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## Abstract

Climate change is reshaping livestock production through chronic heat stress, hydrologic extremes, feed and water volatility, and shifting burdens of climate-sensitive diseases. At the same time, the sector is known as a source of methane and nitrous oxide, creating a dual imperative for adaptation and mitigation. This review synthesizes evidence on climate risks to animal health, welfare, and productivity and evaluates how big data, spanning the Internet of Things (IoT), remote sensing, cloud computing, and artificial intelligence (AI), can convert heterogeneous streams of environmental and biological data into farm-to-policy decisions timely. Drawing on international case studies, we map a practical "digital stack" for climate-smart livestock systems: (1) continuous sensing of animals and housing environments; (2) data integration across on-farm sensors, weather and hydrologic services, and satellite products; (3) predictive analytics for early warning of heat stress, disease emergence, and feed shortages; and (4) automated or decision-supported interventions (cooling, precision feeding, vaccination targeting, and logistics). We outline an architecture for a big-data-enabled early warning system and show how precision nutrition, health surveillance, and pasture biomass forecasting can simultaneously safeguard productivity and lower emissions intensity. At systems scale, we identify governance and infrastructure requirements, such as interoperable data standards, Findable, Accessible, Interoperable, Reusable (FAIR) principles, and open Application Programming Interfaces (APIs), to break vendor lock-in, improve model reproducibility, and aggregate farm-level signals into actionable regional dashboards. We also highlight priority use cases for genetic improvement under warming climates by linking genomics and longitudinal performance data (heat tolerance, disease resistance, feed efficiency). Collectively, the evidence indicates that embedding sensing, prediction, and adaptive control into routine operations can reduce climate-related losses, improve animal welfare, and provide credible metrics for sustainability reporting. We conclude with a policy and investment roadmap that prioritizes national data platforms, targeted incentives for smallholder adoption, and cross-sector partnerships to scale climate-smart livestock technologies. This perspective offers veterinarians, agricultural engineers, and decision-makers an integrated, actionable framework to future-proof animal-source food security under accelerating climate change.

**Keywords**: Climate change, livestock, machine learning, big data, artificial intelligence, Internet of Things.

# Introduction

Livestock supply one-third of the world's dietary protein and irreplaceable micronutrients, yet the sector now faces a triple climate threat: chronic heat stress, recurrent drought and the resurgence of climate-sensitive diseases [1,2]. Recent projections indicate that every hour cattle spend above a wet-bulb temperature of 26 °C trims 0.5 % from daily milk yield, while heat-related losses alone could erase 4 % of global output by 2050 [3]. These shocks disproportionately hit smallholders and regions already grappling with food insecurity. Converging advances in low-cost sensors, edge-to-cloud analytics and open data governance make it technically feasible and economically attractive to detect, predict and manage these risks in real time. We propose a scalable big-data climate-smart livestock architecture that can safeguard productivity, welfare and livelihoods while lowering emissions.

Climate extremes are becoming an increasingly dominant driver of vulnerability within global food systems [4,5]. The livestock sector, which underpins food security for hundreds of millions of people, is particularly exposed to the compound risks posed by heatwaves, droughts, water scarcity, and shifting precipitation regimes [6]. According to the Intergovernmental Panel on Climate Change [7], global surface temperatures have already risen by approximately 1.2°C above pre-industrial levels. These shifts are already disrupting animal health, productivity, and input availability across diverse agro-ecological contexts [8,9].

Livestock systems are inherently climate-sensitive. Elevated ambient temperatures reduce feed intake, compromise immune function, impair reproductive performance, and depress growth rates. Erratic rainfall and water shortages further affect forage production and disease exposure, destabilizing input markets and increasing livelihood risk, particularly in low- and middle-income countries [6,8,10,11]. The economic burden is substantial, heat stress alone is estimated to cost the global dairy sector over US $1.7 billion annually [12]. At the same time, livestock production is a major emitter of methane and nitrous oxide, highlighting the sector's dual role as both a casualty and contributor to climate change [13,14].

While conventional adaptation strategies such as improved housing, selective breeding, and enhanced veterinary care remain valuable, they are increasingly insufficient in the face of compounding and unpredictable climate shocks [3,8,15]. A more transformative approach is needed, one that leverages digital technologies and systems thinking to build resilience at scale. Recent advances in remote sensing, machine learning (ML), and the IoT offer new opportunities for real-time environmental sensing, predictive analytics, and integrated decision support in livestock systems.

This perspective article explores how smart livestock systems can advance climate-resilient food production under increasing environmental volatility. We (1) synthesize the multi-dimensional impacts of extreme weather events on livestock production and food security; (2) assess the role of big data and digital tools in enhancing adaptive capacity and operational efficiency; (3) highlight real-world cases that demonstrate feasible, scalable innovations; and (4) offer policy and investment recommendations to promote inclusive, data-driven transitions in the livestock sector. By framing the challenges and opportunities at the intersection of climate resilience and digital agriculture, this paper aims to inform future research, practice, and policy for ensuring livestock-based food security in a changing world. Figure 1 presents a conceptual architecture for big-data enabled, climate-smart livestock systems. Climate stressors (heatwaves, drought, heavy rainfall/flooding, disease) drive system impacts (reduced productivity, health risks, resource constraints, greenhouse gas emissions), while a big-data pipeline, such as integrating IoT/remote sensing/genomics/weather/market data with AI/ML and cloud-based interoperable platforms, enables smart capabilities (real-time monitoring, precision feeding/watering, climate-resilient breeding, disease surveillance, adaptive housing, and decision support) that intervene to reduce risk and accelerate recovery. These capabilities are sustained and scaled by enabling governance (data infrastructure, standardization, policy and incentives, capacity building, and local adaptation), producing improved outcomes (better health, stable productivity, resource efficiency, and food security) with feedback from outcomes to refine data, models, and management decisions over time.

In this article, we use “big data” to refer to high-volume, high-velocity, and high-variety datasets spanning animal, environmental, and production contexts (e.g., sensors, weather, remote sensing, management logs, and market information). We use “smart farm technology” to describe digital tools that enable sensing, connectivity, analytics, and decision support (including the Internet of Things, cloud computing, and artificial intelligence methods such as ML). Finally, we define “climate-smart livestock systems” as livestock production systems that maintain or improve productivity and animal welfare under climate stressors while strengthening resilience and supporting sustainability outcomes through data-informed monitoring and management.

# Climate change impact on the livestock systems

## Physiological vulnerability and performance decline

Livestock, both ruminant and monogastric species, are highly sensitive to climatic fluctuations, with physiological responses, health outcomes, and productivity closely linked to ambient temperature, humidity, and water availability [16]. Rising temperatures and extreme weather events directly impair animal performance, including growth, reproduction, and immune function [6,8,10,11,17]. One of the most immediate consequences is heat stress, which occurs when animals are pushed beyond their thermoneutral zone [18,19]. Milk yield in dairy cows often begins to decline around Temperature Humidity Index (THI) ≈ 68, and under severe heat load (THI ≥ ~80) double-digit losses (on the order of 10–30%) are commonly reported, alongside reduced fertility and immune function [1,20-22]. Beef cattle experience declines in feed conversion efficiency, and poultry suffer reductions in egg yield, shell quality, and viability [6,23-25]. Recent heatwaves in South Korea have led to increased mortality in pig and poultry farms, mirroring similar patterns in the southeastern U.S., southern Europe, and Australia [26-29]. These physiological stresses compromise both productivity and animal welfare.

## Climate-exacerbated disease risks

Heat stress also increases susceptibility to disease by weakening immune defenses [11,30]. For instance, mastitis, a common and costly infection in dairy cattle, tends to surge during hot and humid periods due to the proliferation of pathogens in bedding, water, and manure [30-32]. Additionally, climate change alters ecological conditions in ways that promote the spread of infectious diseases and parasites. Warmer temperatures and higher humidity improve pathogen survival and extend the range of vectors such as ticks, mosquitoes, and biting flies [33,34]. Notably, Culicoides midges, which transmit bluetongue virus, have expanded into northern Europe due to climate warming [35,36]. Rift Valley fever outbreaks have become more frequent following droughts and subsequent heavy rains, which create ideal mosquito breeding conditions [37-39]. Highly pathogenic avian influenza has similarly shown climate sensitivity, with changes in wild bird migration patterns and environmental persistence contributing to outbreaks [40]. Bacterial diseases such as leptospirosis [41-43], anthrax [44,45], and diarrheal infections [46,47] are all projected to rise with flooding and warming. Parasitic diseases like fascioliasis are also influenced by climate-induced changes in the life cycles of snail intermediate hosts [48,49]. These disease dynamics increase antibiotic use, exacerbating global concerns over antimicrobial resistance [50].

## Resource constraints: water, feed, and infrastructure

Climate change disrupts hydrological patterns, resulting in more frequent and severe droughts and floods [51]. These extreme events adversely impact forage and feed crop yields, drive up feed costs, and destabilize livestock production systems [10]. In Australia, for instance, prolonged droughts have forced widespread destocking, while floods have destroyed pastures and contaminated water supplies [52,53]. The 2010 floods in Pakistan led to the loss of over 200,000 livestock, severely affecting food security and rural livelihoods [54]. During heatwaves, water demand intensifies, with livestock requiring more water, thereby exacerbating competition across agricultural and non-agricultural sectors [55]. Additionally, flooding can damage critical infrastructure such as manure storage and livestock housing, an increasing concern in countries like the Netherlands, where flood risks threaten both farm operations and environmental safety [56].

Beyond acute weather events, chronic water scarcity presents enduring challenges, particularly in arid and semi-arid regions where agriculture and livestock already contend for limited water resources [10,57]. Irrigated feed production in these areas may become unsustainable, prompting transitions to lower-yield or more drought-tolerant crops, shifts that can compromise feed efficiency [6]. Furthermore, access to resilient infrastructure, such as shaded barns, elevated housing, and secure water storage systems, remains uneven across the globe, disproportionately affecting smallholders in developing regions [57,58]. The high cost of upgrading or climate-proofing facilities often exceeds local financial capacity, further reinforcing systemic vulnerability [59]. These interrelated resource constraints intensify pressure on already fragile livestock systems, restricting adaptive capacity and heightening the risk of production losses and animal welfare crises over time [6,58].

## Geographic variability and the need for tailored adaptation

The impacts of climate change on livestock systems vary considerably across regions, necessitating localized and context-specific adaptation strategies. In temperate zones, key challenges include managing episodic heatwaves, excessive rainfall, and associated flooding, which can compromise pasture conditions, animal health, and waste management infrastructure [60,61]. In contrast, arid and semi-arid regions prioritize drought resilience, improved water-use efficiency, and the selection of heat- and drought-tolerant breeds [10,17]. Tropical regions are particularly vulnerable to chronic heat stress and a rising burden of vector-borne diseases, necessitating integrated responses involving housing design, disease surveillance, and enhanced animal health services [16,35,36].

Country-specific examples highlight this geographic variability: the Netherlands faces increasing flood risks that threaten livestock housing and nutrient containment infrastructure, prompting investment in elevated barn construction and water buffering systems [61]. Meanwhile, Australia has focused on climate-resilient rangeland management, including rotational grazing, supplemental feeding, and water-point planning to cope with recurrent droughts [10,62]. In addition to these adaptation demands, livestock systems must confront their own environmental footprint. Globally, animal agriculture accounts for approximately 14.5% of anthropogenic greenhouse gas emissions, with methane from enteric fermentation and nitrous oxide from manure management as the primary contributors [63]. In high-income countries, mitigation strategies increasingly include feed additives to reduce methane, anaerobic digesters, and precision farming technologies, while low-income settings require scalable solutions aligned with local capacities [59,64].

Given this complexity, a system-level approach is needed, one that integrates climate modeling, agroecological assessments, veterinary and animal health expertise, and digital monitoring tools. Such an approach can guide tailored, data-driven interventions that strengthen resilience while reducing environmental impacts, ultimately supporting more sustainable and equitable livestock production under a changing climate [58,65].

# Big Data and Climate Change

## Integrating diverse data for climate adaptation

Amid intensifying climate change impacts, big data technologies are emerging as essential tools to enhance the adaptive capacity of livestock systems. By integrating massive datasets, spanning weather patterns, soil conditions, animal health metrics, and operational practices, big data provides critical insights that inform climate-smart decisions [66,67]. This integrated data framework enables both farmers and policymakers to anticipate environmental stressors, tailor livestock management strategies, and reduce associated risks [68,69]. For example, in dairy production, real-time analytics of millions of biological and environmental data points can flag early indicators of heat stress, triggering automated cooling responses that protect animal welfare and minimize productivity losses [1,70,71].

Figure 2 presents an end-to-end framework for converting multi-source farm data into actionable decision support, with continuous feedback and cross-cutting safeguards. Data are collected from animal, environment, and management sources, then pass through ingestion and quality control (addressing missing data, noise, and bias) and feature engineering (harmonization, standards, and interoperability). These processed data support predictive analytics (risk scoring, forecasting, uncertainty checks, and drift monitoring), which feed into decision support tools (alerts, recommendations, and user-centered thresholds). After actions are taken, intervention tracking and feedback capture outcomes, costs, and welfare impacts, creating learning loops that inform ongoing model and data improvements. Governance and trust (privacy, access, benefit sharing) and equity and capacity (training, usability) are shown as overarching requirements that shape how decision support is deployed and adopted.

## AI and ML for predictive livestock management

At the heart of this transformation are ML and AI, which unlock the predictive potential of big data (Table 1). These technologies excel in detecting complex, non-linear patterns that elude conventional statistical methods, making them indispensable for forecasting climate-linked disruptions [66,72]. AI models trained on long-term climate records and livestock performance data can anticipate events such as heatwaves, disease outbreaks, and feed shortages [73-75]. Real-time biometric monitoring via wearable devices, tracking body temperature, heart rate, and movement, allows AI systems to flag deviations from baseline health indicators, enabling timely intervention [76-79]. In the Netherlands, AI-enhanced prediction models have successfully improved dairy cow productivity through integrated weather and feeding data, enhancing both yields and animal welfare [80]. Moreover, ML can fine-tune nutrition by analyzing consumption trends, offering precision rations that optimize feed efficiency while curbing methane emissions [81].

## Real-time monitoring through IoT and cloud-based platforms

The IoT is another technological pillar driving the shift toward climate-resilient livestock systems (Table 1). IoT devices generate a continuous stream of real-time data on environmental variables such as temperature, humidity, and ammonia levels, as well as animal behavior and physiology [69,82]. These data feed into centralized platforms that trigger automated responses. For instance, poultry house ventilation systems now self-regulate based on sensor inputs, maintaining optimal conditions even during heat extremes [83]. Wearable technologies like smart collars and GPS-enabled ear tags enable detailed tracking of estrus cycles, grazing patterns, and stress-related behavior [84]. In South Korea, these tools have been integrated into smart pig and poultry systems, providing early alerts for disease and optimizing resource use, highlighting the role of IoT in bridging animal health and sustainability [70].

Supporting the backend of these innovations is cloud computing, which offers scalability and computational power required to process vast volumes of sensor and AI-generated data (Table 1) [85]. Cloud-based systems allow farmers and researchers to access advanced analytics and simulation tools without investing in high-cost infrastructure [86,87]. These platforms enable data aggregation across geographies, making it possible to develop regional climate models and predictive dashboards that guide adaptive farm management [66]. Through user-friendly interfaces, accessible via mobile devices, farmers can receive alerts, visualize trends, and make rapid, evidence-based decisions. Furthermore, cloud-based architectures support collaborative data sharing among stakeholders, enhancing coordinated responses during climate-related crises such as disease outbreaks or feed shortages [72].

## Toward integrated smart livestock systems

The convergence of AI, IoT, and cloud computing is giving rise to integrated smart livestock systems that address the dual imperatives of productivity and climate resilience (Table 1). These systems enable holistic farm management, from precision feeding to health diagnostics. For example, automated milking stations now capture individual cow data during each session, such as milk yield, rumination, activity, and weight, enabling detection of subtle health issues like mastitis or lameness via AI algorithms, often days before human detection [88]. Drone and satellite imagery, when combined with ground-level sensors, provide precise pasture monitoring; recent studies demonstrate that Unmanned Aerial Systems (UAS) and Sentinel-2 data, paired with ML, can accurately estimate biomass and forage quality to support data-driven grazing decisions [89]. In Australia, such real-time pasture monitoring guides herd movement to optimize land use and prevent overgrazing [90].

In summary, big data technologies, including AI, IoT, cloud computing, and remote sensing, are no longer optional tools but essential components of climate adaptation for the livestock industry (Table 1). Continuous sensing, predictive modeling, and automated decision-making support enhanced animal welfare, reduced resource waste, and lower environmental footprints (Figures 1 and 2). By embedding these technologies into the fabric of livestock operations, the industry is better equipped to navigate climatic uncertainty and meaningfully contribute to global sustainable food system goals [91].

# Climate Change Response Measures for Livestock Farming Based on Big Data

## Smart farm technologies for climate adaptation and animal welfare

The integration of smart technologies into livestock systems is transforming traditional approaches to animal health and productivity, particularly under the growing pressures of climate change. Smart livestock farms employ real-time monitoring tools and automated environmental controls to maintain optimal living conditions (Table 1) [92-94]. Unlike conventional systems reliant on manual observation, these technologies allow for immediate detection and response to environmental stressors such as heat, humidity, and air quality. Sensors continuously track barn conditions, including temperature, ammonia levels, and illumination, and automatically adjust ventilation, misting, and heating systems to mitigate physiological stress [1,95]. This proactive management reduces the impact of extreme weather events and enhances animal welfare and reproductive performance.

In dairy operations, for instance, real-time milk yield monitoring integrated with biometric data supports individualized feeding and health interventions, contributing to improved milk quality and cow longevity [80,96]. Similarly, poultry farms now leverage AI-based systems to detect early signs of disease through behavioral and physiological indicators such as movement patterns and feed intake (Table 1) [68,97]. These applications not only stabilize productivity but also contribute to sustainability by minimizing waste and optimizing resource use [66].

## AI-enabled disease surveillance and veterinary innovation

As climate change facilitates the spread of pathogens and parasites, early detection and control of livestock diseases have become increasingly critical (Table 1) [39,46]. AI and ML tools are redefining disease surveillance by analyzing massive datasets of historical outbreaks, climate variables, and real-time animal health data [98]. Wearable sensors, such as smart collars and ear tags, capture metrics like body temperature, heart rate, activity, and location, which are used to identify deviations from normal behavior indicative of illness or stress [99,100]. When anomalies are detected, farm managers receive immediate alerts, allowing timely isolation and treatment to prevent wider outbreaks.

In regions vulnerable to vector-borne diseases, AI models further incorporate climate forecasts to predict disease hotspots, enabling targeted vaccination campaigns and strengthened biosecurity (Table 1) [39]. These systems are not confined to monitoring alone; AI is also advancing veterinary clinical practices. For example, Akinsulie et al. [101] demonstrated how image-based features can be converted into quantitative data for improved diagnostics and personalized therapeutic strategies. Additionally, AI models now contribute to the development of precision nutrition plans by correlating dietary inputs with disease resistance and health outcomes [99]. Collectively, these tools improve herd productivity while decreasing antibiotic dependence, addressing the urgent challenge of antimicrobial resistance [50].

### Data-driven sustainability and climate-resilient resource management

The pursuit of sustainability in livestock farming is being fundamentally reshaped by big data-based systems, which provide the precision necessary to navigate the resource unpredictability intensified by climate change. With increased variability in water availability and feed supplies, traditional resource management strategies are proving inadequate. Big data platforms integrate information from weather forecasts, soil sensors, and animal consumption patterns to optimize the use of feed and water resources (Table 1) [66,72]. Advanced feeding systems adjust rations in real time to improve feed conversion efficiency and reduce waste, while smart water systems modulate irrigation and drinking supplies in response to environmental and physiological data (Table 1) [83,99].

Emission monitoring technologies are also playing a critical role, enabling farmers to track and reduce greenhouse gas outputs from manure and enteric fermentation (Table 1). By linking these insights to operational changes, such as dietary adjustments or manure treatment, farms can reduce their carbon footprint [84,102,103]. In flood-prone coastal regions, smart platforms combine hydrological modeling with farm logistics to help producers develop adaptive strategies, including livestock relocation or grazing schedule modification [104,105]. These capabilities enable livestock systems to maintain productivity and ecological balance, positioning them as integral components of climate-smart agriculture. Key digital and engineering solutions discussed in this section are distilled in Table 1.

## Policy Recommendations for Big Data–Driven Climate Action in Livestock Systems

### Building a national data infrastructure

To fully harness the potential of big data in addressing climate change impacts on livestock production, a paradigm shift is needed, moving from fragmented data collection toward a coordinated, integrated system (Table 1). While smart technologies are increasingly deployed at the individual farm level, valuable datasets remain isolated in proprietary systems [106]. A national data collection and sharing platform would enable cross-regional data aggregation, supporting both granular on-farm decisions and broader policy development [107]. Such a platform would facilitate real-time monitoring of animal health and environmental variables, generating early warnings for disease outbreaks, heat stress, or feed disruptions [58,108]. Crucially, standardizing data protocols would improve interoperability and data quality, thus enhancing the robustness of analytics [109]. Aggregated datasets would empower researchers and policymakers to detect long-term trends, refine adaptation strategies, and develop predictive models sensitive to regional nuances [110]. Moreover, shared data infrastructures would encourage collaboration among farmers, public agencies, researchers, and the private sector, fostering transparency and accelerating innovation in climate-smart livestock management [58].

A centralized platform would also underpin the development of nationwide real-time environmental monitoring and early warning systems. By integrating diverse data streams—from IoT sensors, weather stations, and remote sensing technologies, this system could track critical variables such as temperature, humidity, rainfall, air quality, and animal health (Table 1). ML and AI algorithms would analyze these inputs to detect emerging risks and issue alerts to farmers, Extension agents, and policymakers (Table 1). For instance, during a forecasted heatwave, the system could prompt preemptive actions like activating cooling systems or modifying feed schedules. It would also support dynamic risk mapping and targeted resource allocation, enhancing resilience throughout the livestock sector [106,109].

## Enabling climate-resilient breeding and feeding strategies

Big data analytics can transform breeding by enabling climate-resilient genetic optimization (Table 1). Traditional programs have emphasized productivity traits such as growth and milk yield, but climate-smart breeding must also prioritize heat tolerance, disease resistance, and feed efficiency [111,112]. By linking genomic data with performance metrics under diverse environmental conditions, AI-driven models can identify optimal combinations that preserve productivity while enhancing resilience [113-115]. For example, data-driven selection can pinpoint cattle with superior heat tolerance in subtropical regions, or swine lines better adapted to high-humidity environments [20,116]. These insights also support breeding approaches that reduce methane emissions per unit of output [117,118]. Integrating these models into national livestock development plans offers a strategic, proactive path to adaptation [67].

Feed security is another cornerstone of climate resilience, increasingly threatened by extreme weather, market volatility, and disrupted supply chains [6,119]. Big data strengthens feed systems by forecasting disruptions and enabling responsive planning. AI models that combine satellite imagery, weather data, and market trends can anticipate feed shortages and recommend alternative sources or ration adjustments [120]. On-farm, precision feeding systems use real-time biometric data to tailor diets, boost feed efficiency, and reduce waste (Table 1) [121,122]. Feed conversion trends and weight gain trajectories inform timely feed adjustments, while predictive analytics support harvest and storage strategies that maintain nutritional value and minimize spoilage [123,124].

## Designing locally adaptive technologies

Climate-smart livestock systems must reflect specific environmental, cultural, and economic realities to be effective. In Korea, livestock operations face both heat stress during hot, humid summers and cold stress during winter, necessitating dual-function climate control strategies in housing design [125]. Studies have shown that heat stress reduces milk yield and alters feeding behavior, while cold stress increases maintenance energy requirements, reducing growth efficiency [125-127]. Accordingly, smart ventilation, misting, insulation, and heating systems have been proposed to maintain optimal thermal conditions throughout the year [69].

Beyond environmental controls, technologies must be tailored to local production goals, such as the premium placed on high-quality Hanwoo beef, which demands attention to animal welfare, marbling scores, and genetic performance [128,129]. Similarly, dense housing in pig and poultry operations in Korea requires stringent biosecurity measures to control disease spread, including AI-driven surveillance, controlled access systems, and early warning sensors [130,131]. These biosecurity enhancements are particularly critical in light of Korea’s recent experiences with foot-and-mouth disease and avian influenza outbreaks.

The success of these systems also hinges on institutional support and collaboration. Effective adaptation demands coordinated efforts between government agencies, research institutions, and private-sector partners, especially to scale smart farming technologies beyond pilot sites [132,133]. Investment in pilot programs across varied production systems, including smallholder and intensive farms, can generate localized data, validate technologies, and facilitate equitable adoption [134,135]. Moreover, Korea's Smart Farm Innovation Valley initiative exemplifies how public-private partnerships can foster innovation and regional development in climate-resilient agriculture [136].

## Advancing interoperability through open platforms

To scale innovation and enable collaboration, a universal open platform with standardized data protocols is essential. Currently, proprietary and incompatible data formats restrict the integration of insights across systems, leading to data silos that hinder farm-to-policy analytics [137]. A centralized platform with common standards for key metrics, such as animal health, productivity, environmental conditions, and resource use, would enable consistent comparison, longitudinal tracking, and improved analytical precision [138,139]. Open API architectures, such as those adopted in the DEMETER project through the Agricultural Interoperability Space (AIS) and the Agriculture Information Model (AIM), are particularly critical for fostering third-party innovation, allowing startups, extension agencies, and research institutes to develop interoperable applications that serve diverse farm sizes and systems [140-142].

Standardized metadata frameworks, such as those promoted by AIMS and GODAN, have demonstrated the benefits of harmonized vocabularies and ontologies for agricultural data exchange, improving reusability and discoverability across geographies and research domains [139,143]. Governance frameworks must accompany these digital infrastructures to protect data ownership, ensure user consent, and address equity concerns, particularly for smallholders in low-resource settings who may otherwise be excluded from digital value chains [144].

Moreover, the application of FAIR (Findable, Accessible, Interoperable, Reusable) data principles in agricultural technology platforms is increasingly seen as essential for improving the reproducibility of research and ensuring that digital transformation advances inclusive and climate-smart agriculture [138,145]. Empowering all actors, farmers, extension agents, policymakers, and developers, with standardized, secure, and actionable data will accelerate climate adaptation and support a resilient, data-driven livestock sector.

## Discussion

Climate change poses an increasingly complex and urgent threat to the global livestock sector, undermining its productivity, economic viability, and environmental sustainability. The escalating impacts of rising temperatures, unpredictable precipitation patterns, and the intensification of extreme weather events are placing livestock systems under unprecedented stress. These climatic pressures heighten the risks of heat stress, water scarcity, feed insecurity, and disease emergence, disruptions that reverberate throughout food supply chains. Simultaneously, the livestock sector itself contributes significantly to climate change through greenhouse gas emissions, particularly methane from enteric fermentation and nitrous oxide from manure management. This dual role as both a victim and a contributor to the climate crisis highlights the urgent need for integrated adaptation and mitigation strategies that are environmentally sound and economically viable.

Within this context, big data technologies, including AI, IoT, and cloud computing, offer transformative potential for enhancing the resilience of livestock systems (Table 1). These technologies facilitate continuous, real-time monitoring of animal health, environmental conditions, and farm operations, generating actionable insights that enable timely and precise interventions. AI-driven models can forecast weather extremes, optimize nutrition, and inform climate-resilient breeding programs tailored to local conditions. IoT sensors capture environmental and physiological variables, such as temperature, humidity, body condition, and animal behavior, allowing for the early detection of stress and disease. Cloud computing infrastructure supports the processing and integration of vast, heterogeneous datasets, enabling the development of national-level predictive models and early warning systems. Together, these innovations are reshaping livestock farming by improving decision-making, enhancing animal welfare, and reducing environmental impacts.

This review has outlined key strategies for leveraging big data to build climate-smart livestock systems. At the farm level, smart technologies, such as automated ventilation, precision feeding, and health monitoring systems, help maintain productivity and animal well-being under adverse climatic conditions. At the systems level, national data-sharing platforms and standardized open-source infrastructures are essential for aggregating farm-level data into actionable intelligence for policy and investment decisions (Figure 2). The application of big data analytics in genetic improvement programs will further enable the selection of traits that enhance resilience to heat, disease, and resource scarcity, while maintaining or improving production efficiency.

Policy support and effective governance are equally critical to realizing the full potential of big data. Governments should invest in digital infrastructure and provide targeted incentives to promote the adoption of smart livestock technologies, particularly among smallholder farmers. Collaborative partnerships between public institutions, private sector actors, and farming communities can accelerate the development and scaling of solutions. Importantly, training and capacity-building efforts are necessary to ensure equitable access to these technologies. Ethical and legal frameworks must also be established to address concerns related to data ownership, privacy, and equitable benefit-sharing, fostering trust and long-term engagement among all stakeholders.

Smart farm technology is advancing quickly, but several practical constraints still shape whether these tools can be implemented at scale and deliver consistent benefits across real-world livestock systems (Table 2). A primary barrier is infrastructure and cost: many operations, especially in resource-limited settings, lack reliable connectivity, power, and technical support networks, while the up-front and recurring expenses for sensors, data services, calibration, and maintenance can limit adoption and concentrate benefits among better-resourced producers. In addition, interoperability and durability remain persistent challenges. Many platforms rely on proprietary data structures or vendor-specific ecosystems, which complicate integration across devices and can create long-term dependence on external providers. Performance can also degrade under harsh farm conditions (heat, humidity, dust, and animal interference), where equipment failure or data discontinuity undermines continuous monitoring.

Equally important are data and modeling limitations that affect decision support quality (Table 2). Farm data streams are often noisy, incomplete, or biased, and labeled datasets for training predictive models are frequently scarce. Models built in one production context (farm type, breed, climate, or management regime) may not transfer reliably to others, and model performance can erode over time as conditions change (seasonality, shifting disease dynamics, and evolving practices), creating model drift that increases false alarms or missed detections unless systems are routinely validated and recalibrated. Adoption is further influenced by governance, privacy, and trust: unclear data ownership, concerns about surveillance or secondary data use, and uncertainty about downstream implications for market access or regulatory exposure can reduce participation. Finally, equity and workforce capacity shape whether digital tools reduce vulnerability or widen existing gaps, without training, user-centered design, and locally relevant decision support, the technologies may disproportionately benefit operations with greater capital and technical expertise. Collectively, these limitations point toward practical priorities for implementation: strengthening connectivity and service ecosystems, improving interoperability, enforcing data quality control, conducting ongoing model validation and drift monitoring, and establishing transparent governance frameworks that clarify data rights, privacy protections, and benefit-sharing mechanisms.

Looking to the future, the integration of advanced technologies such as robotics, blockchain for traceability, and satellite-based remote sensing will expand the scope and precision of big data applications in livestock farming (Table 1). Interdisciplinary collaboration, linking climate science, veterinary medicine, agricultural engineering, and data analytics, will be essential for generating robust, scalable solutions. Global cooperation will also be vital, both to harmonize data standards and to support knowledge exchange and capacity-building in climate-vulnerable regions.

The convergence of climate stressors and technological advancements presents both a formidable challenge and a unique opportunity for the livestock industry. Embracing big data and digital technologies provides a viable pathway to transition livestock systems toward greater adaptability, sustainability, and resilience. The strategies discussed in this article underscore the importance of coordinated action, uniting farmers, researchers, policymakers, and technology developers, to future-proof livestock farming in a changing climate. Through sustained innovation, inclusive collaboration, and targeted investment, the livestock sector can play a pivotal role in securing food systems, promoting environmental stewardship, and advancing sustainable development worldwide.

# Conclusions

Climate change is increasingly shaping livestock production through heat stress, water and feed constraints, and shifting disease risks, with consequences for productivity, animal welfare, and animal-source food security. Digital approaches, integrating sensing, connectivity, analytics, and decision support, offer a practical pathway for earlier detection of climate-linked risks and more adaptive management across diverse production contexts. At the same time, the value of big data and smart farm technology depends on implementation of realities. Infrastructure and cost barriers, interoperability, data quality, model transferability, and governance concerns can limit effectiveness if not addressed directly. Future progress will require coordinated efforts that combine robust technical design (including routine validation and drift monitoring) with transparent governance frameworks and capacity-building to support equitable adoption. When these conditions are met, climate-smart livestock systems can strengthen resilience while supporting sustainability outcomes across local and global food systems.

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# Figure

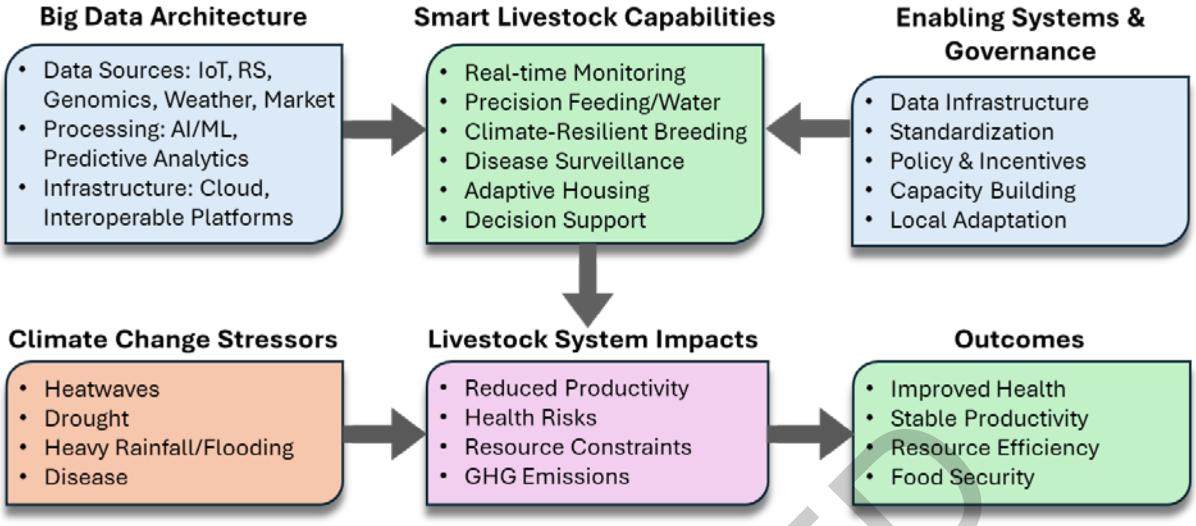

Figure 1. Diagram of the integrated system linking climate change stressors, livestock impacts, big data architecture, smart livestock capabilities, enabling governance, and resilience outcomes with feedback loops.

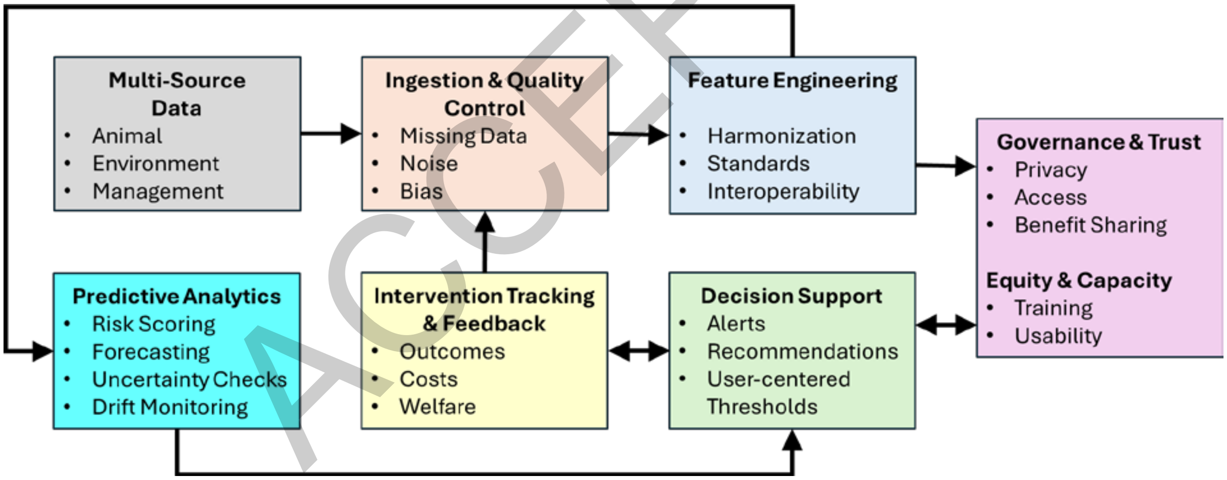

Figure 2. Workflow for climate-risk early warning and decision support in climate-smart livestock systems. The workflow links data ingestion and quality control, predictive analytics with drift monitoring, decision support, and intervention tracking with feedback loops for continuous improvement, while governance and equity considerations shape deployment and adoption.

# Table

Table 1. Climate-smart technologies highlighted in the manuscript.

| Technology/Tool | Function/Benefit | Examples/Features |
|---|---|---|
| Big-data analytics platforms | Integrate weather, soil, animal health and management data to generate real time, climate aware decision support, and early warning insights. | Dairy analytics that flag heat stress risk hours ahead, triggering automated cooling responses. |
| AI/ML models | Detect nonlinear patterns and forecast heatwaves, disease outbreaks, feed shortages; optimize rations and management schedules. | AI models combining decades of climate and performance data to predict productivity dips and fine-tune nutrition. |
| IoT sensor networks | Continuous sensing of barn environment and animal biometrics; stream data to control systems for rapid adaptation. | Smart collars, ear tags, ammonia/temperature sensors that drive ventilation and behavioral alerts. |
| Cloud computing backends | Provide scalable storage and compute for massive sensor/AI streams; host dashboards and region-wide predictive tools. | Edge-to-cloud architectures delivering mobile dashboards for farmers and regional risk maps for policy makers. |
| Smart environmental control systems | Automated ventilation, misting, heating and lighting to keep animals within thermoneutral zones during extremes. | Barn sensors autoadjust airflow and misting during heatwaves, reducing heat stress losses. |
| Precision feeding systems | Real-time ration adjustment to maximize feed efficiency, curb waste and lower enteric methane per unit output. | AI guided feeders tailoring diet by weight gain trajectory and ambient stress. |
| Smart water management systems | Sensor driven control of irrigation and drinking supplies to cope with drought and heat induced demand spikes. | Automated drinker valves modulating flow based on temperature driven consumption patterns. |
| Emission monitoring and mitigation technology | Track GHGs from manure and enteric fermentation; inform dietary tweaks, manure treatment or feed additives. | On-farm GHG sensors linked to dashboards; integration with anaerobic digesters or methane reducing feed. |
| Remote sensing (drones/satellites) | High resolution pasture and biomass mapping to guide adaptive grazing and prevent overgrazing under variable climates. | UAS + Sentinel-2 imagery with ML estimating forage quality for dynamic herd movement plans. |
| National/open data infrastructures | Standardized, interoperable platforms aggregating farm and climate data; power nationwide early warning and policy tools. | Central hubs fusing IoT, weather station and satellite feeds to issue heat stress or flood alerts. |
| Genomic/ AI assisted climate resilient breeding | Link genomic, performance, and climate data to select heat tolerance, disease resistance, feed efficiency, low methane. | Algorithms identifying heat tolerant cattle genotypes for subtropical regions. |
| AI enabled disease surveillance and biosecurity | Wearables and vision/AI detect abnormal behavior, predict vector borne hotspots, and trigger rapid response. | Early alerts from smart collars; AI mapping of Rift Valley fever risk for targeted vaccination. |

Table 2. Key limitations of smart farm technology and practical mitigation strategies.

| Limitation / challenge | Practical mitigation strategy |
|---|---|
| Connectivity and power limitations | Use hybrid edge–cloud designs; enable offline buffering; deploy resilient power and connectivity solutions. |
| High up-front and recurring costs | Phase deployment; prioritize high-impact use cases; consider cooperative/shared services and financing models. |
| Interoperability and vendor lock-in | Adopt open standards and Application Programming Interfaces (API)-based integration; require exportable data formats and portability in procurement. |
| Sensor noise, missing data, and data discontinuity | Implement calibration routines; redundancy; automated quality control pipelines; monitoring for missingness. |
| Limited labeled data and poor transferability across contexts | Use domain adaptation and local fine-tuning; conservative thresholds; include uncertainty checks. |
| Model drift over time | Routine validation; drift detection; scheduled updating and re-training with new data; ongoing performance audits. |
| Governance, privacy, and trust concerns | Clarify data rights and consent; transparent access/reuse policies; privacy protections; fair benefit sharing. |
| Equity and workforce capacity barriers | User-centered design; training modules; extension/technical support networks; locally relevant decision support. |