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Editorial

Reconfiguring livestock value chains for climate resilience: circular and nature-based transitions through transdisciplinary governance

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The synergistic impacts of climatic instability, ecosystem degradation, and public health vulnerabilities have placed the livestock sector at a critical crossroads. Heat waves, prolonged droughts, intensifying monsoons, floods, cyclones, and progressive salinization are no longer isolated disturbances; they interact across spatial and temporal scales to create compound shocks, triggering cascading crisis and disruptions that ripple through livestock value chains, from feed production and on-farm management to processing, distribution, market access, and consumption (IPCC, 2022). Existing livestock systems, characterized by fragmented, linear "take–make–dispose" paradigms, magnify climate vulnerability by relying on fragile supply chains and unregulated waste streams that externalize pollution, health risks, and social inequities. However, when strategically reconfigured around circular resource flows, ecosystem-based buffering, and inclusive governance, livestock systems can transform from brittle liabilities into resilient hubs for food security and 'One Health'. A growing body of interdisciplinary research underscores the need for a fundamental reimagining of how resources, risks, and benefits are produced, distributed, and governed across integrated value chains (Tendall *et al*., 2015). A pragmatic pathway to such transformation harmonizes four mutually reinforcing pillars: (i) circular economy (CE) principles, (ii) nature-based solutions (NbS), comprising ecosystem-based adaptation (EbA), (iii) robust measurement, reporting, and verification (MRV) systems, and (iv) transdisciplinary co-production of knowledge and interventions. Individually, these pillars address material inefficiencies, ecological degradation, informational gaps, and institutional fragmentation; collectively, they unlock synergies that enhance adaptive capacity, strengthen equity, and enable scalable resilience across diverse contexts.

Adaptation practices rooted in circularity principles reconceptualize livestock "wastes," such as manures, crop and market residues, and processing by-products, as valuable resources within closed loops. The CE framework prioritizes actions that eliminate waste and pollution, keep materials in use at their highest value, and regenerate natural systems (Geissdoerfer *et al*., 2017). In livestock contexts, anaerobic digestion (AD) converts organic waste into biogas for cooking, heating, or electricity, while producing nutrient-rich digestate that can substitute for mineral fertilizers and enhance soil fertility (FAO, 2021). Composting and biochar applications improve soil structure, increase water-holding capacity, and stabilize nutrient supply, thereby buffering fodder systems against heat and drought stress (Fierer *et al*. 2021). Insect bioconversion, such as through black soldier fly larvae, transforms wet organic waste into protein-rich feed ingredients and frass fertilizer, reducing dependence on imported feeds and exposure to volatile global markets (Smetana *et al*., 2019; Tepper *et al*., 2024). These circular loops synergize with ecosystem functions to stabilize energy and nutrient flows, making them particularly important for disaster-prone regions where climate shocks are most acutely felt.

Complementing circular material flows, NbS operate at field, farm, and landscape scales to restore and enhance the ecological functions that underpin livestock productivity and resilience. Silvopastoral systems, which integrate trees and livestock forage, provide shade that lowers radiant heat loads, moderates microclimates, and diversifies fodder sources. This mitigates thermal stress and improves animal welfare during heat extremes (Murgueitio *et al*., 2011). Riparian buffers, vegetated drains, and constructed wetlands filter nutrients, sediments, and pathogens from runoff, protect downstream water bodies, and enable safe water reuse for irrigation. In coastal and deltaic regions, mangrove belts and salt-tolerant vegetative buffers attenuate storm surges and enhance sediment stability, providing protective services while supporting ancillary livelihoods. Far from being passive conservation measures, these NbS function as productive ecological infrastructure that delivers measurable gains in resilience, pollution control, and ecosystem services when systematically integrated into livestock production and value chains (Chausson *et al*., 2021).

Examining resilience through a value-chain lens clarifies where integrated interventions generate the greatest leverage and highlights how fragmentation undermines system performance. Climate shocks manifest differently across the nodes of the livestock value chain; therefore, resilience strategies must be tailored accordingly. At the upstream (input) node, vulnerability is often driven by dependence on imported feed ingredients, limited domestic feed markets, exposure to transport disruptions, and price volatility during floods, cyclones, or fuel shocks. Circular feed strategies, including agro-residue upcycling, hydroponic fodder sprouting, and localized insect protein production, are instrumental in enhancing local autonomy, shortening supply chains, and reducing vulnerability to long-distance logistical failures. Studies from low- and middle-income contexts demonstrate that community-managed fodder banks and decentralized feed production systems can significantly reduce livestock losses and distress sales while lowering greenhouse gas emissions associated with feed transport (van Huis *et al*., 2013; FAO, 2021).

At the on-farm production node, climate stressors such as rising heat load, water scarcity, and shifting disease pressure directly affect feed intake, reproduction, and productivity. Nature-based interventions, including silvopasture, clustered shade trees, and vegetated roofing, reduce the temperature–humidity index (THI) and improve thermal comfort, thereby sustaining intake, milk, and egg yields (Edwards-Callaway *et al*., 2021). When combined with circular soil amendments such as digestate, compost, and biochar, these practices enhance soil organic matter, moisture retention, and fodder reliability during dry periods. Integrating low-cost THI and water-stress sensors into decision support systems enables real-time animal welfare responses (e.g., feed timing, emergency cooling). When linked to composite indices, these systems can trigger index-based insurance payouts or rapid microgrants, translating climate signals into actionable risk finance (Carter *et al*., 2017; Tangorra *et al*., 2024). By utilizing sensors and artificial intelligence (AI) to monitor animal health continuously, precision monitoring allows farmers to stay ahead of disease outbreaks and make smarter, data-driven decisions that protect their herds from climate stress.

Live animal markets, milk collection centers, and slaughterhouses at the midstream aggregation and processing nodes are frequently hotspots for pollution and disease transmission. Modularity and decentralization through mobile slaughter units, renewable-energy-powered cold storage, and contingency waste treatment enable continuity of services during floods, power outages, or supply disruptions. Constructed wetlands and AD systems designed with hydraulic buffering reduce uncontrolled effluent discharge during extreme events, protecting downstream ecosystems and public health while producing energy and soil amendments that support post-shock recovery (Rahman *et al*., 2019; Suttles *et al*., 2021).

At the downstream distribution and market node, climate shocks frequently disrupt transportation and market access, disproportionately affecting smallholders who rely on informal trading networks. Shortening value chains through local processing, cooperative marketing, and digital trading platforms enhances flexibility and speeds recovery. By utilizing basic digital tools such as message alerts through mobiles and simple traceability records, farmers receive immediate intelligence on market conditions. Operational market intelligence, combined with incentivized certification schemes, enables producers to redirect products toward functioning markets during floods, stabilizing incomes and food availability while promoting verified resilience practices (Custodio *et al*., 2023; World Bank, 2023).

A critical conceptual shift is required across all value-chain nodes: disaster coping, adaptation, and transformation must be designed concurrently rather than in discrete stages. Short-term coping mechanisms, e.g., emergency feed reserves, raised shelters, mobile veterinary services, and digital price alerts, help preserve assets during acute shocks and create conditions that allow adaptive and transformative interventions to succeed. Adaptive measures stabilize productivity under gradually changing conditions, while regenerative circular economy–nature-based solutions (CE–NbS) strategies enable longer-term transformation toward sustainability and equity (Tendall *et al*., 2015). When integrated into a cohesive value-chain framework, these processes allow livestock systems to absorb shocks, reorganize, and continue functioning without crossing irreversible ecological or socioeconomic thresholds.

Circularity strengthens ecological resilience by stabilizing energy, nutrient and material flows during climate and supply-chain shocks. However, these benefits depend on robust One Health safeguards. Without disciplined source control, routine residue testing, and antimicrobial stewardship, circular reuse pathways can inadvertently amplify antimicrobial resistance (AMR), heavy-metal contamination, and microplastic accumulation across soils, waters, and food chains (Martínez, 2009; Rillig and Lehmann, 2020). Therefore, operationalizing safe circularity requires source segregation at entry points, routine chemical and biological certification of digestate and insect feeds, and nature-based treatment systems designed to intercept debris and microplastics before reuse or discharge. For smallholders, these safeguards must be provided through shared facilities, mobile diagnostics, technical assistance, and cost-sharing mechanisms. Scaling these efforts requires building decentralized lab networks, implementing standardized protocols, and ensuring traceable chains of custody.

Technical options, whether circular or nature-based, do not operate in a social vacuum. Their effectiveness depends on governance arrangements, incentive structures, and local legitimacy; this makes transdisciplinary co-production indispensable. Convening ecologists, animal scientists, veterinarians, engineers, economists, extension agents, private-sector actors, policymakers, and producer communities enables the joint design of interventions that are technically robust, culturally appropriate, and financially viable. These platforms provide a structured approach to implementing sustainable interventions. They not only highlight crucial trade-offs, such as resource efficiency versus potential contamination but also facilitate the co-design of institutional arrangements for operation and maintenance, and create mechanisms for benefit-sharing, data governance, and grievance redress. This ensures that benefits are shared fairly and prevents elite capture, allowing community-engaged CE–NbS interventions to succeed and sustain beyond pilot phases (Notenbaert *et al*., 2017; Hölscher *et al*., 2024). Equity is not ancillary; it is foundational to climate-resilient livestock systems. Women often play a primary role in livestock husbandry yet remain constrained by limited access to capital, land tenure, and decision-making authority, particularly in developing countries. Targeted microfinance, reserved governance seats, women-led training programs, and inclusive digital tools are critical to ensure that resilience dividends reach those most exposed to climate risk (Amoak and Najjar, 2025). Integrating informal actors like market waste recyclers and small slaughter operators into structured monitoring, management, and certification pathways can mitigate hazardous practices while fostering safer, more dignified livelihoods.

Robust MRV systems provide the essential evidence backbone for scaling sustainable practices. Hybrid MRV frameworks integrate a diverse set of tools, including low-cost on-farm sensors, satellite-derived indicators (like NDVI and flood extent), and targeted laboratory diagnostics (such as residue profiles and AMR markers), alongside participatory verification to generate layered, auditable records of environmental, production, and health outcomes. This comprehensive approach, when properly designed into composite indices, effectively reduces basis risk for parametric insurance and forms the foundation for results-based payments, preferential procurement, and the ability to secure price premiums for verified resilient products (Carter *et al*., 2017; Tangorra *et al*., 2024). Furthermore, equity-sensitive data governance, grounded in cooperative stewardship and low-barrier access, is essential for ensuring that inclusive MRV processes and broader digitalization efforts are effective and fair.

At the meso-institutional level, cooperative hubs emerge as catalytic platforms that translate these principles into operational reality. By aggregating feedstocks, hosting anaerobic digestion and insect larvae processing, operating sensor gateways, and facilitating laboratory certification, these hubs can lower transaction costs and professionalize transdisciplinary coordination. They anchor blended finance architectures through a combination of seed grants, concessional loans, first-loss capital, extended producer responsibility funding, and payments for ecosystem services, aligning private incentives with public goods and sustaining long-term adaptation (World Bank, 2023). Additionally, cooperative hubs may serve as living laboratories where participatory trials iteratively refine species selection, operational protocols, and context-specific monitoring indicators, synchronizing ecological functions, circular flows, biosafety safeguards, and institutional arrangements around feasible, locally aligned resilience outcomes.

Technical solutions alone will not create climate-resilient livestock systems. The real hurdles lie in governance, data transparency, and accessing capital, which demand a transformative systemic redesign. Empirical demonstrations, from floating gardens in floodplains to community digesters and constructed wetlands, confirm feasibility while exposing persistent constraints (limited lab capacity, quality-control costs, governance gaps) that require targeted policy reform, blended finance, and sustained capacity building (FAO, 2019; Masoud *et al*., 2022). Therefore, technical reforms integrating CE and NbS that maximize resource use, restore ecological functions, and provide buffers should be blended with digital MRV to validate outcomes that are verifiable and financeable, as well as with transdisciplinary co-production to ensure fitness, legitimacy, and equity. These initiatives, supported by consistent policy and sustained investment, can turn livestock systems from climate liabilities into resilient assets. Immediate priorities should focus on piloting integrated regional hubs, investing in diagnostics, developing finance triggers, and aligning regulations across critical sectors, including waste, agriculture, and One Health domains, to secure a sustainable future. As we navigate a warming world, the capacity to redesign livestock systems as adaptive, regenerative, and inclusive will increasingly determine not only production outcomes but also sustainable livelihoods, nutrition, and ecosystem health for generations to come.

Ethical approval and informed consent
Not applicable.

Data availability
Not applicable.

Conflict of interest
None to declare.

Author's contribution
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