nyong et al., 2007). Enhancing these capacities ensures that communities are better prepared to respond to climate-related challenges and can implement sustainable adaptation strategies. For example, the Livestock and Climate Solutions Hub (ILRI, 2025) developed by the International Livestock Research Institute is a platform designed to support LMICs in transitioning to sustainable,

TABLE 4 Case studies of indigenous livestock breeds enhancing resilience and adaptation to climate change.

Country	Livestock breed	Specific traits	Key information	Reference(s)
Kenya	Red Maasai Sheep	Tolerance to endoparasites (e.g., gastrointestinal worms) Drought resistance	Used in crossbreeding programs to enhance parasite resistance in exotic sheep breeds.	Baker et al. (2003) and Baker et al. (2004)
Ethiopia	Boran Cattle	Heat tolerance - Disease resistance (e.g., tick-borne diseases) Efficient feed utilization	Boran cattle are integral to low-input systems and are being improved through selective breeding for milk and beef traits.	Haile et al. (2011) and Katiyatiya et al. (2017)
Nigeria	West African Dwarf Goat	Tolerance to trypanosomiasis Small size suitable for limited grazing areas	Central to smallholder farming systems for meat and milk production under low-resource settings.	Oseni et al. (2017)
Ivory Coast	Djallonke Sheep	Heat and humidity tolerance Resistance to gastrointestinal nematodes	Improved through an open nucleus breeding scheme to increase productivity without losing adaptability.	Yapi-Gnaore et al. (1997a) and Yapi-Gnaore et al. (1997b)
South Africa	Nguni Cattle	Tolerance to extreme temperatures Resistance to tick-borne diseases	Highly valued for extensive grazing systems and as a genetic resource for climate resilience.	Bayer et al. (2004), Mapiye et al. (2009), and Katiyatiya et al. (2017)
Zimbabwe	Mashona Cattle	Adaptation to semi-arid conditions Efficient use of poor-quality forage	Used in community breeding schemes to improve productivity and maintain adaptability traits.	Nyamushamba et al. (2016) and Tavirimirwa et al. (2019)
Liberia	Liberian Dwarf Goat	Heat tolerance Resistance to common local diseases	Improved productivity through community-based breeding programs (CBBPs).	Karnuah and Dunga (2018)
India	Gir Cattle	Heat tolerance High milk yield under tropical conditions	Gir cattle are extensively used in crossbreeding programs to develop high-yielding dairy breeds for tropical climates.	Patbandha et al. (2020) and Parikh et al. (2024)

climate-smart systems. This hub could potentially be used as a template to build and strengthen the capacity of stakeholders in livestock production in LMICs. The Hub aims to accelerate practical solutions to the challenges posed by climate change to livestock production. This initiative focuses on developing and scaling climate-smart livestock innovations, enhancing resilience and productivity, and guiding countries in meeting their climate goals under the Paris Agreement.

Exploring opportunities for grantsmanship in capacity building for climate change adaptation is another critical avenue. Grants from developed countries can play a significant role in not only building the human capacity necessary to address climate change impacts but also in fostering resilience, improving infrastructure, and raising the standard of living for livestock keepers. These grants can support training programs, infrastructure development, and the adoption of innovative practices that help communities adapt to the changing climate and safeguard their livelihoods.

4.2.4 Institutional policies for climate-smart livestock systems

Strengthening institutional and policy frameworks is critical for enhancing the adaptive capacity of the livestock sector in the face of climate change (USDA, 2013). Effective policies provide a structured approach to implementing adaptation strategies, fostering resilience, and ensuring long-term sustainability. Enacting favorable legislation, subsidies, grants, and insurance schemes can support livestock keepers in adopting climate-smart practices, mitigate financial risks, and secure their livelihoods. For example, in Malawi, the government has integrated Climate-Smart Agriculture (CSA) into national policies to enhance agricultural resilience (World Bank, 2025). This integration includes promoting sustainable land management practices and supporting livestock keepers in adopting climate-resilient strategies. However, in Uganda, efforts to implement climate change adaptation policies in the livestock sector have faced institutional challenges (Ampaire et al., 2017). This highlights the need for coherent policy frameworks and effective institutional coordination to support livestock keepers in adapting to climate change. A well-defined "Climate Change Adaptation Strategy for the Livestock Sector" should be developed to serve as a guiding framework for national, regional, and local governments, as well as research institutions and private stakeholders. This strategy should outline specific actions, allocate resources, and establish measurable goals to ensure effective implementation of climate adaptation initiatives. Integrating climate-smart principles into agricultural policies will not only support livestock resilience but also promote sustainable land use and resource conservation.

The Climate-Smart Agriculture (CSA) approach provides a comprehensive framework for adaptation and mitigation within the livestock sector (Lipper and Zilberman, 2017). By optimizing resource use and reducing greenhouse gas emissions, CSA strategies enhance productivity while minimizing environmental impact (Sekaran et al., 2021; Jalón et al., 2016). Key interventions include precision breeding for resilience, improving feed efficiency, and promoting integrated crop-livestock systems. The adoption of water-efficient irrigation methods, enhanced pasture management, and afforestation programs further contribute to sustainability. A critical component of

TABLE 5 Case studies on government investments in STI for climate adaptation in LMICs.

Country	Climate challenge	Government investment initiative	Science, technology, and innovation (STI) applied	Impact on resilience and adaptation	Quantitative data	Reference
Bangladesh	Frequent flooding and cyclones	Implementation of the Bangladesh Climate Change Strategy and Action Plan (BCCSAP)	Development of climate-resilient infrastructure, such as elevated roads and cyclone shelters	Enhanced community resilience to climate-induced disasters	Over 2,500 cyclone shelters constructed, serving approximately 5 million people	Reid et al. (2012), Islam et al. (2013), and Akon and Mia (2024)
Kenya	Drought and erratic rainfall affecting agriculture	Launch of the Kenya Climate Smart Agriculture Strategy (KCSAS)	Promotion of drought-resistant crop varieties and water-efficient irrigation technologies	Improved food security and farmer livelihoods	Adoption of climate-smart practices by over 600,000 farmers	Kenya Climate Smart Agriculture Strategy (2025) and Waaswa et al. (2024)
India	Water scarcity and heatwaves	National Initiative on Climate Resilient Agriculture (NICRA)	Development of heat-tolerant crop varieties and water-saving technologies	Increased agricultural productivity under climate stress conditions	Yield improvement of 15–20% in stress-prone areas	Venkateswarlu et al. (2013) and Singh et al. (2022)
Ethiopia	Land degradation and drought	Sustainable Land Management Program (SLMP)	Application of soil and water conservation techniques, reforestation, and agroforestry practices	Restoration of degraded lands and improved agricultural productivity	Rehabilitation of over 2 million hectares of land	World Bank (2020) and Schmidt and Tadesse (2019)
Vietnam	Sea-level rise and salinity intrusion	Mekong Delta Plan for Climate Resilience	Construction of salinity intrusion monitoring systems and development of salt-tolerant crop varieties	Protection of agricultural lands from salinity and maintenance of crop yields	Salinity intrusion reduced by 60% in targeted areas	Du et al. (2022) and Hills to Ocean (2023)
Rwanda	Soil erosion and irregular rainfall	Rwanda Climate Change and Low Carbon Development Strategy	Implementation of terracing, rainwater harvesting, and agroforestry	Enhanced soil fertility and water availability for agriculture	Soil erosion reduced by 50% in implemented areas	National Strategy on Climate Change and Low Carbon Development for Rwanda (2011)

climate-smart policies is the promotion of sustainable land management and biodiversity conservation. Encouraging agroforestry, rotational grazing, and pasture rehabilitation can help restore degraded lands, enhance carbon sequestration, and improve livestock productivity. Additionally, leveraging data-driven innovations, such as remote sensing and predictive modeling, will enable better decision-making in climate risk management. To ensure the successful implementation of climate-smart policies, multi-stakeholder collaboration is essential. Governments, research institutions, the private sector, and civil society organizations must work together to develop and enforce policies that support climate adaptation. Providing financial incentives for sustainable practices, investing in early warning systems for climate-related risks, and fostering regional cooperation will further strengthen resilience in the livestock sector. By embedding climate adaptation strategies within national policies and leveraging innovative agricultural practices, LMICs can build a more resilient livestock industry, ensuring food security and sustainable development amid evolving climate challenges.

4.2.5 Precision livestock farming and data-enabled innovations for climate change adaptation

The rapid advancements in technology offer unprecedented opportunities to transform livestock production and make it more adaptive and resilient to the impacts of climate change. Precision livestock farming (PLF), coupled with data-enabled innovations, provides tools to monitor, manage, and optimize livestock production systems in real-time. These innovations enhance decision-making, improve resource use efficiency, and mitigate the adverse effects of climate variability (Pardo et al., 2022; Papakonstantinou et al., 2024). One of the most promising developments in PLF is the deployment of Internet of Things (IoT)-enabled sensors, which are cost-effective and scalable for use in low-resource settings. These sensors provide continuous monitoring of key environmental and animal health parameters, enabling farmers to track temperature, humidity, and other climatic variables within livestock housing systems. For instance, early detection of heat stress conditions allows farmers to implement cooling measures such as misting or ventilation adjustments (Islam et al., 2021). Further, Oseni et al. (2025) utilized low-cost IoT sensors to monitor environmental parameters, such as temperature, humidity and noxious gases, for optimal health and welfare of broiler chickens raised under tropical conditions in Nigeria. In addition, wearable sensors on livestock can monitor physiological metrics such as heart rate, body temperature, and activity levels (Neethirajan, 2017; Alipio and Villena, 2023). These data help detect early signs of illness, or heat stress, enabling timely interventions. Furthermore, sensors can also be integrated into feed bins that can measure feed intake in real-time (Shelley et al., 2016; Gonzalez et al., 2018), allowing precise adjustments to meet nutritional requirements while minimizing waste and greenhouse gas emissions. IoT devices can also monitor water quality and consumption, ensuring that livestock have access to clean water, especially during periods of drought or extreme heat.

Data collected through IoT sensors are analyzed using advanced analytics and machine learning algorithms to provide actionable insights for farmers. Decision support systems (DSS) built on these platforms can be applied for weather forecasts (Ahmad and Hossain, 2019) and historical climate data integrated with livestock performance metrics can predict risks such as heatwaves or disease outbreaks (Bett et al., 2017) to help farmers plan preventive measures. In addition, DSS tools can recommend optimal stocking densities, grazing schedules, and rotational grazing practices based on real-time pasture conditions. Data on animal performance and genetic traits can also guide selective breeding efforts to develop heat- and disease-tolerant livestock. However, while PLF and IoT innovations hold great promise, challenges such as high initial costs, limited internet connectivity in rural areas, and low technical expertise among farmers must be addressed. Governments, NGOs, and private sector stakeholders should collaborate to provide subsidies and financial incentives for adopting PLF technologies, invest in infrastructure to improve internet access in rural areas and organize training programs to build farmers' capacity to use these technologies effectively. Furthermore, IoT-enabled systems can be powered by renewable energy sources, such as solar panels, to ensure sustainability in regions with limited access to electricity. For instance, solar-powered water pumps and ventilation systems can be automated based on sensor inputs, reducing dependency on fossil fuels while ensuring animal welfare.

5 Analysis of climate change adaptation strategies and challenges in their implementation

5.1 Comparative analysis of climate adaptation strategies in livestock production: key factors for success

Climate adaptation strategies in livestock production vary widely across regions, with differing degrees of success. These strategies are influenced by financial resources, community engagement, technical support, and environmental conditions. Therefore, analyzing these strategies provides valuable insights into the critical factors determining their effectiveness. A major determinant of success is technical and financial support. For example, silvopastoral systems (SPS) in Montería, Colombia, achieved success due to the integration of innovative grazing techniques, financial investment, and technical expertise, which enhanced pasture growth and improved carbon sequestration (Rivera et al., 2019; Chará et al., 2017). Similarly, breeding improvement programs in Northern Kenya benefited from structured training, favorable environmental conditions, and community participation, leading to increased productivity (Ojango et al., 2023). In contrast, adaptation strategies such as destocking during droughts in Namibia failed due to low herd sizes, unfavorable market conditions, and cultural barriers (Siririka et al., 2025). Another key factor is community engagement and acceptance. Disease management training in Northern Kenya was successful due to the active participation of pastoral communities and the integration of veterinary services, resulting in improved livestock health (Ojango et al., 2023). Conversely, climate-resilient livestock housing in Bangladesh failed due to high maintenance costs and low farmer adoption, leading to 40% of shelters being abandoned (Rahman, 2022). Institutional and policy support also plays a crucial role. Water management strategies in Namibia had mixed success, highlighting the need for stronger government support and financial assistance (Siririka et al., 2025). Similarly, climate change adaptation efforts in Northeastern Iran were hindered by regulatory weaknesses and inadequate insurance mechanisms, emphasizing the necessity of comprehensive policy frameworks (Sharafatmandrad et al., 2024). Finally, technology integration has shown promising results. Mobile climate advisory services in Uganda effectively reduced livestock losses and increased farm income through real-time weather and market information, facilitated by strong mobile network infrastructure and public-private partnerships (Tuheirwe-Mukasa et al., 2019). A detailed summary of these strategies and their effectiveness is presented in Table 6.

5.2 Challenges in implementing climate change adaptation strategies in LMICs

Several challenges hinder the effective implementation of climate change adaptation strategies. A primary challenge is limited financial resources which significantly impede the adoption of adaptation measures. Many LMICs struggle to allocate sufficient funds for climate initiatives due to competing development priorities. According to Nelson et al. (2016), high poverty levels and limited access to education in LMICs can reduce the capacity of communities to adopt new adaptation strategies. Limited research and development capacity in LMICs also restricts the generation of context-specific adaptation solutions (Obe et al., 2025). This knowledge gap hinders the development and implementation of effective strategies. Furthermore, as noted by Biesbroek et al. (2013), weak institutional frameworks and governance structures also obstruct the coordination and execution of adaptation policies in LMICs. Challenges such as bureaucratic inefficiencies and lack of clear mandates often lead to ineffective adaptation efforts. In addition, inadequate integration of climate adaptation into national policies and development plans can result in fragmented efforts (Lee et al., 2022). Limited access to technology and technical expertise required for some strategies such as data-enable innovations pose significant challenges. Timely response of communities in LMICs climate risks is also limited due to insufficient access to climate information and early warning systems (Guja and Bedeke, 2024). In addition, traditional beliefs and resistance to change can hinder the acceptance of new adaptation practices especially if cultural norms conflict with proposed strategies (Masud et al., 2017). Further, market failures, such as lack of access to credit and insurance, can deter investments in adaptation while geographical challenges, such as susceptibility to natural disasters, can limit the feasibility of certain adaptation strategies. Addressing these challenges requires a multifaceted approach, including strengthening institutional frameworks, enhancing financial mechanisms, improving access to information and technology, and fostering community engagement. Tailored strategies that consider local contexts and actively involve

TABLE 6 Comparative analysis of climate adaptation strategies in livestock production across different regions.

Adaptation strategy	Country/ Region	Implementation approach	Success/ Failure	Key factors for success or failure	Impact	Lessons learned	Reference(s)
Silvopastoral systems (SPS)	Montería, Colombia	Intensive rotational grazing combined with planting trees and shrubs to enhance pasture and provide shade.	Success	Innovative grazing techniques; integration of trees for shade and carbon capture; improved animal health.	Improved pasture growth and potential reduction in greenhouse gas emissions.	Financial and technical support are crucial for adoption	Rivera et al. (2019) and Chará et al. (2017)
Breed improvement programs	Northern Kenya	Introduction of crossbred goats (Indigenous × Galla) and sheep (Indigenous × Dorper and Indigenous × Red Maasai) to improve productivity.	Success	Training on productivity measures; improved rainfall; community interest in rebuilding livestock populations.	Increased flock sizes; enhanced reproductive rates.	Breeding programs should consider environmental conditions; within-breed selection may be more appropriate in arid areas.	Ojango et al. (2023)
Water management strategies	Omaheke Region, Namibia	Water harvesting, conservation, drilling boreholes, purchasing water tanks, and digging earth dams to address water scarcity.	Mixed	Financial constraints; limited government support; lack of information on effective strategies.	Variable success in ensuring water availability during dry seasons.	Financial and informational support are essential; community policies should facilitate adaptation measures.	Siririka et al. (2025)
Destocking during drought	Omaheke Region, Namibia	Selling off livestock in anticipation of drought to reduce pressure on resources and generate income.	Failure	Low herd sizes limiting destocking options; cultural value of livestock; unfavorable market prices during droughts.	Limited reduction in livestock losses; financial losses due to poor market conditions.	Early warning systems and market interventions can improve destocking effectiveness; cultural considerations must be addressed.	Siririka et al. (2025)
Disease management training	Northern Kenya	Training pastoral communities in livestock health management to reduce disease incidence.	Success	Community engagement; acceptance of veterinary services and products.	Reduced livestock mortality rates; improved overall herd health.	Ongoing training and accessible veterinary services are critical; integrating traditional knowledge enhances effectiveness.	Ojango et al. (2023)
Climate change adaptation strategies	Northeastern Iran	Implementation of various strategies to adapt to climate change impacts on pastoral livelihoods.	Failure	Social weaknesses; regulatory and insurance challenges; external factors affecting implementation.	Continued vulnerability to climate change impacts; limited improvement in pastoral livelihoods.	Addressing social and regulatory barriers is essential; comprehensive support systems are needed for effective adaptation.	Sharafatmandrad et al. (2024)
Climate-resilient livestock housing	Bangladesh	Elevated flood-proof livestock shelters	Failure	High maintenance costs, lack of farmer adoption	40% of shelters abandoned	Engage farmers in co-designing solutions for better usability	Rahman (2022)

(Continued)

TABLE 6 (Continued)

Adaptation strategy	Country/ Region	Implementation approach	Success/ Failure	Key factors for success or failure	Impact	Lessons learned	Reference(s)
Mobile climate advisory services	Uganda	SMS-based real-time weather forecasts and market info	Success	High mobile phone penetration, public-private partnerships	Reduced livestock losses and increased farm income	Expand digital literacy programs and improve connectivity	Tuheirwe-Mukasa et al. (2019)

stakeholders are essential for effective climate change adaptation in LMICs.

6 Interdisciplinary approaches to climate change adaptation in livestock production

A successful climate change adaptation strategy for livestock production must be multidisciplinary. This approach should incorporate various fields including agricultural sciences, economics, sociology, policy studies, and environmental sciences. Governments and research institutions must foster collaborations across these disciplines to develop policies, technological solutions, and farmer support programs that align with social, economic, and environmental sustainability. By adopting an interdisciplinary approach, LMICs can enhance their adaptive capacity, ensure food security, and promote sustainable livestock production systems in the face of climate change challenges (Sargison, 2020). Social sciences play a crucial role in adaptation efforts by ensuring that strategies align with the knowledge, traditions, and needs of local communities. Effective adaptation requires participatory approaches where livestock farmers, extension officers, and policymakers collaborate to design context-specific solutions (Andrieu et al., 2019). This could be particularly helpful to encourage farmers to participate in initiatives like the community-based breeding programs suggested. In addition, farmer cooperatives and knowledge-sharing networks can enhance resource pooling and dissemination of best practices for adaptation (Eise et al., 2021). Social perspectives could also be key to addressing resistance to new technologies through behavioral change campaigns. Economic strategies are also essential in making adaptation measures financially viable and attractive to livestock producers in LMICs. Governments, financial institutions, and international organizations should invest in mechanisms that support adaptation at different scales. For example, climate insurance and credit access that provide livestock farmers with insurance schemes against climate-induced losses can enhance resilience and encourage investment in climate-smart technologies (Kramer, 2023). Further, market incentives for climate-smart livestock products such as the implementation of certification programs and premium pricing for sustainably produced meat, dairy, and eggs can encourage farmers to adopt adaptive practices. Public-private partnerships (PPPs) in form of collaboration between governments, research institutions, and agribusinesses can also facilitate investment in precision livestock farming, renewable energy integration, and early warning systems. Sustainable adaptation strategies should focus on minimizing the environmental footprint of livestock farming while improving resilience to climate stressors. This could be through agroecological approaches by integrating silvopastoral systems (trees, shrubs, and pasture) into livestock production systems. This can enhance carbon sequestration, improve forage quality, and provide shade to reduce heat stress in livestock. Further, effective water and feed resource management through promotion of rainwater harvesting, efficient irrigation systems, and the use of climate-resilient fodder crops can ensure sustainable feed availability. Further, utilization of livestock waste for biogas energy can reduce methane emissions while providing renewable energy sources for rural farmers.

7 Future research directions

Future studies should explore a range of methodological approaches to deepen our understanding of climate adaptation strategies in livestock production. One promising avenue is field experiments, which can be used to test the effectiveness of various climate adaptation measures, such as precision feeding, heat stress mitigation strategies, and improved pasture management systems. For instance, on-farm trials incorporating climate-resilient livestock breeds could provide empirical evidence on their performance under changing climatic conditions. Farmer surveys and participatory research are also critical for capturing the lived experiences of livestock keepers and their adaptation strategies. Surveys could explore factors influencing the adoption of climate-smart practices, including socio-economic barriers, institutional support, and access to resources. Longitudinal studies tracking how farmers respond to climate variability over time could offer valuable insights into the sustainability of different adaptation strategies.

Moreover, climate modeling and geospatial analysis can be leveraged to predict the impact of climate change on livestock production at regional and national scales. High-resolution climate models can be integrated with livestock productivity data to simulate potential future scenarios which would allow policymakers to design targeted interventions. Additionally, remote sensing and Geographic Information System (GIS) technologies can be employed to monitor changes in rangeland conditions, water availability, and vegetation cover, all of which are crucial for sustainable livestock production. Given the increasing role of technology in climate adaptation, future research should also focus on data-driven innovations such as Internet of Things (IoT)-enabled livestock monitoring, machine learning applications for prediction, and the use of big data analytics to optimize livestock production systems under climate change. Collaborative research involving multidisciplinary teams including animal scientists, climatologists, economists, and social scientists will also be essential in developing holistic and effective adaptation strategies.

8 Conclusion

The livestock sector in LMICs faces significant challenges from climate change, including heat stress, reduced feed availability, increased disease prevalence, and extreme weather events. Addressing these issues requires the implementation of simplified and context-specific adaptation strategies tailored to the unique environmental and socio-economic conditions of LMICs. Key strategies such as the exploitation of indigenous livestock genetic resources, adoption of climate-smart technologies, precision livestock farming and data-enabled innovations, and diversification of livestock species and breeds are essential for building resilience. Successful case studies indicate that when adaptation strategies are well-funded, community-driven, and supported by strong policies, they yield significant improvements in productivity, resilience, and sustainability. However, fragmented policies, socio-economic constraints, and infrastructure gaps remain significant obstacles to adoption and scaling up these initiatives in many LMICs. Targeted investments in research, capacity building, and policy integration are crucial for bridging these gaps. Further, strengthening institutional frameworks, increasing financial support, and fostering public-private partnerships will be key to accelerating climate adaptation efforts. Additionally, ensuring that adaptation strategies are tailored to local contexts through participatory approaches could enhance their effectiveness and long-term sustainability.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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