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Breaking Down the Carbon Footprint: Beef Cattle Farming Strategies Towards Net-Zero Emissions

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ABSTRACT

The beef cattle farming industry is a significant contributor to global greenhouse gas (GHG) emissions, primarily through methane (CH_4) released from enteric fermentation and nitrous oxide (N_2O) originating from manure management and fertilized soils. Achieving net-zero emissions in this sector is therefore critical for climate change mitigation and for meeting international commitments such as the Paris Agreement. This article reviews and synthesizes current knowledge on the carbon footprint of beef cattle production systems and evaluates key mitigation strategies across the entire supply chain. Life Cycle Assessment (LCA) is highlighted as a central tool for quantifying emissions from cradle-to-farm gate or cradle-to-grave and for identifying major emission hotspots. Evidence indicates that emissions vary widely among production systems, driven by differences in feed composition, herd management, productivity, and land-use practices. Effective mitigation pathways include optimizing animal nutrition to reduce enteric methane, improving manure management technologies, enhancing pasture quality and grazing management to increase soil carbon sequestration, and integrating land-use strategies such as agroforestry and afforestation. While global demand for animal protein continues to rise, an integrated approach that combines productivity gains with emission reductions is essential. This review demonstrates that no single strategy is sufficient to achieve net-zero emissions; instead, coordinated interventions that balance environmental performance, economic viability, and production efficiency are required to transition beef cattle farming toward climate-neutral systems.

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INTRODUCTION

The global livestock sector plays a crucial role in food security, rural livelihoods, and economic development; however, it is simultaneously recognized as one of the major contributors to anthropogenic greenhouse gas (GHG) emissions (Gerber et al., 2013; Grossi et al., 2019; Herrero et al., 2016). Among livestock commodities, beef cattle farming is consistently identified as one of the most emission-intensive agricultural activities due to its reliance on ruminant digestion processes and land-based production systems (Herrero et al., 2016; Capper, 2011). The dominant greenhouse gases emitted from beef cattle systems are methane (CH_4), primarily generated through enteric fermentation in the rumen, and nitrous oxide (N_2O), largely originating from manure management practices and nitrogen inputs to agricultural soils (Hristov et al., 2013; IPCC, 2019). Carbon dioxide (CO_2) emissions, although comparatively smaller at the animal level, arise indirectly from feed production, energy use, transportation, and land-use change, particularly deforestation associated with pasture expansion (Gerber et al., 2013; Garnett et al., 2017).

Globally, agriculture is estimated to account for approximately 10–15% of total anthropogenic GHG emissions, with livestock production contributing a substantial share of this total (Gerber et al., 2013; Herrero et al., 2016). In many regions, livestock-related emissions exceed those from crop production, reflecting both biological processes and management practices inherent to animal agriculture (Grossi et al., 2019). Beef cattle production, in particular, has attracted increasing scrutiny due to its relatively high emissions per unit of edible protein compared with other animal-source foods (Capper, 2011). In regions such as Latin America, beef cattle systems are not only major sources of methane emissions but are also closely linked to land-use change, including deforestation and forest degradation (Garnett et al., 2017; Gerber et al., 2013).

International climate policy frameworks, most notably the Paris Agreement, have intensified pressure on all economic sectors to contribute to climate change mitigation by limiting global temperature rise (IPCC, 2019). For the beef cattle sector, this expectation has translated into the ambitious and complex objective of achieving net-zero emissions (Herrero et al., 2016). Net-zero emissions imply that residual GHG emissions are fully balanced by removals, either through biological sequestration processes, such as soil carbon storage and afforestation (Stanley et al., 2018; Rowntree et al., 2020).

The diversity of beef production systems worldwide further complicates mitigation efforts (Gerber et al., 2013). Extensive pasture-based systems often exhibit higher emissions per unit of product due to lower animal productivity and longer production cycles, whereas intensive systems may achieve lower emission intensities but rely more heavily on external inputs (Capper, 2011; Herrero et al., 2016).

The primary sources of GHG emissions in beef cattle systems are well documented. Enteric methane emissions typically account for 40–60% of total emissions in many beef production systems (Hristov et al., 2013; Beauchemin & McGinn, 2005). Methane and nitrous oxide emissions from manure management constitute another significant source (IPCC, 2019). Feed production contributes indirectly through emissions associated with fertilizer manufacture and application (Rotz et al., 2010). In addition, land-use change can represent a dominant source of CO_2 emissions in certain regions (Garnett et al., 2017).

To comprehensively quantify and compare these diverse emission sources, Life Cycle Assessment (LCA) has emerged as the most widely adopted methodological framework (Rotz et al., 2010; Gerber et al., 2013). Numerous LCA studies have demonstrated substantial variability in beef carbon footprints, driven by differences in feed composition, animal productivity, and land management practices (Capper, 2011; Herrero et al., 2016).

Nutritional interventions have received particular attention due to their potential to directly reduce enteric methane emissions (Beauchemin et al., 2020; Knapp et al., 2014). Genetic selection for animals with improved feed conversion efficiency also represents a longer-term mitigation pathway (Herrero et al., 2016). Manure management technologies such as anaerobic digestion and improved storage systems can substantially reduce methane and nitrous oxide emissions (Hristov et al., 2013; IPCC, 2019). Land-use and pasture management strategies such as rotational grazing and agroforestry can enhance soil carbon sequestration (Stanley et al., 2018; Rowntree et al., 2020; Garnett et al., 2017).

METHODS

Life Cycle Assessment (LCA) was adopted as the primary methodological framework in the reviewed literature to evaluate greenhouse gas (GHG) emissions associated with livestock production systems (Rotz et al., 2010; Gerber et al., 2013). Most studies quantified emissions in terms of carbon dioxide equivalents (CO_2e) using 100-year global warming potential (GWP100) values in accordance with the guidelines of the Intergovernmental Panel on Climate Change (IPCC, 2019).

System boundaries in the reviewed studies typically ranged from cradle-to-farm gate, although some extended to cradle-to-slaughter or cradle-to-retail, depending on data availability and study objectives. Emission sources commonly included enteric fermentation, manure management (both storage and field application), feed production and processing, on-farm energy use, and land-use change associated with feed cultivation and pasture expansion. In several studies, indirect emissions related to fertilizer use, transportation of feed and inputs, and infrastructure were also incorporated. Functional units such as kilograms of live weight gain, carcass weight, edible meat, or protein-corrected output were used to standardize emission estimates and facilitate cross-study comparisons (Herrero et al., 2016; Gerber et al., 2013).

Data inputs for the LCA models were derived from a combination of primary farm-level measurements, experimental trials, and secondary data obtained from national inventories, peer-reviewed literature, and international databases. Emission factors were predominantly sourced from

IPCC Tier 1 or Tier 2 methodologies, while some studies employed region-specific Tier 3 models to improve accuracy. Allocation methods, including mass-based, economic, or energy-based allocation, were applied where multiple co-products were generated, and assumptions related to allocation were clearly reported when available.

Litigation strategies identified in the reviewed literature were categorized into animal nutrition, manure management, genetics, land-use, and production system optimization (Hristov et al., 2013; Beauchemin et al., 2020; Henderson et al., 2017). Nutritional strategies included feed additives aimed at reducing enteric methane emissions (Beauchemin et al., 2020; Knapp et al., 2014). Manure management strategies focused on anaerobic digestion and optimized manure application techniques (Hristov et al., 2013). Land-use strategies included improved grazing practices and agroforestry integration (Stanley et al., 2018; Rowntree et al., 2020).

The effectiveness of each mitigation strategy was evaluated based on reported reductions in absolute GHG emissions and/or emission intensity per unit of product. Where available, quantitative estimates of emission reduction were extracted and synthesized to provide comparative insights across strategies and production systems. In addition, the feasibility of on-farm implementation was qualitatively assessed by considering factors such as technological readiness, economic costs, scalability, and applicability to smallholder and extensive production systems. This integrated approach allowed for a comprehensive evaluation of both the environmental impact and practical relevance of mitigation strategies reported in the literature.

RESULTS

Across the reviewed studies, beef cattle farming exhibited a high and variable carbon footprint, with reported values differing substantially by region and production system. Enteric fermentation consistently emerged as the dominant emission source, followed by manure management and feed production.

1. Carbon Footprint of Beef Cattle Production Systems Reported in Recent Studies

Table 1. Carbon Footprint of Beef Cattle Production Systems Reported in Recent Studies

Production System	Region	Functional Unit	Carbon Footprint (kg CO_2e)	Dominant Emission Source
Pasture-based cow–calf	Latin America	kg live weight (LW)	18–28	Enteric CH_4
Feedlot finishing	North America	kg carcass weight (CW)	12–20	Feed production + CH_4
Mixed crop–livestock	Europe	kg meat	14–25	Manure N_2O
Extensive grazing	Africa	kg LW	25–40	Enteric CH_4 + land use

Integrated agroforestry	Brazil	kg meat	10–15	Balanced (CH_4 offset)

Table 1 shows that the carbon footprint of beef cattle production varies significantly depending on the production system and geographic location. Extensive pasture-based systems tend to have higher emissions per unit of product due to low productivity and high enteric methane emissions. In contrast, integrated systems such as agroforestry and efficient feedlots exhibit lower carbon footprints, especially when improved feed efficiency and soil carbon sequestration are taken into account. These findings underscore the importance of a systemic approach in strategies toward net-zero emissions.

2. Contribution of Greenhouse Gas Sources in Beef Cattle Farming

Table 2. Contribution of Greenhouse Gas Sources in Beef Cattle Farming

Emission Source	GHG Type	Contribution (%)	Description
Enteric fermentation	CH_4	45–65	Rumen microbial digestion
Manure management	CH_4, N_2O	15–30	Storage and field application
Feed production	CO_2, N_2O	10–20	Fertilizer use, transport
Energy use	CO_2	3–8	Fuel and electricity
Land-use change	CO_2	Variable	Deforestation, pasture expansion

Table 2 confirms that methane from enteric fermentation is the largest emission source in beef cattle systems. These emissions are a primary target for mitigation strategies due to their high global warming potential (GWP). Manure management and feed production also contribute significantly, primarily through N_2O emissions from nitrogen fertilizers. Therefore, a net-zero approach must prioritize methane reduction while simultaneously improving nutrient and energy efficiency.

3. Mitigation Strategies for Reducing Carbon Footprint in Beef Cattle Farming

Table 3. Mitigation Strategies for Reducing Carbon Footprint in Beef Cattle Farming

Strategy Category	Specific Intervention	Emission Reduction Potential (%)	Additional Benefits
Animal nutrition	Methane inhibitors (e.g., 3-NOP)	20–40	Improved feed efficiency

Feed quality	Improved forage digestibility	10–25	Higher weight gain
Manure management	Anaerobic digestion	30–70	Renewable energy
Pasture management	Rotational grazing	5–20	Soil carbon sequestration
Land integration	Agroforestry systems	Net-zero to negative	Biodiversity, resilience

Table 3 summarizes scientifically proven mitigation strategies for reducing greenhouse gas emissions from beef cattle farming. Animal nutrition-based strategies, particularly the use of methane inhibitors, show significant emission reduction potential in the short term. Meanwhile, land-based approaches such as rotational grazing and agroforestry play a significant role in offsetting emissions through carbon sequestration, making them key components in the transition to a net-zero beef cattle system.

DISCUSSION

The results confirm that achieving net-zero emissions in beef cattle farming requires addressing multiple emission sources simultaneously. Enteric methane remains the largest challenge, but significant reductions can be achieved through dietary interventions and improved productivity. Manure management within integrated farming systems has been shown to improve soil fertility and crop productivity by increasing soil nutrient content and microbial activity. The integration of manure with inorganic fertilizers has also shown superior results compared to the use of chemical fertilizers alone, and supports more environmentally friendly and sustainable agricultural practices.

An integrated systems approach is therefore essential. Combining nutritional, genetic, managerial, and land-use strategies can yield synergistic benefits that exceed the impact of individual measures. Policy support, carbon accounting frameworks, and economic incentives will be crucial to enable widespread adoption of these practices.

CONCLUSIONS

Beef cattle farming is a major contributor to agricultural greenhouse gas emissions, but it also offers substantial opportunities for mitigation. Through the combined application of improved nutrition, manure management, genetic selection, and land-use strategies, the sector can move toward net-zero emissions. Achieving this transition will require coordinated efforts among producers, researchers, policymakers, and industry stakeholders to ensure that emission reductions are compatible with productivity, profitability, and food security.

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