



LIVESTOCK UNDER SCRUTINY: INTERPRETING EMISSIONS, WATER, AND LAND METRICS IN CONTEXT

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Abstract: A growing global population and finite natural resources have intensified debate over the environmental sustainability of food production systems. Within this landscape, the livestock sector is frequently criticized based on greenhouse gas emissions, water footprint, and land use; yet these assessments often involve methodological inconsistencies and comparisons detached from biophysical context. This review re-examines common claims directed at livestock by drawing on the scientific literature and by placing sectoral impacts within a data-driven framework. The composition and origins of livestock-related greenhouse gas emissions are discussed, and the core distinction between the biogenic methane cycle and fossil fuel-derived carbon emissions is emphasized. Water footprint debates are addressed through the green, blue, and grey water taxonomy, highlighting that a substantial share of water associated with livestock production derives from precipitation rather than from withdrawals that directly compete with domestic or industrial demand. From a land-use perspective, attention is given to ruminants' capacity to utilize grasslands and rangelands that are largely unsuitable for cropping, as well as to the potential for carbon sequestration under well-managed grazing systems. This narrative review draws on literature published between 2006 and 2025, prioritizing both foundational references and recent advances in methane accounting, emissions-intensity frameworks, and mitigation strategies. Evidence indicates that interventions including productivity gains, herd health and reproductive management, reproductive biotechnologies, feed technologies, manure management, and biogas production can meaningfully reduce emissions intensity without constraining output. Collectively, the findings suggest that mitigation priorities should focus less on restricting livestock per se and more on reducing dependence on fossil fuels while scaling scientifically grounded practices within livestock systems. A livestock sector managed on scientific principles may contribute to global food security and, under appropriate governance and practice, form part of a credible climate mitigation portfolio.

Keywords: Animal production, Climate change, Veterinary medicine, Sustainability, Efficiency, Greenhouse gas emission

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1. Introduction

Current estimates place the global population above 7.44 billion, with projections reaching 9.6 billion by 2050 (FAO, 2025). This demographic pressure increases demand on constrained natural resources and places the long-term viability of food production systems under sustained scrutiny. Animal-source proteins remain central to human nutrition, providing essential amino acids, including tryptophan and phenylalanine, that are considered necessary for growth, development, and cognitive function. These amino acids also participate directly in the biosynthesis of neurotransmitters that are relevant to human health and wellbeing. Livestock production, therefore, is not merely an economic activity; it intersects with global public health and food security in ways that are difficult to replace through simplistic substitution narratives (Fernstrom, 1994; Wu, 2016; Elmadfa & Meyer, 2017).

Since the Industrial Revolution, expanding fossil fuel use

and other anthropogenic activities have contributed to environmental challenges, including global warming and climate change. In recent years, however, public discourse has at times assigned a disproportionate share of climate responsibility to livestock systems. Following the publication of the FAO report *Livestock's Long Shadow* (2006), livestock greenhouse gas (GHG) emissions became a focal point of policy debate. Some assessments, nonetheless, appear to underweight the complex biological cycles inherent to animal production and the ecosystem services such systems can provide, thereby framing livestock as a larger "environmental culprit" than the evidence necessarily supports (Steinfeld et al., 2006; Pitesky et al., 2009; Mitloehner et al., 2020; IPCC, 2021).

This review evaluates livestock-sector impacts on climate change through three primary lenses: greenhouse gas emissions, water footprint, and land use. It also interrogates methodological choices that can generate



misleading generalizations, and it considers technology-oriented mitigation strategies compatible with sustainable production.

2. Review Methodology

This study is a narrative review that re-examines common claims regarding livestock-related environmental impacts through three main dimensions: greenhouse gas emissions, water footprint metrics, and land-use patterns. The objective is to interpret these indicators within a biophysical and methodological context rather than to generate original quantitative estimates.

Relevant literature was identified through targeted searches of major scientific databases and search engines (e.g., Web of Science, Scopus, and Google Scholar), complemented by reports from international organizations such as FAO, IPCC, and UNFCCC. The primary screening focused on publications from 2006 to 2025, allowing inclusion of both foundational studies and recent advances in methane accounting, emissions-intensity frameworks, and mitigation strategies.

Search keywords included combinations of "livestock emissions," "enteric methane," "biogenic methane," "GWP and GWP*," "water footprint," "green water," "blue water," "land use," and "rangelands." Priority was given to peer-reviewed articles and assessment reports with clearly defined system boundaries.

Findings were synthesized qualitatively by comparing methodological choices, system boundaries, and indicator definitions across studies. Given differences in regional production systems and accounting frameworks, results are interpreted comparatively and contextually rather than as precise universal values.

3. Results

The literature reviewed reveals diverse environmental impacts related to livestock farming. Studies show that absolute emission values alone provide a limited basis for comparison between production systems. When emissions are expressed per unit of output, significant variability emerges, and productivity level, animal health, and management intensity, rather than species-specific biological processes, appear as primary determinants of emission intensity.

Methane use significantly influences the outcomes regarding livestock farming's impact on the climate. Studies using traditional GWP_{100} measures tend to attribute disproportionate warming impacts to livestock systems, while studies incorporating alternative frameworks such as GWP^* report distinctly different results, particularly in systems with stable or declining herd sizes. This difference highlights the importance of metric selection in shaping both scientific interpretation and policy narratives.

Furthermore, when considering resource use, livestock-related water and land footprints are frequently directly

correlated with, and often dominate, human food or freshwater resources. While green water from rainfall accounts for the vast majority of reported water use, a significant portion of the land used by ruminant systems consists of pastures unsuitable for agricultural production. These findings demonstrate that the impacts of livestock farming are resource-use dependent and may not be accurately represented by global averages.

3.1. Greenhouse Gas Effects

Livestock activities produce greenhouse gas emissions because of biological processes. The sources, composition, and atmospheric behavior of these emissions, however, follow dynamics that differ in important respects from emissions dominated by fossil carbon.

Recent studies show that the climate impact attributed to livestock methane depends on the accounting metric applied, and that stable methane emissions may result in little or no additional warming when alternative metrics such as GWP^* are used (Correddu et al., 2025).

The livestock sector is estimated to account for approximately 14.5% of global anthropogenic GHG emissions, corresponding to roughly 7.1 gigatonnes of CO_2 -equivalent per year (Gerber et al., 2013). Sectoral emissions can be broadly characterized as follows.

Enteric fermentation: Methane (CH_4) produced via microbial fermentation in the digestive systems of ruminants (cattle, sheep, goats) represents approximately 39–44% of livestock-related emissions. Reports indicate that an adult bovine rumen can generate 500–1500 liters of gas per day, with methane comprising roughly 30–40% of that volume (Johnson et al., 1995).

Feed production: The cultivation, processing, and transport of feed crops contributes the largest share of emissions attributed to livestock (about 45%). These emissions largely reflect nitrous oxide (N_2O) releases associated with fertilizer use and carbon dioxide (CO_2) emissions linked to agricultural mechanization and energy inputs (Bouwman et al., 2002; Smith et al., 2008).

Manure management: Storage and handling of manure accounts for approximately 10% of livestock-sector emissions (FAO, 2013).

3.2. Regional and Species-Level Distribution

When emissions are disaggregated by product category, beef and dairy typically account for the largest shares, contributing about 41% and 20% of total livestock emissions, respectively. Pork and poultry products (meat and eggs) tend to have smaller shares, around 9% and 8%, respectively. Regionally, enteric fermentation often dominates in many developing regions, including parts of Asia, Latin America, and Africa, whereas in high-income settings emissions linked to energy use and manure management may be more prominent. In Türkiye, the share of livestock within total national GHG emissions has been reported at about 7.2, below the global average of 8.2, while China and the United States remain among the leading countries in both aggregate emissions and livestock production volume (Gerber et al., 2013; Herrero

et al., 2013; FAO, 2025). These patterns are informative, but they should be interpreted cautiously because system boundaries, accounting conventions, and production structures differ markedly across datasets and jurisdictions.

National-scale analyses further demonstrate that livestock-related greenhouse gas emissions exhibit strong spatial and temporal heterogeneity, with emission hotspots linked to regional production intensity and management practices, as shown in recent assessments of the Turkish livestock sector (Yalcinkaya, 2024).

3.3. Scientific Misconceptions and the Methane Cycle

A substantial portion of criticism directed at livestock rests on methane's global warming potential (GWP), which is commonly cited as roughly 28 times that of CO₂ over a 100-year horizon. Yet such comparisons frequently overlook the difference between "new" carbon introduced from fossil reservoirs and "biogenic" carbon circulating within a relatively short biological loop. Methane emitted by ruminants typically persists in the atmosphere for about 10–12 years before oxidizing to CO₂, which can then be re-assimilated by plants through photosynthesis. This describes a short-cycle, largely closed carbon pathway. Fossil fuel combustion, by contrast, transfers carbon that has been geologically sequestered for millions of years into the active atmosphere-ocean-biosphere system, adding net loading rather than recycling recent biogenic carbon (Allen et al., 2018; Mitloehner, 2021). These distinctions do not imply that methane is inconsequential; they do suggest that representing livestock as the sole or primary driver of climate change is a reductionist interpretation that may obscure higher-leverage mitigation opportunities.

3.4. Water and Land Use

Livestock resource use is often criticized, particularly in relation to water withdrawals and land demand. A closer reading of the underlying metrics indicates that many widely circulated claims depend on decontextualized aggregates and on water accounting categories that are not always clearly communicated to non-specialist audiences.

Water footprint discussions frequently invoke striking figures such as "15,000 liters of water for one hamburger" (Mekonnen & Hoekstra, 2012). When the accounting is unpacked, however, more than 87% of the total water footprint associated with livestock products is typically "green water," defined as precipitation stored in soil and used by vegetation (Schyns et al., 2019). This water would fall and largely evaporate or be transpired through plants even in the absence of livestock production, and it does not necessarily compete directly with drinking water supplies or industrial withdrawals. "Blue water," reflecting surface and groundwater withdrawals, often constitutes a comparatively small fraction of the total in livestock systems, reported at around 6.2% overall and falling below 4% in pasture-based systems (Zonderland-Thomassen et al., 2014). Intensive systems that rely heavily on concentrate feeds can increase blue and grey water footprints, but the dominant contribution of rainfall-derived green water remains a defining feature of many livestock water footprint estimates. This does not absolve the sector from local water governance concerns, particularly in water-stressed basins; it does indicate that global headline numbers can be misleading if interpreted as direct consumption of scarce potable water (Figure 1).

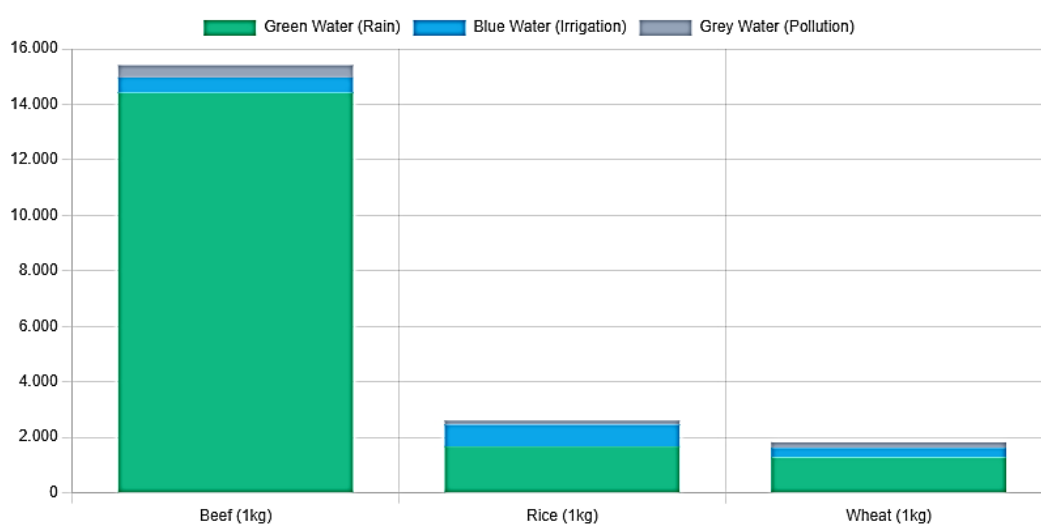


Figure 1. Water use by source: livestock and crop products (Mekonnen et al., 2012).

Although livestock uses a large share of global agricultural land, much of this area consists of grasslands and rangelands that are not suitable for cropping (FAO, 2018). Ruminants convert cellulose-rich plant material and various agricultural by-products, which humans cannot efficiently digest, into nutrient-dense animal-

source foods, providing a pathway that can complement rather than directly compete with crop-based human diets. Well-managed grazing lands can also store carbon in soils. Global modeling studies suggest that improved grassland management could retain on the order of 0.4–0.6 gigatonnes of CO₂-equivalent per year in soils

(Conant et al., 2001; Wilkinson, 2011). These estimates are context-dependent, and sequestration is neither limitless nor guaranteed; it can saturate over time and may be reversed by mismanagement, drought, or land conversion. Still, the evidence supports the view that livestock systems can be designed to deliver both food and ecosystem services, rather than functioning solely as net resource drains. The distribution of global agricultural land use, based on Mottet et al. (2017),

illustrates this point: roughly 68% of agricultural land is marginal pasture unsuitable for crop cultivation, while only about 12% of arable land is used to produce animal feed. This pattern suggests that a substantial fraction of livestock production occurs on land that does not readily compete with direct human food cropping, though the degree of competition varies by region, production system, and feed sourcing (Figure 2).

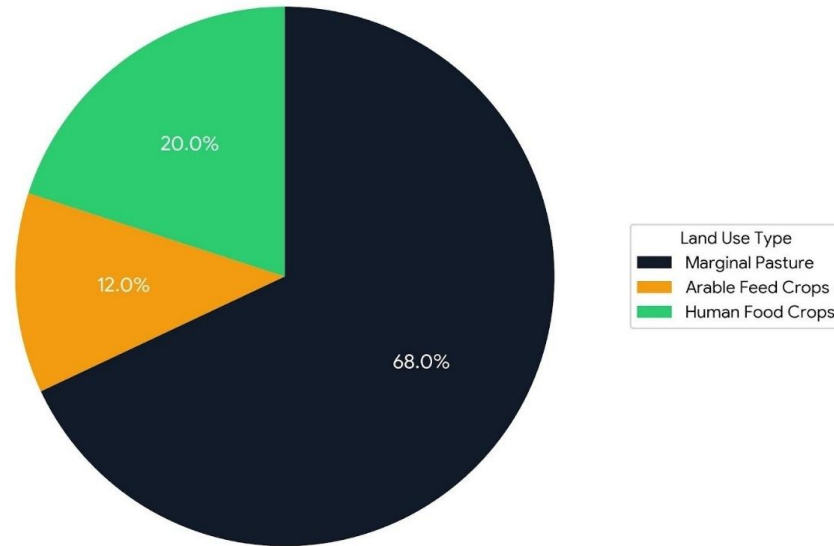


Figure 2. Distribution of land use in livestock production (Mottet et al., 2017).

3.5. Comparisons with Other Sectors

Fair evaluation of livestock's environmental impact requires methodologically consistent comparisons across sectors. The frequently cited claim that "livestock causes more emissions than transport" illustrates how boundary choices can distort public understanding. In the FAO's 2006 report, livestock emissions were estimated using life cycle assessment (LCA), while transport emissions were often represented only by direct tailpipe emissions. When both sectors are evaluated using comparable system boundaries, transport's share of global emissions is estimated at about 16.9%, whereas livestock's direct emissions are closer to about 7% (FAO, 2006). In Türkiye, a similar pattern has been reported: transport accounts for approximately 13.5% of total emissions, while livestock's direct contribution is around 1.3% (UNFCCC, 2023). These figures should be interpreted with care because inventories evolve, sectoral definitions differ, and data quality varies; nonetheless, the underlying methodological point remains robust.

3.6. Where the Dominant Emissions Lie: The Energy System

Sectoral breakdowns of global greenhouse gas emissions consistently identify energy-related activities (electricity production, heating, transport, and industry) as the dominant source, at about 76.2% (IPCC, 2022). Agriculture, including livestock, is typically estimated at roughly 11–14%. Since 1990, emissions attributed to energy systems have increased by around 163%,

whereas growth in agricultural emissions has been reported at roughly 1% in the referenced synthesis (Victor et al., 2019). While any single estimate depends on methodological conventions, the broader inference is difficult to escape: deep decarbonization of energy supply and demand is likely to remain the central lever for climate mitigation, with livestock mitigation best understood as complementary rather than substitutive (Figure 3).

3.7. Mitigation Strategies

Rather than restricting animal-source food production or attempting abrupt, large-scale dietary shifts, mitigation can be pursued through efficiency gains and targeted technological interventions within existing systems. Reported differences in emissions intensity across producers imply substantial abatement potential: narrowing these gaps could reduce global livestock emissions by approximately 18–30% (Herrero et al., 2016). Such estimates should be treated as conditional on adoption, governance capacity, and local constraints, but they are broadly consistent with the idea that "how" livestock is produced often matters at least as much as "how much."

Increasing output per animal (milk, meat, eggs) is among the most effective routes to lower emissions per unit of product. Under an emissions intensity framework, production from high-performing animals and well-managed systems typically carries a smaller footprint than production from low-yield systems, even if absolute

emissions remain non-trivial (Figure 5). Improvements in herd health, reductions in mortality, and enhanced reproductive performance reduce the proportion of animals consuming resources without contributing proportionally to output. Equivalent production can then be achieved with fewer animals, lower feed demand, and reduced waste generation. Reproductive biotechnologies, including estrus synchronization, artificial insemination,

embryo transfer, and genomic selection, can accelerate genetic progress at the herd level, producing durable improvements in fertility, robustness, and productivity. Artificial insemination and structured breeding programs facilitate rapid dissemination of superior genetics, raising per-animal production and indirectly lowering emissions intensity (Figure 4).

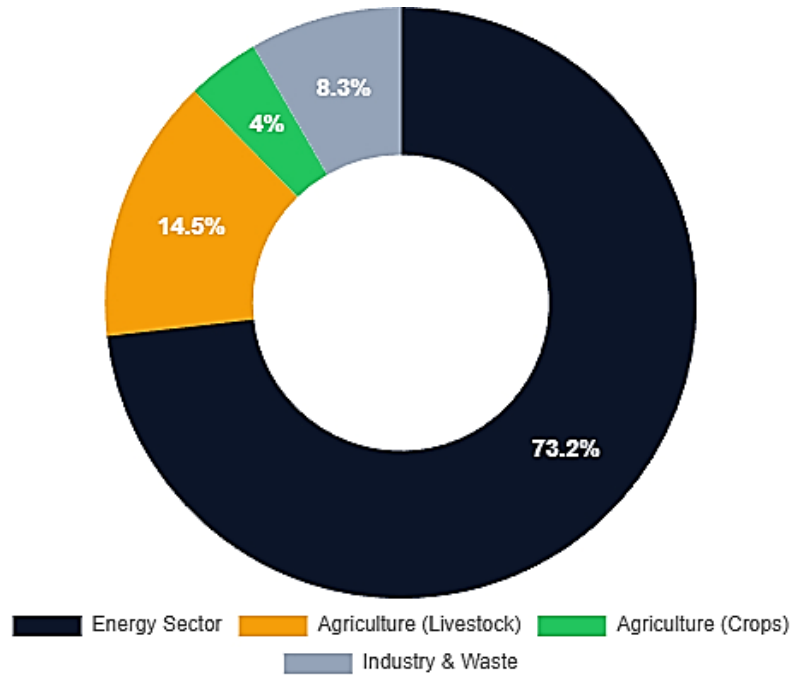


Figure 3. Sectoral distribution of global greenhouse gas emissions (FAO, 2013).

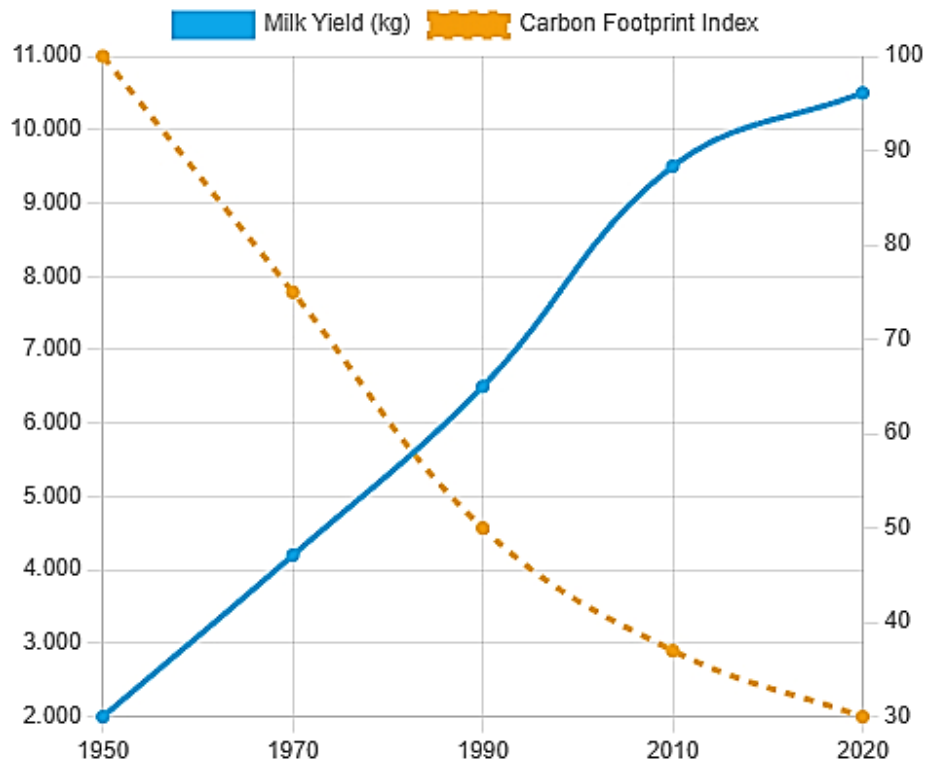


Figure 4. Inverse relationship between milk yield per animal and carbon footprint index (1950–2020).

Expanded veterinary services, through earlier disease detection and prevention, can reduce productivity losses and stabilize output over time. In many low- and middle-income settings, productivity gaps are plausibly linked to limitations in animal health infrastructure, reproductive management, and genetic improvement. In these contexts, widening access to veterinary care and modern reproductive technologies could reduce emissions intensity without reducing total production, although outcomes will depend on economics, extension capacity, and producer incentives (Capper et al., 2009; Thornton, 2010; Gerber et al., 2011; Herrero et al., 2016; Mottet et al., 2017; FAO, 2018).

Improvements in feeding strategies are among the most direct approaches to reducing enteric methane. Increasing digestibility, optimizing ration balance, and minimizing feed losses can lower emissions substantially. Biotechnological approaches, including the use of lipids, nitrates, and feed additives, have been shown to suppress methane formation at the source under certain conditions (Beauchemin et al., 2008; Hristov et al., 2013). Translating controlled-study results to diverse farm contexts, however, requires attention to animal health, cost, supply chains, and the risk of unintended effects on productivity or nitrogen cycling.

Nutritional strategies influence livestock methane emissions primarily through changes in productivity and emission intensity rather than through consistent reductions in absolute daily methane output. Improvements in diet formulation and feed efficiency

may increase milk yield, thereby lowering methane emissions per unit of product even when total emissions per animal remain relatively unchanged, particularly in intensive dairy systems, while outcomes may differ in extensive production contexts (Hristov, 2023). These findings indicate that the mitigation potential of feeding strategies should be evaluated using intensity-based metrics alongside absolute emissions.

Appropriate manure management can reduce both methane and nitrous oxide emissions while enabling renewable energy production. Anaerobic digestion in biogas facilities captures methane that would otherwise be emitted, converts it into usable energy, and can reduce odor and water pollution risks (Montes et al., 2013). Performance depends on storage practices, digester design, operational reliability, and how digestate is subsequently handled. Poor implementation can erode expected benefits.

Grassland rehabilitation, prevention of overgrazing, and rotational grazing can improve vegetation cover and soil structure, increasing the potential for soil carbon storage. These approaches may allow livestock systems to contribute actively to mitigation rather than being treated solely as emission sources (Lal, 2004; McSherry & Ritchie, 2013). The limitations are non-trivial: sequestration rates vary widely, can plateau, and are sensitive to climate variability and management consistency. Even so, where conditions are favorable and governance supports durable practice, soil carbon strategies can complement emissions reductions.

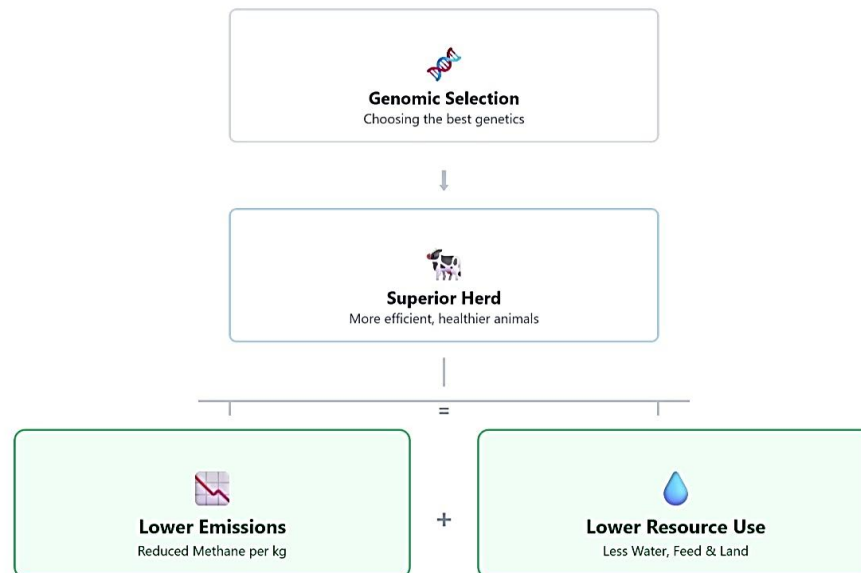


Figure 5. Genomic selection for efficient and low-emission livestock production.

4. Discussion

The findings of this review suggest that simplified narratives framing livestock as a primary driver of climate change often overlook key biophysical and methodological considerations. While livestock systems emit greenhouse gases, particularly methane, their climate impact differs fundamentally from fossil fuel-

based emissions and is frequently overstated when evaluated using static metrics.

Rather than focusing on reductions in livestock numbers, the literature highlights the effectiveness of emissions-intensity-based mitigation strategies. Improvements in productivity, herd health, reproductive efficiency, and nutritional management consistently emerge as the most

feasible pathways for reducing environmental impacts without compromising food security.

Veterinary interventions play a central role in this context. Enhanced animal health, fertility management, and reproductive biotechnologies contribute directly to higher output per animal, thereby lowering emissions intensity. These approaches are particularly relevant in regions with significant productivity gaps, where substantial mitigation can be achieved through efficiency gains.

Overall, the evidence supports a mitigation strategy centered on technological improvement and system optimization within livestock production, complemented by broader decarbonization efforts in the energy sector. Under such an approach, livestock systems can continue to contribute to global nutrition while aligning more closely with climate mitigation objectives.

5. Conclusion

Livestock production plays a central role in meeting the nutritional needs of a growing global population while supporting rural livelihoods and food system resilience. The evidence reviewed in this study indicates that the environmental impacts attributed to livestock are frequently overstated when evaluated using inconsistent system boundaries or static metrics that do not adequately reflect biogenic carbon dynamics. Fossil fuel-based energy systems remain the dominant driver of global greenhouse gas emissions, whereas livestock-related emissions constitute a smaller and more source-use-dependent share.

A mitigation pathway centered on efficiency gains, technological improvement, and sound veterinary management emerges as more credible than strategies focused on reducing livestock numbers. In this context, the adoption of modern scientific approaches in livestock production plays a critical role in increasing output per animal. Improvements in herd health management, reproductive biotechnologies, genetic improvement programs, balanced nutrition strategies, and data-driven decision-support systems can substantially enhance production efficiency while reducing environmental impacts on a per-unit-of-product basis. When combined with advances in manure management and grassland stewardship, such approaches allow livestock systems to contribute to climate mitigation objectives without undermining food security. Future research should therefore focus on comparative, long-term evaluations of these practices across different livestock production systems, with particular attention to quantifying the contribution of veterinary services and technology adoption using robust performance indicators.

Some limitations of this review should also be considered. The findings are based on secondary data from studies employing different system boundaries, accounting frameworks, and impact measures, which restricts direct quantitative comparisons across sources. Reported emission and resource-use values vary

according to production system characteristics, regional conditions, and methodological assumptions. In addition, cross-country comparisons may be influenced by differences in livestock systems, feed resources, climatic conditions, and data quality. These considerations indicate that caution is warranted when interpreting global estimates and underscore the need for context-specific assessments.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	H.D.	A.K.
C		100
D	100	
S		100
DCP	50	50
DAI	50	50
L	50	50
W	50	50
CR	50	50
SR	50	50

C=concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision.

Conflict of Interest

The authors declare that there is no conflict of interest.

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