



Innovative Approaches and Solutions for Climate Resilient and Sustainable Livestock Systems

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ABSTRACT

As the impacts of climate change continue to escalate, ensuring the sustainability and resilience of livestock systems has become a global necessity. Increasingly frequent extreme weather events, shifting precipitation patterns, and the proliferation of pests and diseases are putting immense pressure on conventional livestock practices. These challenges call for a transition to adaptive and climate-resilient approaches that can withstand environmental stressors. Rising temperatures, prolonged droughts, erratic rainfall, and water scarcity are having significant effects on animal health, productivity, and overall farm operations. This issue is especially pressing in Mediterranean regions, where agriculture is highly vulnerable to climate variability. Traditional livestock systems are under growing threat, making immediate and context-specific adaptation strategies essential. In this context, comprehensive climate risk assessments are indispensable tools for identifying

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regional vulnerabilities and designing appropriate responses tailored to local socio-economic and environmental conditions.

This paper outlines the foundational principles of climate-resilient livestock systems, emphasizing sustainability, genetic and ecological diversity, and system adaptability. Key strategies include the use of heat- and disease-tolerant livestock breeds, rotational and adaptive grazing techniques, integrated crop-livestock systems, and improved management practices for pasture, forage, and water resources. These approaches not only enhance resilience but also promote environmental conservation and long-term agricultural viability. Risk management is another critical component. Tools such as weather-indexed insurance, accessible credit, and early warning systems are essential for helping farmers absorb shocks and recover from climate-related losses. Embedding these instruments within national climate adaptation frameworks is vital for ensuring systemic resilience. The paper also presents global case studies illustrating the successful implementation of climate-resilient livestock practices. These examples highlight the importance of innovation, community engagement, and context-specific adaptation. Lessons learned from these cases offer valuable insights that can inform policy and practice across different regions.

Furthermore, the role of government policy, international cooperation, and institutional support is discussed. Financial incentives, training programs, and technical assistance are crucial for promoting the widespread adoption of climate-resilient practices. In conclusion, the transition to sustainable and climate-resilient livestock systems is not only an environmental imperative but also a social and economic necessity. It demands coordinated efforts, strategic investment, a strong policy framework at all levels.

Keywords: *Sustainable livestock production; climate resilience; innovative agricultural technologies; animal health; farm management.*

1. INTRODUCTION

Climate change presents a significant global challenge, posing risks to agriculture and livestock systems through rising temperatures, water scarcity, extreme weather, and the spread of diseases. These impacts compromise food security and necessitate the adoption of sustainable and climate-resilient livestock practices (Philemon et al., 2018; Fushai et al., 2025).

The vulnerability of food systems depends on climate exposure, the adaptive capacity of production systems, and regional socio-economic contexts. Strategies like the European Green Deal and the EU Adaptation Strategy to Climate Change aim to enhance regional resilience by promoting smart, inclusive, and timely adaptation while fostering international collaboration (Food and Agriculture Organization (FAO, 2007; Bilotto et al., 2024).

In the Mediterranean, climate variability and frequent extreme events are disrupting food supply chains, reducing agricultural productivity, and compromising access to affordable, nutritious livestock products. These pressures coincide with population growth and rising demand for animal-source foods, further intensifying resource use and environmental

strain. As a result, governments and international organizations now prioritize adaptation and greenhouse gas (GHG) mitigation as essential pillars of climate action (Harrison et al., 2021).

The Mediterranean livestock sector is a significant GHG emitter, particularly in low-productivity systems found across Southern Europe, North Africa, and the Eastern Mediterranean. These regions contribute more than 40% of agricultural emissions, and livestock production is expected to grow despite their limited adaptive capacity (Opio et al., 2013; Intergovernmental Panel on Climate Change (IPCC), 2019). Even highly developed countries like Spain and Italy face production losses and system disruptions, emphasizing the pervasive nature of the crisis (FAO, 2021).

Adaptation efforts must account for variation across agro-ecological zones, livestock species, and production systems. Climate change affects livestock directly—through heat stress, reduced fertility, and altered behavior and indirectly via feed availability, water resources, and disease dynamics. Research in the Mediterranean has focused on climate-resilient genotypes, such as drought- and heat-tolerant crops and animals (IPCC, 2019). For instance, the adoption of deep-rooted pasture species can enhance forage productivity, improve soil carbon storage, and

reduce GHG emissions, particularly in arid environments.

However, most studies address adaptation and mitigation separately, with limited integration across farming systems (Meier et al., 2020). There is no universal solution to reducing emissions or improving resilience; context-specific, scalable, and integrated approaches are needed. While emission intensity can be reduced through improved practices and technologies, questions remain about their broader applicability in Mediterranean systems (Herrero et al., 2016; Fushai et al., 2025).

This review highlights the central role of livestock in Mediterranean societies, not only as environmental stressors but also as sources of food, income, and cultural heritage. It examines the sector's exposure to climatic, economic, and geopolitical shocks, assesses historical production losses, and emphasizes the importance of forecasting, preparedness, infrastructure development, and local adaptation.

Additionally, the paper analyzes the livestock sector's contribution to regional GHG emissions and identifies the key drivers behind these trends. It presents analytical frameworks to support inclusive, sustainable transitions in livestock systems, suitable for Mediterranean contexts across various scales. It also outlines the conditions required for transformative change—including cost-effectiveness, user engagement, and strong institutional support—and emphasizes building local adaptive capacity.

The unique challenges facing Mediterranean livestock systems demand a holistic approach that integrates scientific research, traditional knowledge, and coherent policy frameworks. This comprehensive strategy is essential to ensure continued access to safe and nutritious food while minimizing the sector's environmental footprint. Accordingly, this work proposes a tool for rapid climate risk assessment to support Eastern Mediterranean governments in identifying sectoral vulnerabilities and designing targeted adaptation strategies.

2. CLIMATE CHANGE & ANIMAL FARMING INTERACTION

Climate change poses a critical threat to livestock systems worldwide. Rising global temperatures and shifting weather patterns affect the availability of essential resources such as

feed and water. These environmental changes also influence animal health, productivity, and all stages of the livestock supply chain—from production to processing, storage, transportation, and consumption. The cumulative effect of these impacts undermines the sustainability of livestock systems and their ability to meet the growing demand for animal-derived food.

2.1 Effects of Climate Change on Animal Physiology and Productivity

Livestock are directly affected by changes in physical, biological, and chemical environmental conditions. Extreme temperatures, such as intense heat or cold, increase the costs of shelter and reduce performance traits like milk and meat productivity. Heat stress, for instance, has been shown to decrease both the quantity and quality of milk and shorten lactation periods (Chase et al., 1988).

Reproductive functions are also compromised. Elevated ambient temperatures disrupt uterine blood flow and raise uterine temperatures, which may lead to reduced fertility, poor embryonic development, and increased early embryonic mortality (De Rensis et al., 2002). The growth of young animals is particularly vulnerable to such thermal stress (Koluman Darcan et al., 2009).

2.2 Broader Systemic Effects and Gaps in Current Research

While the effects of climate change on crops are well studied, the livestock sector remains relatively under-researched in this context (IPCC, 2014). Most studies focus narrowly on specific species, production stages, or adaptation strategies, overlooking the differentiated vulnerabilities of regions and communities (Rivera-Ferre et al., 2016). This review addresses that gap by analyzing climate-related risks across the entire livestock value chain, with attention to food security dimensions such as availability, accessibility, utilization, and stability, as well as impacts on non-food goods and services like wool, hides, and manure.

2.3 Environmental Hazards and Resource Competition

Climate-related hazards—both short-term extremes and long-term trends—interact with the exposure and vulnerability of livestock systems. Elevated temperatures not only lower voluntary feed intake but also reduce feed efficiency and

extend fattening periods (Silanikove, 2000). Droughts, salinization, and sea level rise are expected to decrease the quality and quantity of grazing lands and feed crops. This intensifies competition between food and feed crops, particularly in regions where crop production for human consumption is prioritized.

As climatic conditions, including extreme events such as droughts, salinization, and sea level rise, are projected to worsen due to climate change, the quality and quantity of grazing lands and feed crops are expected to decline significantly. This will not only compromise the productivity of grazing systems but will also intensify competition between food and feed crops, particularly in regions where crop production for human consumption takes precedence. The increased pressure on land and water resources will likely exacerbate the challenges of balancing food and feed demands, resulting in a heightened need for sustainable agricultural practices.

Moreover, the shifting rainfall patterns, increasingly frequent regional droughts, and rising salinity levels will further affect the viability of traditional grazing lands. These environmental stresses could lead to a higher reliance on crops that are both drought- and salt-tolerant, especially in areas facing arid conditions. As highlighted by Song et al., (2019), various factors such as soil conditions, species distribution, and disturbance regimes introduce significant uncertainty regarding the ecological responses to climate change, further complicating the ability to predict future grazing land productivity.

Notably, some plant species, including deep-rooted woody plants, may benefit from these harsh conditions due to their ability to access water from deeper soil layers. For instance, goats, which possess high adaptability to salinity and drought stress (Koluman Darcan et al., 2009), may benefit from the increased presence of such species in the landscape. These resilient species could play a role in ensuring the persistence of grazing lands under increasingly extreme environmental conditions. However, despite these potential benefits, Wang et al. (2019) stress that the uncertainty in the effectiveness of these species' responses, as well as the diversity of management strategies and technologies used for ecosystem manipulation, further complicates the overall understanding of how changing climates will affect livestock systems.

In addition to these modeling challenges, the physiological effects of climate change on plant and soil systems are critical in understanding the response of grasslands to changing environmental conditions. For instance, warming conditions are expected to increase carbon (C) accumulation in the root system, reflecting physiological changes in root respiration. As root biomass increases (due to the enhanced growth of roots at higher temperatures), there is likely to be a depletion of soil nutrients, particularly in systems with low nutrient availability, as noted by Bellochi et al. (2023). On the other hand, systems with higher nutrient supply, such as intensively managed systems, may exhibit smaller or less pronounced effects. These root growth dynamics can lead to shifts in the shoot: root ratio, as plants prioritize root growth to support nutrient acquisition under changing environmental conditions.

Furthermore, changes in the carbon-nitrogen (C-N) equilibrium caused by environmental changes—such as higher temperatures or drought—can result in altered plant biomass allocation, influencing soil mineralization processes. According to Bellochi et al. (2023), warming may stimulate soil organic matter mineralization, releasing more nutrients, which plants can then absorb through their roots. Additionally, moderate drought conditions, as discussed by researchers, may encourage carbon partitioning to roots, further impacting the photosynthesis and respiration balance in plants. Under these conditions, low management intensity may alleviate nitrogen (N) limitations by stimulating N mineralization and uptake.

These complex feedbacks in the ecosystem, where plant biomass inputs drive changes in soil nutrient cycling, underscore the intricate interactions between climate change and agricultural systems. The literature, as well as simulation models, are still limited in their ability to accurately predict these interactions in multi-species, long-term systems, which remain on the same soil for extended periods. The complexities introduced by different plant species' responses and their interactions with environmental stressors underscore the need for further research in this area.

Grasslands, unlike annual crops, are characterized by permanent vegetation covers and often involve mixtures of plant species with varying functional traits. These systems exhibit highly dynamic source-sink relationships, which

are influenced by factors such as plant growth stage, grazing intensity, and mowing timing. This complexity makes it difficult to define certain plant parameters or management practices in models, as the regrowth of plants after cutting or grazing cannot always be precisely estimated. Additionally, the senescence process of plant organs, which drives the relationship between aboveground biomass and plant residues, is difficult to model accurately. Senescence and litterfall are critical processes in nutrient cycling but are often not fully represented in models, leading to possible misestimation of yields.

2.4 Climate-induced Shifts and Tipping Points

Limited understanding of the complex interactions between climate change and livestock hampers the development of effective adaptation frameworks. Additionally, some climate mitigation strategies might unintentionally compromise food security, equity, or nutritional outcomes (Harrison et al., 2021).

The risk of abrupt system-wide shifts is growing, especially if global temperatures exceed 1.5°C. "Tipping points" in climatic, socio-economic, or geopolitical systems can trigger cascading effects. For example, the potential collapse of the Atlantic Meridional Overturning Circulation may lead to decades-long mega-droughts and catastrophic biodiversity losses (Armstrong McKay et al., 2022; Bilotto et al., 2024).

2.5 Breeding for Climate Resilience

Historically, breeding programs have prioritized traits linked to productivity. However, in the context of climate change, there is a growing need to emphasize resilience traits such as heat and disease resistance, drought tolerance, and longevity. Local breeds offer significant advantages, including thermoregulation capacity, immunity to endemic diseases, and the ability to survive on marginal vegetation (Koluman Darcan et al., 2009).

Breeding strategies should focus on conserving and utilizing these resilient local breeds, many of which are at risk due to the expansion of industrial systems and the homogenization of genetic pools (FAO, 2007).

2.6 Water Scarcity and Animal Health

Water resources are under increasing pressure due to changing precipitation patterns and

droughts. These changes reduce water availability for livestock, degrade land, and restrict irrigation for feed crops. Efficient water use, improved irrigation, and storage infrastructure are therefore essential for sustainable livestock production.

Animal health is also directly influenced by climatic conditions. Heat stress and water scarcity weaken immune systems, increase disease prevalence, and impair reproductive performance. Strengthening biosecurity, disease surveillance, and water management are critical steps in ensuring animal welfare under changing climatic conditions.

2.7 Regional and Context-Specific Strategies

Livestock farming systems show varying degrees of vulnerability depending on their structure and the environmental and socio-economic contexts in which they operate. According to IPCC Working Group II (2022), both climate and non-climate stressors must be considered to fully understand system vulnerabilities and adaptation capacities.

2.7.1 Grazing systems

These systems are often found in remote or marginal lands with limited access to services or investments. Their vulnerability is heightened by land-use changes, demographic pressures, and the marginalization of traditional knowledge. Although increased market integration offers potential opportunities, it also poses risks, such as over-exploitation and unequal access to benefits for small-scale pastoralists.

2.7.2 Mixed crop-livestock systems

In contrast, mixed systems face challenges related to land-use constraints and low mobility. These systems are particularly vulnerable to seasonal feed shortages, capital limitations, and competition for land with crop production. Additionally, regulatory shifts, such as stricter food safety standards, may increase production costs and reduce market access.

2.7.3 Industrial systems

Industrial livestock systems are mainly affected by internal factors, such as their dependence on fossil fuels, limited genetic diversity, and waste management challenges. Their adaptability is

constrained by the rigidity of infrastructure and management systems.

As a result, climate change presents multidimensional challenges for livestock farming, influencing productivity, health, resource access, and system sustainability. A comprehensive understanding of the interplay between climate hazards, resource constraints, and socio-economic drivers is essential. Strengthening resilience will require integrated approaches that include genetic diversity conservation, context-specific adaptation strategies, efficient water management, and the preservation of traditional and local knowledge.

3. SUSTAINABLE LIVESTOCK PRACTICES AND CLIMATE RESILIENCE HEADINGS

The climate impact on livestock is mostly indirect, affecting natural resources, land, and water essential for production. Key interventions focus on pasture and forest management, water access, biodiversity, and invasive species control. Enhancing productivity and diversifying income sources strengthen sector resilience. Livestock production has evolved to meet global demand, but traditional coping strategies for natural disasters are now limited. New approaches are needed to address climate change, extreme weather, and disease risks. This section explores resource efficiency, biodiversity conservation, animal health, and ecosystem adaptation, alongside sustainable practices like rotational grazing and mixed farming.

3.1 Efficient Use of Resources

World resources are not infinite or limitless; every resource has its boundaries. The most crucial limited natural resource is water. Water is vital for all living organisms, and the limited freshwater resources are increasingly threatened due to factors such as climate change, overuse, pollution, and population growth. Water losses in agriculture arise from evaporation, surface runoff, infiltration, inefficient irrigation methods, plant transpiration, and salinization. Among other critical limited resources, soil is at the top. However, water is considered one of the most critical natural resources since life cannot continue without it. Approximately one-third of the global agricultural water footprint is associated with the production of animal-derived products. The water footprint of animal products

generally exceeds that of plant-based alternatives with comparable nutritional content. For instance, the water footprint of beef per calorie is approximately 20 times greater than that of cereals and starchy roots. Similarly, the water footprint of milk, eggs, and poultry per gram of protein is 1.5 times higher than that of legumes. This relatively higher water footprint of animal products, in contrast to plant-based foods, can primarily be attributed to the inefficient feed conversion rates in livestock production (Naylor et al., 2005). A significant portion of water usage in livestock farming is concentrated in the feed production phase. Variations in the water footprint of feed crops between countries are influenced by differences in climate conditions and agricultural practices (Mekonnen and Hoekstra, 2012).

Recently, water restriction practices have been increasingly applied in both plant and animal production. It has been observed that restricting the daily water intake of dairy cattle by 25% or 50% reduces feed consumption, weight gain, and milk yield (Göncü et al., 2022). When cattle are moved from 18°C to 30°C conditions, their water requirements increase by 29%, while water loss through feces decreases by 33%, and water loss through urine, sweating, and respiration increases by 15%, 59%, and 50%, respectively (Murphy et al., 1983). However, different animal species and breeds show varying degrees of drought resistance. Goats and sheep, for example, can use their fore-stomachs as water reservoirs, enabling them to survive even if more than 20% of the body's water is lost (Casamassima et al., 2008; Vosooghi-Postindoz et al., 2017; Kaliber et al., 2016). Studies have shown that dehydration has no significant effect on respiration rate, but it reduces the respiration rate by 30% (Alamer 2006; Aganga et al., 1990; Casamassima et al., 2016). Studies on blood values observed that urea levels in milk and blood, as well as plasma sodium and hematocrit levels, increased (Viola et al., 2001). In poultry, water restriction (10%, 20%, 30%, 40%) has been found to severely impair feed consumption, weight gain, and feed conversion efficiency (Ndlela et al., 2019). Additionally, the meat of these animals after slaughter was found to be paler and eggs were smaller with thinner shells and more reddish (Chikumba et al., 2014).

3.2 Biodiversity Conservation

According to the FAO, (2007), approximately 20% of the 7,616 known animal breeds are

currently at risk, with nearly one breed vanishing every month. The species most vulnerable to extinction include poultry (33%), pigs (18%), and cattle (16%). Global warming has profound impacts on species, influencing their reproduction, migration patterns, mortality rates, and geographic distribution (Steinfeld et al., 2006; Thornton et al., 2009) argue that the primary driver of biodiversity loss is the widespread adoption of production practices that prioritize productivity and economic gains, often at the expense of resilience to extreme environmental conditions. The IPCC's Fifth Assessment Report (2019) suggests that a temperature increase of 2 to 3°C above pre-industrial levels could result in a 20 to 30% reduction in biodiversity across both plant and animal species. Furthermore, as climate change intensifies, both plants and animals are expected to face significant challenges related to disease resistance, pest management, and adaptation. (Bharali & Khan, 2011) highlight these challenges, including shifts in species distribution, an increase in the number of extinctions, changes in reproductive cycles, and alterations in the growing season duration for plants. Given these challenges, future research aimed at exploring the inherent genetic diversity of breeds and identifying those that are more adaptable to changing climate conditions is critical for long-term sustainability (Rojas-Downing et al., 2017).

3.3 Animal Health

In addition to its direct effects, global warming also influences animals indirectly by affecting their ability to adapt to warmer climates, altering microbial populations, facilitating the spread of vector-borne diseases, influencing host resistance to infectious agents, and exacerbating shortages of feed and water, as well as foodborne diseases (Nardone et al., 2010). Temperature plays a crucial role in the development rates of arthropod vectors, thereby influencing the risk of transmission of vector-borne diseases (Thornton & Herrero, 2008; Githeko et al., 2000; Ahumada et al., 2004). As feeding rates increase, the likelihood of pathogen transmission between vectors and hosts also rises, while temperature fluctuations further impact infection rates and the distribution of pathogens in vector populations (Bett et al., 2017). The impact of ecosystem changes on the spread of infectious diseases is contingent upon the specific ecosystem, alterations in land use,

disease-specific transmission dynamics, and the vulnerability of populations at risk. Climate change will not only affect disease cases that are ecologically sensitive but also pose serious health risks associated with floods or inundations resulting from irregular rainfall. In this context, it is suggested that the predicted disease spread can be prevented through disease monitoring, DNA fingerprinting, genome sequencing, resistance identification tests, antiviral drugs, hybrid breeding systems, and many other technological applications (Thornton et al., 2009). The dependence of animals' exposure to these diseases or their effects on various factors makes it difficult to predict the actual disease risk. New technological interventions, such as monitoring collars and electronic tracking systems, are being purchased to meet the needs of animals, pets, and livestock. Shelter management for animals during intense heat or rainy seasons needs to be regulated, as it can cause diseases and increase mortality rates. It has been reported that with appropriate shelter provision, mortality rates can decrease by 10 to 12%, and spending on animal treatments can also be reduced (Nardone et al., 2010).

3.4 Adaptation to Local Ecosystems

Climate change can have varying impacts depending on the specific climatic regions. For example, while increased CO₂ levels may enhance photosynthesis, water-use efficiency, and crop yields, rising temperatures can exacerbate plant diseases and water stress, ultimately diminishing productivity. Consequently, livestock species that inhabit restricted environments, have small populations, limited mobility, and low reproduction rates are particularly vulnerable. Livestock is primarily concentrated in arid and semi-arid regions around the world, especially within tropical and subtropical zones. In these regions, heat stress has already contributed to higher rates of morbidity and mortality in livestock. While warmer temperatures in temperate zones may boost livestock productivity, extreme heat and the proliferation of pests can negatively affect productivity. The impacts of climate change, such as rising temperatures, increased winter rainfall, and extended growing seasons, could potentially improve crop and forage production, as well as create opportunities for planting new crops. Moreover, longer growing seasons may reduce the need for livestock housing, lowering associated costs. However, these benefits might

be more pronounced on low-efficiency soils while potentially decreasing yields on highly productive soils (Steinfeld et al., 2006).

3.5 Sustainable Strategies in Livestock

Climate change exerts environmental pressures on livestock by limiting the availability of grazing land and feed resources, exacerbated by factors such as drought, extreme temperatures, ozone levels, elevated carbon dioxide, soil water availability, and salinity. Consequently, understanding how these stressors affect feed production and finding strategies to mitigate their adverse effects has become a critical area of focus. In this context, effective grazing management practices that promote carbon sequestration are highly recommended. These practices include: i) maintaining a balanced livestock-to-pasture ratio to prevent overgrazing and exceeding pasture carrying capacity, ii) implementing rotational grazing systems, and iii) safeguarding degraded pastures to promote recovery. Research has shown that grazing management and the history of land use can either exacerbate or reduce greenhouse gas emissions, depending on the specific climate and ecosystem. While grazing can contribute to greenhouse gas emissions, employing proper grazing strategies can significantly help in minimizing these emissions (Herrero et al., 2014).

3.6 Rotational Grazing, Use of Various Forage Crops, and Mixed Farming Systems

The use of high-quality feeds in livestock farming enhances digestibility, allowing animals to produce less methane while absorbing more nutrients, ultimately improving productivity. This results in reduced methane emissions and increased production efficiency. According to Thornton and Herrero (2010), incorporating small amounts of leaves from trees such as *Leucaena leucocephala* (subabul), commonly found in tropical areas, into the diet of dairy cattle can significantly increase daily milk yield, quadruple daily weight gain, and reduce methane production per kilogram of meat and milk. However, the production, processing, and transportation of feed and forage crops, alongside the use of synthetic fertilizers, account for 45% of the anthropogenic greenhouse gas emissions from global livestock, predominantly in the form of CO₂, N₂O, and NH₄⁺ (Thornton and Herrero, 2008). Fertilizer use, packaging,

transport, and application processes contribute over 40 million tons of CO₂ annually, with synthetic fertilizers providing 40% of the nitrogen absorbed by crops. Ammonia volatilization losses from synthetic nitrogen fertilizers further contribute to greenhouse gas emissions. Around 4 to 5 million tons of mineral fertilizers are used in animal feed production, with an average ammonia volatilization loss of approximately 14%. Consequently, the livestock sector is responsible for an estimated 3.1 million tons of ammonia volatilization annually. The use of fertilizers, agricultural nitrogen fixation, and atmospheric nitrogen accumulation generally lead to an increase in N₂O emissions, a potent greenhouse gas. Assuming an average N₂O-N loss rate of 1% from mineral fertilizers, the livestock sector contributes approximately 0.2 million tons of N₂O-N to global emissions annually (Steinfeld et al., 2006).

Steinfeld et al., (2006) also estimated the contribution of legumes such as soybeans, alfalfa, and clover, commonly used in animal feed, to N₂O-N emissions by considering their global cultivation area. When the contributions from legumes are combined with fertilizer use, the total annual N₂O-N emissions reach 0.7 million tons. As the use of fertilizers and animal manure increases, N₂O emissions are projected to rise by 35-60% by 2030, potentially adding 0.9 to 1.1 million tons of N₂O-N annually (Steinfeld et al., 2006).

3.7 Mixed-farming Systems and Food Security Adaptation

Globally, mixed-farming systems, which combine livestock, dairy, and crop production—such as sorghum, rice, and cereals—are vital for food production, contributing to over half of the global supply of milk, meat, and crops (Herrero et al., 2014). Adapting mixed-farming systems is an effective strategy for improving food security (Herrero et al., 2021). These systems can produce more food with fewer resources and less land (Herrero et al., 2016). For example, during drought years, managing feed and pasture resources, such as storing corn silage for summer feeding and preserving crop residues as straw, has proven to increase feed reserves. Additionally, milk production in these areas saw an increase of approximately 10-15%, and the calving interval was reduced by 45-60 days, leading to healthier calves and overall improvements in livestock production.

4. INNOVATIVE AGRICULTURAL TECHNOLOGIES AND ENHANCING CLIMATE RESILIENCE WITH AI INTEGRATION

Addressing climate-related risks in agriculture necessitates the integration of multifaceted strategies, among which Climate-Smart Agriculture (CSA) has emerged as a comprehensive and adaptive framework. CSA aims to sustainably increase agricultural productivity, enhance resilience (adaptation), reduce or remove greenhouse gases (mitigation), and ensure national food security and development goals (FAO, 2021). Within the livestock sector, CSA emphasizes the need to manage rising global demand for animal-source foods while minimizing environmental degradation and maintaining animal welfare.

The core components of CSA include the adoption of climate-resilient crop and forage varieties, conservation tillage, agroforestry, precision agriculture, advanced irrigation and water management systems, and sustainable livestock practices. Importantly, these approaches must be adapted to local ecological, economic, and sociocultural conditions to ensure effectiveness (Andrews and Reisinger, 2013).

4.1 Technological Innovations and AI Applications for Climate Resilience

Emerging agricultural technologies—especially those integrating Artificial Intelligence (AI)—are playing an increasingly vital role in building climate-resilient food systems. However, it is essential to analyze their applicability, scalability, limitations, and sector-specific constraints, particularly within livestock systems.

4.1.1 Drip irrigation and AI-enabled sensor systems

Drip irrigation, when combined with AI-supported soil moisture and weather sensors, enables precise water delivery based on real-time environmental feedback. These systems are particularly valuable in mitigating the effects of water scarcity. However, the adoption of such systems in livestock forage production is limited due to high installation costs and the need for technical capacity in system management. The scalability is further hindered in regions lacking infrastructure or stable energy sources (Barman et al., 2020).

4.1.2 GPS, drones, and AI-based analytics

Precision agriculture technologies—enhanced by AI—enable spatial analysis of fields, monitoring of herd movements, and optimization of input use such as fertilizers and pesticides. In livestock farming, AI models are increasingly used for early detection of diseases, monitoring animal behavior, and optimizing feeding strategies. Nevertheless, challenges include data management complexity, lack of standardization, and limited digital literacy among smallholders (Wolfert et al., 2017).

4.1.3 Genetic engineering and AI in genomic selection

AI is revolutionizing genomic selection by enabling faster, more accurate predictions of desirable traits in crops and livestock. This is especially relevant for breeding animals that are more resilient to heat stress or diseases linked to climate change. However, concerns about genetic diversity, public acceptance, and regulatory frameworks remain critical limitations (Qaim, 2020).

4.1.4 Regenerative agriculture supported by AI monitoring

Practices such as rotational grazing, cover cropping, and no-till farming improve ecosystem services and carbon sequestration. AI-powered platforms are now used to monitor soil health and grazing intensity via remote sensing and satellite imagery. Despite their benefits, regenerative practices demand long-term commitment and supportive policy environments, which are not universally available (LaCanne & Lundgren, 2018).

4.1.5 Satellite imaging and AI-powered weather forecasting

AI-driven satellite systems provide predictive insights into weather variability, drought onset, and forage availability. These are essential for strategic planning in livestock systems. However, disparities in internet access and technological infrastructure may prevent small-scale farmers from fully benefiting from such systems, especially in the Global South (Thornicroft et al., 2016).

4.1.6 Biofertilizers, biopesticides, and AI in microbial formulation

Biotechnological inputs like biofertilizers and biopesticides contribute to environmental

sustainability. AI is increasingly used to model soil microbiomes and optimize microbial combinations for better efficacy. However, their field-level performance is still inconsistent due to variable soil and climate conditions, and their scalability is affected by limited market availability and knowledge dissemination (Malusá & Vassilev, 2014).

4.2 Livestock-specific Considerations in AI-driven Technologies

While AI-based technologies offer transformative potential for climate-resilient agriculture, their application in livestock systems presents unique challenges:

- **Real-time monitoring and disease detection:** AI can enhance early disease detection through image recognition, wearable sensors, and behavioral analysis, improving animal welfare and reducing mortality. However, data quality, system maintenance, and cost remain barriers to adoption.
- **Climate-responsive livestock housing systems:** AI-controlled ventilation and temperature regulation systems help mitigate heat stress, improving productivity and animal welfare. Their high cost and technical complexity limit widespread deployment in small-scale farms.
- **Integration with traditional knowledge systems:** AI systems often fail to account for the nuanced, context-specific knowledge that local farmers possess, underscoring the need for participatory technology development approaches.

Innovative agricultural technologies, particularly those incorporating Artificial Intelligence, have demonstrated significant potential to enhance the climate resilience of both crop and livestock systems. However, effective deployment requires a systems-thinking approach that addresses socioeconomic, infrastructural, and ecological complexities. The future of climate-resilient agriculture lies in inclusive innovation, where digital and biotechnological advances are tailored to local realities and supported by strong institutional frameworks, capacity-building, and equitable access.

4.3 Drip Irrigation and AI-enabled Sensor Systems: Applicability in Resource-constrained Settings

Drip irrigation, particularly when integrated with AI-supported soil moisture and weather sensors,

enhances water-use efficiency by delivering precise amounts of water directly to plant roots based on real-time environmental data. This technology is especially valuable in the context of increasing water scarcity due to climate change, as it helps reduce water loss from evaporation and runoff while improving crop yields (Gaitan et al., 2025).

However, the applicability of these systems in resource-constrained environments such as arid and semi-arid regions or low income rural settings remains limited due to several interrelated challenges (Gaitan et al., 2025):

- **High initial investment costs:** The installation of drip systems combined with digital sensors and AI-based controllers can be prohibitively expensive for smallholder farmers. The financial barrier is especially significant in regions lacking access to affordable credit or government subsidies.
- **Technical capacity and maintenance:** These systems often require ongoing technical support, including sensor calibration, software updates, and routine maintenance. In many rural areas, there is a shortage of trained personnel or extension services to provide such support.
- **Infrastructure and power supply limitations:** Reliable electricity or internet connectivity, which is necessary for many AI-enabled systems to function, is frequently lacking in remote agricultural zones.

To address these challenges and improve **accessibility for small-scale farmers**, several practical and policy-oriented solutions can be proposed (Gaitan et al., 2025).

- **Low-cost modular systems:** Developing simplified, modular drip irrigation kits that can be scaled up gradually may help reduce upfront costs and encourage adoption. Solar-powered or gravity-fed versions can also mitigate energy constraints.
- **Community-based infrastructure sharing:** Encouraging cooperatives or farmer groups to invest in shared irrigation infrastructure can distribute costs and risks while enhancing collective water management.

Table 1. Towards climate-resilient livestock systems: A strategic framework

Strategy	Description	Real-World Example	Required Support
Conservation of Local Breeds	Integration of climate-resilient indigenous breeds into genetic improvement programs	Preservation of Awassi sheep in rural areas of Turkey	Government-supported gene banks
AI-Based Early Disease Warning Systems	Early detection of infections through sensor and camera data	AI systems for disease detection in dairy cattle in Israel	Infrastructure, farmer training
Rotational Grazing Planning	Preventing overgrazing and enhancing carbon sequestration on pastures	Implementation in arid regions of Morocco	Satellite-based grazing analysis systems, government support programs
Rainwater Harvesting and Micro-Irrigation Systems	Efficient water use in drought-prone areas	Low-cost water harvesting systems in Greece	Collaboration with local governments and NGOs, farmer training programs

- **Public-private partnerships and microfinance support:** Targeted subsidies, low-interest loans, or lease-to-own programs—especially when implemented through public-private partnerships—can lower financial barriers for resource-poor farmers.
- **Mobile-based interfaces and training:** Simplifying AI interfaces for mobile access and offering local-language digital literacy programs can enhance farmers' ability to monitor and manage irrigation without requiring advanced technical skills.

In summary, while drip irrigation and AI-enabled water management systems hold immense potential for improving agricultural water use efficiency and climate resilience, their effective implementation requires context-sensitive adaptations that prioritize affordability, accessibility, and farmer empowerment. Without addressing these foundational barriers, such technologies may exacerbate existing inequalities in agricultural productivity and climate adaptation capacity.

In response to critiques regarding the need for clearer strategic direction, this section introduces a structured framework titled "Towards Climate-Resilient Livestock Systems." The framework outlines actionable strategies supported by real-world examples and the necessary support mechanisms for effective implementation. These strategies are designed to guide policymakers, researchers, and practitioners in developing adaptive livestock systems that can withstand climate-related stresses. The Table 1 provides

an overview of selected interventions that integrate local adaptation, technological innovation, and sustainable resource management. Future research should focus on evaluating the long-term effectiveness and scalability of adaptive livestock strategies under varying climatic scenarios. This includes genomic studies to identify heat- and drought-resilient traits in indigenous breeds, and the development of AI-powered diagnostic tools tailored to low-resource settings. Additionally, interdisciplinary research that integrates climate science, animal physiology, socioeconomics, and spatial analysis is critical for modeling climate impacts on livestock productivity and health. Expanding pilot projects into diverse agro-ecological zones and conducting comparative studies on adaptation outcomes will be essential to validate and refine resilience strategies globally.

To ensure effective transformation towards climate-resilient livestock systems, integrated policy frameworks are needed. These should promote the conservation of genetic diversity through public-private partnerships, fund digital infrastructure for AI applications in rural areas, and provide incentives for the adoption of sustainable grazing and water management practices. Moreover, national policies should facilitate multi-stakeholder platforms that include pastoralists, researchers, technology providers, and local governments to co-design region-specific adaptation plans. Institutional support for capacity building, especially for smallholders, is essential to ensure equitable access to innovations and to strengthen local adaptive capacity.

5. CONCLUSION

The integration of innovative agricultural technologies particularly those supported by artificial intelligence has demonstrated considerable potential to enhance the climate resilience of both crop and livestock systems. However, this transformation is far from complete. As climate change continues to intensify environmental stressors, a multidimensional and inclusive approach is essential to ensure that technological innovations translate into equitable and sustainable agricultural practices on the ground.

Several research gaps warrant further investigation. These include the long-term socio-economic impacts of digital technologies on smallholder farmers, the environmental trade-offs associated with large-scale adoption of AI-driven systems, and the compatibility of high-tech solutions with traditional ecological knowledge. Moreover, livestock-specific studies remain underdeveloped, particularly regarding AI-enabled animal welfare monitoring and the role of low-cost technologies in extensive pastoral systems.

On the policy front, governments and international agencies must prioritize the development of enabling environments that facilitate the adoption of climate-resilient technologies. This includes (Breuer et al., 2023):

- Expanding rural infrastructure (electricity, internet access),
- Investing in farmer training and digital literacy programs,
- Supporting inclusive innovation through public-private partnerships and cooperatives,
- Designing subsidy and credit mechanisms tailored for small-scale producers.

Future efforts must also focus on context-specific solutions that reflect regional ecological conditions and socio-cultural dynamics. A one-size-fits-all technological approach may risk exacerbating inequalities and eroding resilience. Instead, participatory frameworks that integrate farmers' voices into the design and deployment of technologies are vital for long-term success.

In summary, building climate-resilient agricultural and livestock systems requires not only technological advancement but also robust policy frameworks, targeted research, and inclusive

implementation strategies. Bridging these domains will be critical for shaping a sustainable and equitable future in the face of ongoing climate change.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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