



Environmental Impact and Mitigation Approaches in Livestock Production Systems: A Review

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Review Article**Received: 22/05/2025****Published: 08/08/2025****ABSTRACT**

Livestock production systems are critical to global food security, economic development, and rural livelihoods, yet they impose considerable environmental burdens. The environmental impacts and mitigation strategies associated with livestock systems, focusing on greenhouse gas emissions, land degradation, water pollution, biodiversity loss, and antimicrobial resistance. Ruminants such as cattle and buffalo are major contributors to methane emissions through enteric fermentation, while pig and poultry operations generate significant amounts of ammonia and nutrient-rich effluents that contaminate water resources. Intensive systems accelerate land-use change for feed crop cultivation, leading to soil erosion and forest fragmentation, whereas extensive pastoral systems often result in overgrazing and desertification in fragile ecosystems. Technological interventions, including low-emission diets, precision feeding, anaerobic digestion, and biogas recovery, have demonstrated potential to mitigate environmental footprints. Genetic improvement programs targeting feed efficiency and methane-reducing traits, alongside indigenous breed conservation, offer complementary strategies. The integration of Internet of Things (IoT), artificial intelligence (AI), and microbiome engineering enables real-time monitoring and reduction of emissions at the farm level. Socio-economic factors such as livelihood dependency, gender dynamics, and market-driven sustainability influence the adoption of climate-smart livestock practices. Challenges include high technology costs, lack of emission data, institutional fragmentation, and behavioural resistance among smallholders. Climate-resilient infrastructure and silvopastoral systems provide adaptive solutions aligned with both productivity and ecological integrity. Coordinated policy frameworks, public awareness programs, and financial incentives are essential to support sustainable transitions. Livestock systems contribute significantly to environmental change. A science-based, multi-disciplinary approach integrating technological innovation, farmer empowerment, and systemic policy reform can enhance sustainability without compromising food and livelihood security. Bridging knowledge gaps and fostering inclusive, adaptive livestock development pathways remain key to achieving long-term resilience and low-carbon agricultural transformation. Advancing sustainable livestock calls for coordinated policy, transdisciplinary research, and farmer-centric innovation, ensuring ecological balance without compromising food and livelihood security.

Keywords: *Livestock; sustainability; emissions; biodiversity; manure; grazing; innovation.*

1. INTRODUCTION

Livestock are the domesticated animals raised in an agricultural setting to provide Labour and produce diversified products for consumption, such as meat, eggs, milk, fur, leather, and wool. The term is sometimes used to refer solely to animals that are raised for consumption, and sometimes used to refer solely to farmed ruminants, such as cattle, sheep, goats, and pigs (Uzonwanne et al., 2023). The agricultural sector is faced with the daunting challenge of producing food for a growing global population, which is expected to reach 8.5 billion by 2030, 9.7 billion by 2050, and 11.2 billion by 2100 (Ominski et al., 2021). Livestock production systems are agro-ecological frameworks that encompass the breeding, rearing, and management of domesticated animals such as cattle, sheep, goats, buffaloes, pigs, and poultry

for meat, milk, eggs, fibre, and draft purposes (Kumar et al., 2008). These systems are broadly categorized as extensive, intensive, or mixed crop-livestock systems based on land use, feed input, and productivity. For millennia, livestock have been a symbol of wealth and power across civilizations, and India is lucky to have the world's largest and most diverse livestock population (Singh et al., 2022). Livestock contributes approximately 40% of global agricultural GDP and supports the livelihood of over 1.3 billion people worldwide. The sector supplies 33% of dietary protein intake and 17% of global kilocalorie consumption. It plays a central role in the agro-based economy by integrating nutrient cycles and ensuring biomass recycling through manure. Livestock is a cornerstone of rural socio-economic frameworks, especially in low- and middle-income countries, by supporting income diversification, risk

management, and nutritional security. The World Bank reported that nearly 80% of smallholder households depend on livestock as a primary or supplementary income source (Herrero et al., 2013). The sector provides direct employment to around 600 million poor farmers and indirectly supports millions more through feed supply, veterinary services, processing industries, and marketing channels. Animal-derived foods such as milk, eggs, and meat supply essential nutrients like protein, iron, zinc, and vitamin B12, which are critical for addressing hidden hunger and child malnutrition. Livestock is also used as social capital and insurance against crop failure, enhancing resilience among vulnerable communities. While livestock contributes significantly to food and economic security, it is also a leading contributor to environmental degradation (Ehui et al., 1998). The sector is responsible for 14.5% of total anthropogenic greenhouse gas emissions, including methane (44%), nitrous oxide (29%), and carbon dioxide (27%). Intensive livestock farming exacerbates deforestation, biodiversity loss, water scarcity, and soil degradation through high feed demand, manure mismanagement, and land-use change. Rising consumer demand for animal products, projected to increase by 70% by 2050, necessitates an urgent transition towards sustainable and climate-resilient livestock practices. Without intervention, the environmental costs of livestock production could surpass its economic and nutritional benefits (Steinfeld et al., 2010). Synthesizes the environmental impacts and mitigation strategies associated with livestock systems, focusing on greenhouse gas emissions, land degradation, water pollution, biodiversity loss, and antimicrobial resistance.

2. TYPES OF LIVESTOCK PRODUCTION SYSTEMS

Extensive pastoral systems rely on the natural availability of grazing lands and are predominantly practiced in arid and semi-arid regions. These systems involve low-input and low-output livestock management, often characterized by free-range grazing, seasonal migration, and minimal external supplementation. The Food and Agriculture Organization (FAO) estimates that pastoralism supports around 200 million households globally and occupies approximately 25% of the Earth's land surface. Livestock densities are relatively low, which limits environmental degradation per unit area but may

still cause localized overgrazing, especially during droughts or under communal land tenure regimes. Soil compaction, desertification, and vegetation loss are common in degraded rangelands. Mixed systems integrate animal husbandry with crop cultivation, enabling nutrient cycling, diversified income sources, and efficient land use. Livestock are fed on crop residues and by-products while providing manure for soil fertility. This system accounts for nearly 50% of global livestock production and supports over 70% of smallholders. These systems are typically more sustainable due to the reuse of biomass and reduced dependency on synthetic inputs. Integration helps minimize waste and enhances farm resilience, though intensification pressures may lead to nutrient imbalances, especially when animal densities exceed nutrient absorption capacities of the farm (Sims et al., 2005). Intensive systems are highly mechanized and capital-intensive, involving confined animal feeding operations (CAFOs), standardized feed, and controlled environments (Abubakar et al., 2023). These systems produce large volumes of meat, milk, or eggs per unit area and represent the dominant model in developed economies and emerging economies. While they offer high productivity and biosecurity, they are also linked to significant environmental issues such as high greenhouse gas emissions, ammonia volatilization, antibiotic overuse, and water contamination due to concentrated manure discharge. Land use is optimized, but external feed production drives deforestation and land conversion elsewhere. Organic and integrated systems emphasize ecological balance, animal welfare, and minimal chemical input. Organic livestock systems prohibit synthetic hormones, prophylactic antibiotics, and Genetically Modified Organisms (GMOs), while requiring pasture access and organic feed. Integrated systems combine aquaculture, horticulture, and livestock (e.g., duck-fish-rice systems), aiming for closed-loop nutrient flows and ecological synergy (Mills & Driscoll, 2022). Though productivity is generally lower than in intensive systems, environmental outcomes are more favorable. Organic systems show 30–40% lower energy inputs and reduced nitrate leaching compared to conventional livestock farming. Manure management, crop rotation, and species diversity enhance ecosystem services, but widespread adoption is limited by certification costs and yield constraints. Ecological footprint varies markedly among livestock systems. Beef produced in extensive systems emits approximately 22–30 kg CO₂-eq/kg meat, while intensive beef systems

emit around 12–14 kg CO₂-eq/kg due to higher feed conversion efficiency but more fossil fuel input. Poultry and pig systems show lower emission intensities (~3–6 kg CO₂-eq/kg), particularly under intensive operations (Chakrabarti et al., 2015). Organic and integrated systems have reduced external input dependency and improved soil carbon sequestration, but may show higher land use per unit of product. The trade-off between efficiency and environmental sustainability remains complex, influenced by scale, local resources, and management practices. Sustainable intensification and adaptive grazing offer transitional models for balancing productivity with ecological stewardship.

3. ENVIRONMENTAL IMPACTS OF LIVESTOCK PRODUCTION

3.1 Greenhouse Gas Emissions

Methane is a potent greenhouse gas with a global warming potential 28–34 times higher than carbon dioxide over a 100-year period (Skytt et al., 2020). Livestock is a major source of anthropogenic methane, contributing approximately 44% of total agricultural emissions. Ruminants such as cattle, buffalo, sheep, and goats produce methane during enteric fermentation, a microbial digestive process in their rumen. Globally, enteric fermentation accounts for 89% of methane emissions from livestock, with manure management contributing the remaining 11%. An adult dairy cow can emit 250–500 litres of methane daily, depending on diet and physiological status. Nitrous oxide has a global warming potential nearly 298 times that of carbon dioxide and is emitted from manure decomposition and the application of nitrogenous fertilizers on feed crops. Manure contains organic nitrogen compounds that undergo nitrification and denitrification, releasing N₂O under aerobic and anaerobic conditions. Livestock manure and urine contribute to 50–60% of global N₂O emissions from agriculture. Intensive pig and poultry farms with concentrated manure storage are hotspots for N₂O generation, especially under warm and wet conditions. Land clearing for pasture and feed crop cultivation releases substantial amounts of CO₂ through biomass burning and soil carbon loss. Feed production alone contributes nearly 45% of total

Greenhouse Gas (GHG) emissions in the livestock value chain (Opio et al., 2013). Mechanized operations such as feed transport, processing, and temperature regulation in confined animal housing require significant fossil fuel inputs, compounding CO₂ emissions. Deforestation linked to soy and maize feed production for livestock has been a major contributor to emissions in Latin America and Southeast Asia. Life-cycle assessments (LCA) integrate emissions from feed production, animal husbandry, processing, transportation, and retail. According to FAO, beef production emits approximately 26.6 kg CO₂-eq per kg of edible product, followed by lamb (24.5 kg), pork (6.1 kg), and poultry (5.0 kg). Dairy emissions vary widely from 1.3 to 3.4 kg CO₂-eq per litre of milk, depending on production system and region. Feed conversion ratio, animal species, manure management, and energy source critically influence the emission intensity across systems.

3.2 Land Degradation and Deforestation

Overgrazing by unmanaged herds reduces vegetative cover, leading to soil exposure, erosion, and reduced infiltration (Blanco et al., 2023). It depletes root biomass, weakens soil structure, and promotes desertification. Livestock trampling causes compaction, reducing pore space and microbial activity. According to the United Nations Environment Programme (UNEP), over 20% of global rangelands are moderately to severely degraded due to excessive livestock pressure. Around 33% of global cropland is dedicated to producing feed for livestock, especially maize, soybeans, and barley. This expansion often displaces natural vegetation, contributes to biodiversity loss, and reduces carbon sequestration. Intensive feed crop production relies on heavy agrochemical use, causing long-term soil nutrient depletion and loss of organic matter. Livestock expansion has been identified as a primary driver of deforestation in tropical biomes. Between 1990 and 2015, over 71% of deforestation in Latin America was linked to pasture expansion. Forest-to-pasture conversion disrupts habitat continuity, impacts pollinators, and fragments critical corridors for wildlife movement. Soil nutrient leaching and edge effects degrade forest integrity even beyond the cleared zones (Weathers et al., 2001).

Table 1. Environmental Impacts of Livestock Production (Skytt et al., 2020, Opio et al., 2013)

S.No.	Impact Category	Cause	Environmental Consequence	Example
1	Greenhouse Gas Emissions	Enteric fermentation, manure, feed production	Global warming due to methane (CH ₄), nitrous oxide (N ₂ O), and carbon dioxide (CO ₂) release	Cattle release methane through digestion
2	Land Degradation	Overgrazing, deforestation for pasture	Soil erosion, desertification, loss of vegetative cover	Amazon deforestation for cattle ranching
3	Water Pollution	Manure runoff, improper waste disposal	Eutrophication, contamination of surface and groundwater	Algal blooms from livestock farm runoff
4	Water Scarcity	High water demand for animals and feed crops	Depletion of freshwater resources	Water use in beef production
5	Air Pollution	Ammonia, particulate matter from housing/manure	Respiratory issues, acid rain	Ammonia from pig farms affecting nearby communities
6	Biodiversity Loss	Habitat destruction, chemical inputs	Decline in wildlife, endangered species, ecosystem imbalance	Conversion of forests to grazing land
7	Antimicrobial Resistance	Overuse of antibiotics in livestock	Development of resistant bacteria, public health risks	Resistant Salmonella in poultry production
8	Climate Change Amplification	Intensive systems, fossil fuel dependency	Increased carbon footprint, disruption of climate regulation cycles	Energy use in industrial dairy farms
9	Waste Generation	Manure, carcass disposal	Odor issues, disease transmission, nutrient overload	Excess manure accumulation in confined animal units
10	Zoonotic Disease Emergence	Close human-animal interactions	Spillover of diseases from animals to humans	COVID-19 linked to wildlife trade and livestock mixing

3.3 Water Use and Pollution

Water demand varies by species and production system. It takes an estimated 15,400 liters of water to produce 1 kg of beef, compared to 4,300 liters for pork, 3,900 litres for chicken, and 1,000 liters for eggs. Water is used for animal drinking, feed crop irrigation, cleaning, and processing. Intensive systems require more blue water (irrigation), while extensive systems use more green water (rainfall). Livestock operations discharge large volumes of organic waste, pathogens, hormones, and heavy metals into water bodies. Nutrient-rich runoff from manure lagoons and feedlots leads to algal blooms and oxygen depletion. According to the United States Environmental Protection Agency (USEPA), animal agriculture is one of the leading causes of nonpoint source water pollution in rural areas of many countries. Improper manure management results in leaching of ammonia, nitrate, and phosphate into groundwater and surface waters (Khan et al., 2018). High nutrient loads, especially nitrogen and phosphorus, accelerate eutrophication in aquatic ecosystems. This leads to algal blooms, fish kills, and loss of aquatic biodiversity. Livestock-associated nitrate contamination is a major concern for drinking water safety. Levels exceeding 10 mg/L NO₃-N pose risks for methemoglobinemia in infants. Nitrate leaching from manure-applied fields persists for years, even after corrective measures are taken.

3.4 Biodiversity Loss and Habitat Fragmentation

Conversion of grasslands, wetlands, and forests to pasture displaces native species and alters ecological balance (Briggs et al., 2005). Grazing pressure favors invasive and unpalatable species while reducing palatable grasses and herbs. Ground-nesting birds, large herbivores, and pollinators are particularly vulnerable to habitat loss and food web disruption. Livestock movement and feed importation facilitate the introduction of invasive plant species, which outcompete native vegetation and degrade habitats. Introduction of high-yielding exotic breeds often results in loss of native livestock genetic diversity, limiting the gene pool for adaptation to climate stressors. Monoculture cultivation of feed crops like maize and soybean contributes to pest outbreaks, pollinator decline, and disruption of soil microbial communities. Repeated chemical use depletes beneficial insects and affects amphibian and reptilian populations that depend on aquatic and semi-aquatic systems bordering fields.

3.5 Antimicrobial Resistance (AMR) and Chemical Residues

Sub-therapeutic use of antibiotics in livestock for growth promotion and disease prevention accelerates the emergence of antibiotic-resistant bacteria (Kumar et al., 2018). These resistant

genes transfer to humans through direct contact, environmental pathways, or consumption of animal products. The World Health Organization (WHO) identified animal agriculture as a significant contributor to the global AMR crisis. Residual antibiotics alter soil and aquatic microbiomes, reducing microbial diversity and ecosystem resilience. Heavy metals such as copper and zinc used in animal feed accumulate in soils and water through manure application. These elements are persistent, toxic to soil organisms, and inhibit plant growth. Hormonal residues and antiparasitic drugs disrupt aquatic fauna and endocrine systems in wildlife. The long-term bioaccumulation of such residues poses a threat to food safety and public health.

4. REGIONAL AND SPECIES-SPECIFIC ENVIRONMENTAL CONCERNS

Livestock species exhibit varying degrees of environmental impact, primarily driven by differences in digestive physiology, feed conversion efficiency, and waste output (Herrero et al., 2013). Ruminants, such as cattle, sheep, and goats, possess a complex stomach that enables fermentation of fibrous plant material. This process produces substantial quantities of methane through enteric fermentation, making ruminants significant contributors to greenhouse gas (GHG) emissions. According to FAO, ruminants account for 77% of the livestock sector's methane emissions, with cattle alone contributing 65% of the sector's total emissions. The GHG emission intensity of beef production is approximately 26.6 kg CO₂-eq per kg of meat, while lamb emits 24.5 kg CO₂-eq/kg. Monogastric animals, such as pigs and poultry, do not produce methane through enteric fermentation and have higher feed conversion efficiencies. Poultry emits 5.0 kg CO₂-eq per kg of meat, while pork results in 6.1 kg CO₂-eq/kg. These species also require less land and water per unit of protein output. Despite lower direct emissions, monogastric systems exert considerable environmental pressure through high demand for concentrated feed grains like maize and soybeans, intensifying land-use change and biodiversity loss linked to monocultures. Waste from intensive pig and poultry operations, rich in nitrogen and phosphorus, is a major contributor to water eutrophication and soil pollution (Sajjad et al., 2024).

Buffalo contributes to environmental concerns through methane emissions, though slightly

lower than cattle due to different rumen fermentation dynamics. They are heavily dependent on low-quality roughage and produce approximately 55–60% of the methane emissions per unit of milk compared to exotic dairy cattle. Buffalo are also often raised in regions with water constraints, and their higher water requirements for cooling and drinking increase blue water consumption. Goats, due to their browsing habits, are well-suited to arid and semi-arid conditions but can exacerbate vegetation degradation through selective overgrazing, especially of shrubs and regenerating trees. Over time, this browsing pressure contributes to bush encroachment, soil erosion, and reduced biodiversity in fragile rangelands. Goats emit lower methane per unit body weight but may have higher methane emission intensities per unit of meat due to slower growth and lower productivity (Pragna et al., 2018). Poultry farming, while efficient in terms of feed-to-protein conversion, generates concentrated waste rich in ammonia, leading to air and water pollution. Intensive poultry operations are hotspots for antimicrobial usage, contributing to antimicrobial resistance (AMR) development. Feather and litter management remains a challenge, as their disposal without adequate treatment results in nutrient leaching and surface water contamination.

Livestock practices exert differentiated environmental impacts across agro-ecological zones (AEZs), influenced by climatic conditions, soil properties, vegetation cover, and socio-economic systems (Seo et al., 2008). In humid tropics, high rainfall and poor drainage amplify the risk of nutrient leaching and eutrophication from manure and urine deposition. In arid and semi-arid zones, overstocking and prolonged grazing periods intensify desertification, soil compaction, and vegetation loss, especially under communal grazing systems. In mountainous and hilly zones, livestock contributes to slope instability and forest encroachment. Trampling and manure deposition on steep terrains accelerate erosion and downstream sedimentation. In high-altitude pastoral systems, livestock affects fragile alpine biodiversity and contributes to glacial melt via localized warming. In coastal and deltaic regions, livestock effluents from pig and poultry farms pollute mangrove ecosystems and estuarine fisheries. Salinization from improper manure disposal in waterlogged zones degrades land and freshwater resources. Regionally adapted strategies such as rotational grazing in semi-arid

zones, manure management in humid AEZs, and agroforestry integration in mountainous systems are essential to mitigate these ecological burdens (Ondrasek & Zhang, 2023).

5. MITIGATION APPROACHES FOR SUSTAINABLE LIVESTOCK PRODUCTION

5.1 Nutritional and Feed Management Strategies

Livestock diets significantly influence enteric methane emissions (Bell et al., 2016). Inclusion of high-digestibility feeds such as legume-based forages and bypass proteins reduces methane production per unit of output. Feeding strategies like total mixed rations (TMR) and lipid supplementation (e.g., linseed oil, coconut oil) reduce enteric fermentation rates. Fat inclusion in ruminant diets can reduce methane emissions by up to 20%. Nitrate-based feed additives act as alternative hydrogen sinks in the rumen, decreasing methanogenesis. Synthetic compounds such as 3-nitrooxypropanol (3-NOP) have shown methane reduction efficacy up to 30% in beef and dairy systems. Probiotics and direct-fed microbials alter rumen microbial populations, promoting propionate production over acetate, thereby reducing hydrogen availability for methanogens. Condensed tannins from plants like quebracho and essential oils such as thymol and eugenol possess antimicrobial properties that suppress methanogenic archaea. Tannins at 2–4% of dry matter can reduce methane by 10–25% without affecting digestibility. These phyto-additives offer natural, residue-free solutions compatible with organic systems. Precision feeding technologies match nutrient supply with animal requirements, improving feed conversion and reducing nutrient excretion (Empel et al., 2016). Phase feeding in monogastric systems involves adjusting feed formulations across different growth stages, optimizing protein and energy use. This approach reduces nitrogen excretion by 20–30%, mitigating ammonia volatilization and nitrous oxide emissions. Near-infrared spectroscopy and automatic feeders support real-time diet adjustments and minimize overfeeding.

5.2 Manure Management and Waste Recycling

Anaerobic digesters convert manure into methane-rich biogas and nutrient-dense slurry under oxygen-free conditions (Ahmad et al.,

2019). This not only captures methane that would otherwise escape into the atmosphere but also produces renewable energy. One ton of cattle manure can yield 20–25 m³ of biogas, replacing 6–7 kg of firewood or 2–3 liters of diesel. Digestate retains macro and micronutrients, reducing chemical fertilizer dependency. Aerobic composting stabilizes manure, reduces odor, and lowers pathogen load. Proper composting reduces nitrogen loss through ammonia volatilization and inhibits methane production. Vermicomposting, using species like *Eisenia fetida*, accelerates organic matter breakdown, enhances microbial diversity, and improves soil structure when applied to fields. Studies have shown vermicompost improves crop yields by 15–20% over raw manure application. Constructed wetlands are engineered ecosystems that use aquatic plants and microbial communities to filter manure-laden wastewater. They significantly reduce biochemical oxygen demand (BOD), total nitrogen, and phosphorus. Nutrient recovery systems like struvite precipitation capture phosphorus for reuse in agriculture (Saliu & Oladoja, 2021). These technologies prevent water pollution and enhance circularity within livestock systems.

5.3 Genetic Improvement and Breeding Techniques

Animals with high residual feed intake (RFI) require less feed for the same output and emit less methane (Hegarty et al., 2007). Genetic selection for low RFI improves herd productivity and environmental sustainability. Low-RFI cattle emit 15–20% less methane than their high-RFI counterparts. Local breeds are adapted to specific agro-ecological conditions, requiring fewer inputs and exhibiting higher disease tolerance. They are better suited for extensive and organic systems. For instance, Sahiwal cattle and Black Bengal goats show superior heat tolerance and resource efficiency compared to exotic breeds. Promoting such breeds conserves genetic diversity and reduces ecological pressure. Genomic tools enable precise identification of desirable traits such as disease resistance, methane reduction, and improved feed utilization. Marker-assisted selection and CRISPR-based genome editing target genes like DGAT1 (milk yield) or MSTN (muscle growth) for enhanced productivity. Gene-edited animals, when ethically and legally validated, could accelerate sustainability in the livestock sector (Hallerman et al., 2024).

Table 2. Mitigation Approaches for Sustainable Livestock Production (Source: Bell et al.,2016, Ahmad et al., 2019)

S.No.	Approach Category	Mitigation Strategy	Key Benefits	Example/Application
1	Feeding and Nutrition	Use of balanced rations, feed additives, improved digestibility	Reduces methane emissions, improves feed efficiency	Addition of tannins or oils in cattle diets
2	Manure Management	Anaerobic digestion, composting, bio-slurry utilization	Reduces GHGs, produces biogas and organic fertilizer	Biogas plants using cow dung
3	Breeding and Genetics	Selection for low-emission and high-efficiency breeds	Enhances productivity, reduces emissions per unit of output	Breeding heat-tolerant, disease-resistant animals
4	Housing and Waste Systems	Improved ventilation, waste separation systems	Lowers ammonia emissions, improves animal welfare	Slatted floors and separate urine-feces systems
5	Pasture and Grazing Management	Rotational grazing, silvopasture, cover crops	Prevents overgrazing, enhances carbon sequestration	Silvopasture in tropical regions
6	Health and Disease Control	Vaccination, biosecurity, regular health checks	Reduces antibiotic use, improves animal performance	FMD vaccination programs
7	Water Resource Efficiency	Rainwater harvesting, efficient watering systems	Reduces water footprint, conserves freshwater	Drip irrigation for fodder crops
8	Climate Smart Practices	Integration with agroforestry, carbon credits	Increases resilience, provides co-benefits like income diversification	Livestock-agroforestry in mixed farms
9	Policy and Institutional Support	Incentives, subsidies, awareness programs	Promotes adoption of sustainable practices	Payments for ecosystem services to livestock farmers
10	Monitoring and Technology Use	Sensors, traceability systems, mobile advisory platforms	Enhances decision-making, real-time health and emission tracking	Wearable health trackers for dairy cattle

5.4 Housing and Farm Management

Improved animal housing enhances thermal comfort, reduces stress, and improves productivity. Insulated roofing, natural ventilation, and solar-powered fans reduce energy use. Bioclimatic shelters using bamboo, clay tiles, and green roofing reduce GHGs by minimizing mechanical cooling. Energy-efficient housing also facilitates mechanized waste collection and better hygiene. Automatic manure scrapers in dairy barns collect waste continuously, reducing anaerobic decomposition and methane release. Efficient drainage channels reduce urine stagnation and ammonia emission. These systems also reduce Labour and enhance biosecurity, particularly in closed animal housing. Biological filters, microbial sprays, and organic deodorants help mitigate odor and fly infestations associated with manure. Fly-repelling plants like *Ocimum basilicum* or neem leaf extracts offer natural vector control (Bootyothee et al., 2022). Proper waste management, combined with such ecological approaches, improves animal welfare and neighbor compliance.

5.5 Pasture and Grazing Management

Rotational grazing involves periodic movement of animals across paddocks, allowing forage

regeneration and reducing overgrazing (Smith et al., 2011). Deferred grazing schedules specific rest periods to enhance root biomass and carbon sequestration. These techniques improve soil fertility and reduce erosion. Silvopastoral systems integrate trees, shrubs, and pasture, enhancing biodiversity and productivity. Leguminous trees such as *Leucaena leucocephala* fix nitrogen and provide protein-rich forage. These systems sequester carbon, mitigate microclimate extremes, and offer diversified income. Silvopastoral models could sequester 1.5–3.0 tons of CO₂/ha/year, making them viable climate mitigation tools. Degraded pastures can be rehabilitated through re-seeding with climate-resilient grasses like *Brachiaria* or *Panicum maximum*. Inclusion of legumes such as *Stylosanthes* or *Desmodium* improves soil nitrogen content and enhances animal nutrition. These practices reduce the need for chemical fertilisers and improve forage productivity by 20–40%.

6. ROLE OF RESEARCH, INNOVATION, AND TECHNOLOGY ADOPTION

Precision livestock farming (PLF) integrates advanced digital tools, sensors, and data analytics to monitor, manage, and optimize animal health, productivity, and environmental

performance in real time (Kaledio & Russell, 2023). These technologies enable individualized animal management by tracking parameters such as body temperature, feeding behaviour, weight gain, rumination patterns, and estrus cycles. Electronic identification (EID) tags, automatic milking systems (AMS), and real-time location systems (RTLS) are widely employed to enhance decision-making and reduce resource wastage. Research indicates that PLF can improve feed efficiency by 15–20%, reduce methane emissions by optimizing diet schedules, and decrease antimicrobial use through early disease detection. For instance, acoustic sensors used in swine production can detect respiratory diseases up to 4 days earlier than visual inspection. The Internet of Things (IoT) facilitates the continuous collection of environmental and animal data through interconnected sensors and devices, enabling accurate emission profiling and real-time adjustments in farm operations. AI-driven algorithms process large datasets to detect patterns and predict future trends in livestock productivity, health, and emissions (Ali et al., 2025). Remote sensing tools, including satellite and drone imagery, are utilized for pasture monitoring, mapping grazing intensity, and detecting stress conditions. Combined, these tools help reduce overgrazing and optimize manure application by identifying nutrient-deficient zones. AI models trained on historical emissions data from livestock barns can predict peak methane release periods, allowing farmers to synchronize feed formulations accordingly. Integration of IoT and AI has shown potential to reduce GHG emissions by up to 25% in commercial livestock units. Microbiome engineering focuses on altering the gut microbial composition of livestock to enhance nutrient utilization and suppress methane-producing archaea. Strategies include selective breeding for low-methane microbiota, use of direct-fed microbials (DFMs), and early-life microbial colonization management. Rumen manipulation through inoculation of methanotrophic bacteria and use of bacteriophages targeting methanogens is emerging as a viable approach to reduce enteric methane production. A study demonstrated that specific microbiome signatures could reduce methane emissions by 20–30% without affecting animal growth. Moreover, microbial enzymes that degrade lignocellulosic biomass improve feed digestibility and reduce fibre-related emissions (Bhandari et al., 2023). Synthetic biology approaches aim to create designer microbial consortia tailored for methane mitigation, feed efficiency, and animal

health. Climate-resilient infrastructure involves structural designs and operational protocols that reduce vulnerability to heat stress, flooding, and other climate extremes. Passive cooling technologies such as high-albedo roofing, misting systems, evaporative cooling pads, and ventilated housing reduce heat-induced productivity losses. Studies show that heat stress can reduce milk yield in dairy cattle by up to 25% while increasing susceptibility to mastitis and reproductive failure. Mobile animal shelters and raised flooring prevent disease spread during heavy rainfall events, especially in flood-prone zones. Integration of solar-powered systems for water pumping, lighting, and ventilation reduces dependence on fossil fuels and lowers operational emissions. Climate-smart livestock shelters, when combined with digital environmental controls, contribute to a 10–15% improvement in feed efficiency and a 20% reduction in heat-related mortality (Ayoola et al., 2025).

7. SOCIO-ECONOMICS AND CULTURE

7.1 Livelihood Dependency and Rural Employment

Livestock production systems are vital for rural livelihoods, offering income, employment, draught power, food security, and asset accumulation. Globally, livestock supports the livelihoods of over 1.3 billion people, with more than 600 million poor farmers directly dependent on animal husbandry for sustenance and cash income. Smallholder and mixed crop-livestock systems are dominant in low- and middle-income economies, where they account for up to 70% of livestock output. Beyond direct income, livestock contributes to employment across value chains, including feed supply, processing, marketing, veterinary services, and transportation. Livestock provides up to 35% of total household income in pastoral systems and 15–25% in integrated mixed systems. Ruminants, particularly cattle and buffalo, are central to traditional livelihoods in arid and semi-arid regions, while poultry and goats serve as accessible entry points for asset creation among landless and resource-poor households. Livestock also functions as a financial buffer, enabling risk coping during crop failure or emergencies (Matter et al., 2021). The multi-functional role of livestock in food, income, security, and social capital makes it indispensable in rural socio-economic structures.

7.2 Gender Roles and Smallholder Farmer Participation

Livestock rearing exhibits significant gender dimensions (Kinati & Mulema, 2018). Women play a predominant role in backyard poultry, small ruminant care, and milk processing, often performing more than 60% of the Labour associated with animal husbandry tasks. Despite this, gender disparities persist in access to livestock ownership, credit, extension services, and decision-making. Male-dominated land rights and inheritance systems limit women's ability to scale production or invest in sustainable technologies. Women are often excluded from livestock markets and cooperatives due to socio-cultural barriers, impacting their ability to participate in formal economies. Empowering women through targeted training, credit access, and inclusive value chains has been shown to improve livestock productivity and household nutrition outcomes. A study revealed that households with women in control of dairy income invested more in children's education and health.

7.3 Public Awareness and Behavioural Change Models

Environmental impacts of livestock production remain poorly understood among producers and consumers (Poore & Nemecek, 2018). Traditional practices often persist due to limited exposure to sustainable alternatives or mistrust of modern techniques. Public awareness campaigns on topics such as antimicrobial resistance, waste management, and GHG emissions can improve producer compliance with environmental standards. Behavioural change communication (BCC) models based on community engagement and peer learning show higher adoption rates of climate-smart livestock practices. Participatory rural appraisal, farmer field schools, and village-based animal health workers are effective platforms for disseminating information. Media interventions combined with mobile-based advisory systems have improved vaccination rates and reduced misuse of antibiotics (Schranz et al., 2025). Social norms and peer influence play critical roles in decision-making, indicating that culturally aligned approaches yield better behavioural outcomes than top-down enforcement models.

7.4 Market Incentives and Consumer-driven Sustainability

Market-based instruments such as certification schemes, carbon credits, and green labelling

influence producer practices by linking environmental performance with economic gains (Negra & Havemann, 2020). Eco-labelling of meat, milk, and eggs based on emissions, welfare, and residue-free production allows consumers to make informed choices, fostering demand for sustainable products. The emergence of climate-smart value chains and public procurement policies that priorities low-emission food systems encourages producers to adopt improved practices. Subsidies for bio-digesters, water-saving equipment, or rotational grazing infrastructure reduce transition costs for smallholders. Access to carbon markets for manure management or silvopastoral systems creates an additional revenue stream. Sustainability certification in livestock can improve farm incomes by 10–25% through premium pricing and better market access. Consumer preferences are increasingly shifting towards ethically produced and traceable livestock products, exerting pressure on the supply side to innovate sustainably (Moran & Blair, 2021).

8. CHALLENGES AND LIMITATIONS IN IMPLEMENTATION

8.1 Technological Gaps and Cost Barriers

The adoption of sustainable livestock practices is hindered by limited access to advanced technologies, particularly among smallholders and resource-poor farmers (Vasavi et al., 2025). Precision livestock farming tools, automated feeding systems, and emission-monitoring sensors often require high initial investment, maintenance, and technical expertise. Studies show that the cost of installing an automated milking system ranges between USD 150,000–250,000, making it inaccessible to small-scale producers. Anaerobic digesters and biogas units also entail capital costs that exceed the financial capacity of many livestock households, despite their long-term benefits. Limited rural infrastructure and weak extension networks contribute to technological stagnation. For instance, only 25–30% of livestock producers globally have access to digital advisory services or mechanised systems. Without financial incentives, credit support, or cooperative-based resource pooling, transitioning to low-emission or climate-resilient systems remains economically unfeasible for a large segment of farmers. This leads to continued reliance on traditional, less sustainable practices.

8.2 Lack of Data, Skilled Manpower and Awareness

Monitoring, reporting, and verification (MRV) systems essential for quantifying emissions, tracking productivity, and guiding policy are underdeveloped in the livestock sector (Wilkes et al., 2017). Data on species-specific emissions, manure nutrient composition, feed efficiency, and disease prevalence remain fragmented or outdated. As noted, reliable emission inventories are only available for a limited number of regions and species, limiting the design of targeted mitigation strategies. The shortage of skilled veterinarians, livestock nutritionists, and animal health technicians further restricts the implementation of science-based interventions. A global average of 0.4 veterinarians per 1,000 livestock units reveals a significant service gap, with many remote areas lacking veterinary access entirely. Farmers often lack awareness of GHG emissions, AMR risks, and waste recycling options due to inadequate training and education, resulting in low uptake of best practices (Fuller et al., 2023).

8.3 Policy Fragmentation and Institutional Overlaps

Sustainable livestock governance suffers from fragmented institutional responsibilities, with overlapping mandates between ministries of agriculture, environment, rural development, and livestock. This leads to poor coordination, duplication of efforts, and gaps in service delivery. For instance, manure management may fall under environmental regulations while animal health is governed by agricultural departments, resulting in misaligned objectives. Lack of harmonized policies and coherent incentive frameworks undermines the scalability of mitigation efforts. While some programs support climate-resilient livestock initiatives, others continue subsidizing high-emission practices like feed-intensive commercial expansion without environmental conditionalities. The need for cross-sectoral integration to align livestock development with climate adaptation and biodiversity goals (Berry et al., 2015). Inconsistent enforcement of environmental laws and weak compliance mechanisms further diminish policy effectiveness.

8.4 Resistance to Change in Traditional Practices

Deep-rooted cultural norms, customary knowledge, and risk aversion influence farmer

decisions more than environmental or economic rationale (Shackleton et al., 2015). Traditional herders and pastoralists often resist controlled grazing systems, rotational paddocking, or stall feeding due to perceived loss of autonomy or incompatibility with migratory lifestyles. Transitioning from open grazing to enclosed or semi-intensive systems involves behavioural shifts that require long-term engagement and trust-building. Mistrust of modern veterinary inputs, scepticism about feed supplements, and reluctance to adopt new breeds persist in many rural communities. Behavioural inertia is compounded by low literacy, lack of demonstration models, and absence of community champions promoting sustainable practices. Adoption of innovations in livestock systems is slow unless perceived as immediately beneficial, affordable, and compatible with existing knowledge systems (Lema et al., 2021).

9. CONCLUSION

Livestock production systems contribute significantly to global food supply and economic stability, yet they exert complex environmental pressures, including greenhouse gas emissions, land degradation, water contamination, biodiversity loss, and antimicrobial resistance. This synthesis underscores that mitigation requires a multi-faceted approach combining feed optimization, manure valorization, genetic selection, and precision technologies. Integrating IoT and AI enhances real-time emission control, while microbiome engineering reduces enteric methane without sacrificing productivity. Silvopastoral practices and rotational grazing restore degraded lands and boost carbon sequestration. Socio-economic considerations such as livelihood dependence, gender dynamics, and affordability strongly influence technology uptake. Constraints like institutional fragmentation, limited emission data, and behavioural resistance hinder progress. Future resilience hinges on climate-smart infrastructure, local breed conservation, inclusive extension systems, and market-based sustainability incentives. Advancing sustainable livestock calls for coordinated policy, transdisciplinary research, and farmer-centric innovation, ensuring ecological balance without compromising food and livelihood security.

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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