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Carbon footprint reduction strategies in dairy and beef production

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Abstract

The dairy and beef sectors play a vital role in global food security but also contribute significantly to greenhouse gas emissions. Major emissions including methane, nitrous oxide and carbon dioxide arise from enteric fermentation, manure handling, feed production and overall farm operations. Tools such as Life Cycle Assessment (LCA) are used to evaluate the carbon footprint of these systems, although results can differ depending on farm practices and local environmental conditions. A range of mitigation strategies is available, including nutritional approaches such as feed additives, improved feeding practices, advanced manure and waste management technologies and precision livestock farming (PLF) systems that support better health, fertility and production efficiency. Together, these strategies can reduce emissions while helping maintain productive, sustainable and profitable dairy and beef production systems.

Keywords: Support better health, fertility and production efficiency, beef production systems

Introduction

The dairy and beef sectors are very important parts of the global food system and will continue to play a big role in feeding the world. The demand for livestock products is expected to increase by 76% by 2050 because of population growth, higher incomes and more people living in cities (Baltussen *et al.*, 2017) ^[1]. These sectors provide about 16% of the energy in human diets (Rapiya *et al.*, 2025) ^[32] and are especially important for nutrition in developing countries. Bovine meat and milk also play a key role in improving human nutrition, health and economic security (Tona *et al.*, 2021) ^[41]. Demand for dairy is increasing faster in developing countries (Herrero *et al.*, 2013) ^[17]. However, this growth must be managed carefully because livestock production is a major contributor to greenhouse gas emissions.

Livestock production contributes about 14.5-18% of all human-caused greenhouse gas (GHG) emissions, although the exact amount depends on how it is measured (Kaur *et al.*, 2019) ^[23]. These emissions mainly include methane (CH₄), nitrous oxide (N₂O) and carbon dioxide (CO₂). Livestock is responsible for 35-40% of global methane emissions, 65% of nitrous oxide emissions and about 9% of carbon dioxide emissions (Sejian *et al.*, 2016) ^[35]. Beef and dairy cattle are the biggest contributors, making up 74% of livestock-related emissions. Emissions come from enteric fermentation (methane from digestion), manure handling, feed production, land-use change and the processing and transport of animal products. Between 1961 and 2010, global livestock GHG emissions increased by 51%, with developing countries seeing a 117% rise (Caro *et al.*, 2014) ^[9].

The carbon footprint is the total amount of greenhouse gases (measured in CO₂-equivalent) released by an activity or system. Livestock production is a major source of these emissions and contributes about 14.5% of global GHG emissions (Flachowsky *et al.*, 2015) ^[13]. The carbon footprint differs by product: Beef has the highest emissions at 20.51±8.39 kg CO₂-eq per kg of meat, while pork produces about 4.24±1.07 kg CO₂-eq per kg. Major emission sources are enteric fermentation, feed production and manure management. Different gases contribute in different amounts: methane is the biggest contributor for beef and milk (50-58%), while nitrous oxide is the main contributor for pork.

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Sources of greenhouse gas emissions in dairy and beef systems: Enteric fermentation

Enteric fermentation is the main source of methane emissions in both dairy and beef cattle production. According to Beauchemin *et al.*, 2013, ruminant animals contribute about 8-10% of global human-caused greenhouse gases and Meale *et al.*, 2012^[25] reported that more than 90% of these emissions come specifically from enteric fermentation. Similarly, Dunkley *et al.*, 2013^[11] confirmed that enteric fermentation is the major source of methane emissions in beef cattle. Research also shows that methane emissions are closely linked to cattle feeding behavior. Min *et al.*, 2022 found strong positive relationships between methane output and dry matter intake, with correlation values (R^2) ranging from 0.37 to 0.50 for both dairy and beef cattle. Overall, the scientific literature clearly identifies rumen microbial activity as the main biological process responsible for producing methane in cattle.

Manure management

Manure management is an important part of reducing greenhouse gas (GHG) emissions, particularly methane (CH_4) and nitrous oxide (N_2O), which are mainly produced during anaerobic decomposition. Livestock manure contributes significantly to global emissions, with livestock generating 37% of CH_4 and 65% of N_2O released into the atmosphere (Sudars *et al.*, 2015)^[38]. The major sources of these emissions are manure storage, where anaerobic conditions lead to high CH_4 production and land application, where soil processes such as nitrification and denitrification create N_2O depending on moisture and organic carbon levels (Hristov *et al.*, 2013)^[20]. Several strategies can help reduce these emissions, including anaerobic digestion, which captures CH_4 and converts it into biogas to replace fossil fuels and improved nutrient management through dietary adjustments that lower nitrogen excretion. However, the success of these methods varies with local conditions and some practices may unintentionally increase N_2O emissions, highlighting the need for a balanced and comprehensive approach to manure management (Symeon *et al.*, 2025)^[40].

Feed production and processing

Feed production and processing are major contributors to Greenhouse Gas (GHG) emissions in livestock systems, mainly due to the use of fertilizers, farm machinery and long-distance transportation. Research shows that feed production can make up a large share of the total carbon footprint in meat production, highlighting the need for focused mitigation efforts. Nitrogen fertilizers alone contribute 33% to 44% of emissions during crop planting and account for about 16% of the total carbon footprint in pig production, while the processing and transport of feed ingredients add another 17%, especially when feed materials travel long distances because of planting-feeding separation (Zhou *et al.*, 2018)^[43]. In poultry systems, feed production is even more significant, responsible for 56.8% of total GHG emissions. Several strategies can help reduce these impacts, including lowering the use of nitrogen fertilizers which can cut emissions by up to 7% and reducing transport distances, which can decrease overall emissions by about 18%. Additionally, the use of renewable energy in feed processing offers further potential for emission reduction (Yang *et al.*, 2023)^[42].

Assessment of carbon footprint in livestock

The calculation of carbon footprints in agricultural sectors

like dairy production uses several methods, with Life Cycle Assessment (LCA) being the most common. LCA evaluates environmental impacts from production to final disposal and uses functional units such as emissions per kilogram of milk or protein produced. Emission intensity varies widely across regions because of differences in feeding practices, herd size and environmental conditions. Other tools also contribute to carbon accounting, including Input-Output Analysis (IOA), which links production and consumption data but has built-in uncertainties (Rosales and Dhakal, 2024)^[33] and the Ecological Footprint (EF), which measures sustainability by comparing the demand for natural resources with the available supply (Biagetti *et al.*, 2023)^[7]. Common functional units include fat and protein-corrected milk (FPCM) for standardizing milk emissions and emissions per hectare to assess land-use efficiency. Differences in emission intensity arise from production practices such as grazing versus housed feeding systems (Sorley *et al.*, 2023)^[36], variations in farm size where smaller farms often show higher emissions per unit of milk and local environmental or nutritional management factors (Stolarski *et al.*, 2025)^[37]. Although these tools are valuable, the accuracy of carbon footprint estimates is affected by challenges such as data collection difficulties (Moschini, 2022)^[14], differences in calculation methods that limit comparability and assumptions in accounting models that may not fit all production systems.

Nutritional and feeding strategies

Nutritional and feeding strategies are among the most effective methods for reducing enteric methane emissions in ruminants, with different interventions showing reduction potentials ranging from 10% to 90% depending on the approach used (Morshidy *et al.*, 2025)^[29]. Enteric fermentation contributes 15-20% of global anthropogenic methane emissions and leads to a 2-12% loss of gross energy in ruminants, making methane mitigation important for both environmental sustainability and production efficiency (Ingale *et al.*, 2013)^[22]. Dietary manipulation through feed additives has shown strong potential, with plant secondary compounds such as essential oils, tannins and saponins providing moderate methane reductions of up to 30%, while more powerful inhibitors like 3-nitrooxypropanol (3-NOP) consistently reduce daily methane emissions by 28-32% without affecting dry matter intake or milk yield (Hristov *et al.*, 2022)^[19]. Seaweed-based additives, especially those from *Asparagopsis* species, have demonstrated near-complete methane suppression in controlled trials, although practical challenges still limit their widespread use. Traditional feeding practices including increasing grain levels, using lipid supplements (which reduce methane by about 6%) and adjusting the concentrate-to-forage ratio (which can cut emissions by up to 50%) are more easily adopted by farmers because they also enhance overall production efficiency (K. Beauchemin *et al.*, 2008)^[4]. Despite these options, large-scale adoption is limited by factors such as cost, variable effectiveness across production systems, risks of reduced feed intake or performance at higher additive levels and the need for long-term evidence to confirm stable results without harming farm profitability. Future research should focus on integrated feeding solutions that improve digestive efficiency while maintaining animal health and reproductive performance, ensuring that mitigation strategies remain practical, cost-effective and compatible with profitable ruminant meat and milk production (Bayat *et al.*, 2012)^[3].

Manure and waste management

Effective manure and waste management requires a coordinated approach that uses multiple advanced technologies to reduce the environmental impacts of livestock production, which is responsible for about 65% of human-caused N₂O emissions and 64% of NH₃ emissions worldwide (Gómez-Brandón *et al.*, 2013) ^[15]. Anaerobic digestion is a key technology in this process, as it produces useful biogas energy, stabilizes manure, lowers methane emissions during storage and generates nutrient-rich digestate suitable for safe land application (Đurđica Kovačić *et al.*, 2022) ^[24]. Solid-liquid separation systems, especially when combined with coagulation and flocculation, help improve nutrient distribution by producing liquid fractions with better N:P ratios and solid fractions that can be further treated. Research shows that shifting from simple liquid storage to solid-liquid separation combined with mitigation strategies can cut greenhouse gas emissions by 65% and reduce ammonia emissions by 78% (Hjorth *et al.*, 2009) ^[18]. Composting technologies, particularly when enhanced with bulking agents, can reduce nitrous oxide and methane emissions by 50-71%, although careful control is needed to avoid increasing ammonia emissions through pollution swapping (Pardo *et al.*, 2014) ^[30]. Adding biochar to composting systems offers an especially promising improvement, cutting methane emissions by 79% compared to standard composting and providing additional benefits through carbon sequestration (Harrison *et al.*, 2022) ^[16]. Controlled storage practices such as shortening storage time, adjusting for seasonal temperature variations, using covers, applying manure through injection and using additives like urease and nitrification inhibitors form a comprehensive set of mitigation options. These strategies should be assessed at the whole-farm level to ensure that reducing emissions in one stage does not unintentionally increase them in another (Montes *et al.*, 2013) ^[28].

Farm management and production efficiency

Modern dairy farm management and production efficiency rely heavily on Precision Livestock Farming (PLF) technologies and systematic management approaches that integrate real-time monitoring, health optimization, and reproductive management to maximize productivity while minimizing environmental impact. Precision livestock farming uses automated monitoring systems to increase animal productivity, improve welfare and health, and reduce environmental impact by alerting farmers instantly when problems arise Cox *et al.*, 2003 ^[10], with these technologies now capable of reducing greenhouse gas emissions by up to 6.72% through improved fertility and yield management Ferguson *et al.*, 2024 ^[12]. Critical health factors significantly impact farm efficiency, as higher somatic cell counts, greater age at first calving and longer calving intervals decrease technical efficiency and translate into significant profit losses José Pérez-Méndez *et al.*, 2020 ^[31], while farms with low lameness rates (below 10% of the herd) demonstrate significantly higher technical efficiencies than those with higher lameness prevalence Barnes *et al.*, 2011 ^[2]. Reproductive efficiency is closely tied to dairy herd profitability, requiring systematic reproductive management programs that utilize efficient timed artificial insemination protocols to achieve high 21-day pregnancy rates and reduce calving intervals Carlos Eduardo Cardoso Consentini *et al.*, 2021 ^[8], while longevity optimization focuses on extending productive life rather than simply maximizing lifespan, as production efficiency and profitability are served by

optimized rather than longest herd life Schuster *et al.*, 2020. Farm-level decision making is enhanced through production indices that help farmers identify low-performing animals for culling when their production index falls below 0.6 and farms with production indices below 1.0 should modify management programs to improve efficiency Suriyasathaporn *et al.*, 2003 ^[39], supported by novel monitoring systems that provide fast, real-time and affordable objective measures for feed utilization, health, fertility and behavioral traits that were previously costly or impossible to obtain Bell *et al.*, 2018 ^[6].

Conclusion

In conclusion, the dairy and beef sectors are important for feeding the world, but they also produce a large amount of greenhouse gases. These emissions are increasing, especially in developing countries, making it important to reduce the carbon footprint of livestock production. Most emissions come from enteric fermentation, feed production and manure management, so these areas need targeted solutions. Overall, it is important to meet the growing demand for milk and meat in a way that is environmentally friendly, while still supporting good nutrition and economic growth.

Conflict of Interest

Not available

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Not available

Reference

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