Chapter 6

Greenhouse Gas Emissions and Mitigation Strategies in Dairy Cattle Farms[1]

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Abstract

Global warming results from the accumulation of greenhouse gas (GHG) in the atmosphere, which trap heat and raise the Earth's temperature. The emission of these gases and their effects on the global climate have become a major international concern. The carbon footprint (CF) primarily arises from the release of GHGs such as carbon dioxide (CO_2), produced through various biological and anthropogenic activities. On farms, significant sources of emissions include enteric methane (CH_4) from ruminants, CO_2 and nitrous oxide (N_2O) from manure during storage and land application. The dairy industry is recognized as one of the largest contributors to the global GHG emissions. Nonetheless, there are considerable opportunities to mitigate climate change by reducing emissions from dairy cattle. Addressing livestock-related emissions is therefore critical to significantly curbing their impact on global warming. Reducing dairy cattle-derived GHG emissions remains a central objective in efforts to lower agriculture's environmental footprint. Potential mitigation strategies include housing feeding menagement, grazing and pasture management, manure storage and treatment, manure application to soil, disease control and genetic selection. Although these approaches show great promise, further research is needed to validate their effectiveness and to determine their practical potential for reducing CH_4 emissions in dairy cattle. This review aims to investigate GHG and reduction strategies in dairy farms.

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1. Introduction

Climate change has had a significant impact on agriculture, livestock production, and the overall food supply, leading to serious global environmental and economic challenges. Research indicates that the relationship between climate change and the livestock industry is bidirectional (Kumaş and Akyüz, 2024). Alongside the global climate crisis, food insecurity has emerged as a critical issue, posing a major threat to human societies and becoming more severe in many regions due to increasingly unfavorable weather conditions (Kyriazakis et al., 2024).

There is clear evidence that climate change is occurring, primarily driven by greenhouse gas (GHG) emissions (Jose et al., 2016). The release of GHGs into the atmosphere and their potential effects on the global climate have become pressing concerns worldwide (Chianese et al., 2009). In recent years, policymakers have shown growing interest in reducing agricultural GHG emissions. This heightened attention stems from the agricultural sector's significant share in both global and national emissions, as well as the relatively cost-effective opportunities it offers for mitigation compared with other industries (Glenk et al., 2014).

Over the past five decades, the discussion regarding the anthropogenic influence on climate change has intensified, as the harmful consequences of rising global temperatures have become increasingly acknowledged by both scientific and non-scientific communities (Ozlu et al., 2022). The livestock industry not only plays a major role in driving climate change through its GHG emissions but also faces direct impacts from it. Rising atmospheric temperatures, extreme weather events, and overall climate instability pose serious risks to livestock systems. These changes influence the sector directly, by affecting animal health, growth, and productivity, and indirectly, through reduced water availability, declining feed quality, and diminished soil fertility. Consequently, the livestock sector is both a contributor to climate change and one of its victims (Kumaş and Akyüz, 2024).

A variety of human activities such as burning fossil fuels, clearing forests, transportation, industrial processes, farming, and livestock production play a major role in driving climate change (Symeon et al., 2025). Considerable efforts have been made to measure GHG emissions from key sources on dairy farms; however, monitoring and quantifying all emissions from an entire farm or production system simultaneously remains nearly impossible and prohibitively costly (Rotz, 2018). In recent years, interest in the GHG effect closely linked to the rise in global temperatures has grown substantially. The three most important GHGs are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Smith et al., 2007; Burbi, 2014; Króliczewska et al., 2023). These gases are largely emitted through processes such as enteric fermentation, feed production, dietary management, and total farm output (Singaravadivelan et al., 2023). They trap heat in the atmosphere by absorbing solar energy and slowing its release back into space (Króliczewska et al., 2023). Although the majority of emissions originate from fossil fuel use, agriculture and livestock production account for roughly 12% of global emissions (Symeon et al., 2025). Among livestock sources, cattle are responsible for approximately 65% of these emissions (Kumaş and Akyüz, 2024).

While the global agricultural sector is dispensable for sustaining human livelihoods and supporting economies worldwide, it is also a major source of GHG emissions, highlighting the need for sustainable farming practices particularly through smart farming approaches. The adoption of information and communication technologies in agriculture holds considerable promise for enhancing both sustainability and productivity. Nevertheless, a substantial gap persists in our understanding of how these technologies influence overall GHG emissions This gap emphasizes the complexity of agriculture's environmental role and the necessity of developing more comprehensive approaches to assess the net effects of technological interventions (Polymeni et al., 2024). Although climate change poses the greatest long-term challenge, farmers face more immediate difficulties in managing GHG emissions at the farm level (Clark et al., 2011).

In recent years, there has been growing policy interest in reducing GHG emissions from agriculture. This attention stems from the agricultural sector's significant contribution to GHG emissions at both global and national levels, as well as the relatively cost-effective opportunities for mitigation it offers compared to other sectors. Policymakers face the complex task of designing and implementing effective GHG abatement strategies for agriculture. This involves identifying mitigation practices that are both cost-efficient and capable of delivering substantial emission reductions, followed by selecting appropriate policy instruments to encourage their adoption (Glenk et al., 2014). While climate change presents the most significant long-term challenge, farmers must address the immediate task of managing GHG emissions at the farm level (Clark et al., 2011). The livestock sector, in particular, should focus its mitigation efforts on practical management strategies that can be applied directly in field conditions (Jose et al., 2016).

2. Climate Change and Dairy Farming

Dairy farming is a major contributor to GHG emissions throughout the life cycle of milk and dairy products. According to Thoma et al. (2013), roughly 72% of total emissions associated with the national fluid milk supply chain are generated prior to the milk leaving the farm. This highlights the importance of identifying emission sources at the farm level and understanding the processes that generate them. A deeper understanding of these sources and mechanisms provides valuable opportunities to develop effective mitigation strategies (Rotz, 2018).

As shown by recent data from the U.S. Department of Agriculture in Figure 1, the agricultural sector contributes roughly 10% of total emissions, highlighting its significant role in influencing climate patterns (Polymeni et al., 2022).

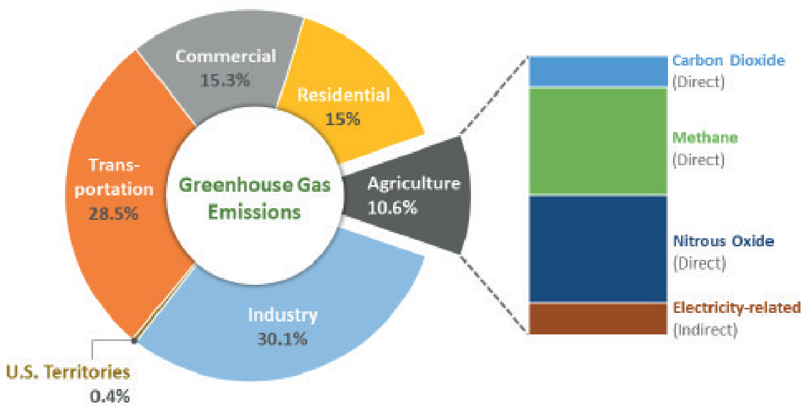


Figure 1. Global GHG emissions (Polymeni et al., 2022)

The main contributors to GHG emissions on dairy farms are CH_4 released through enteric fermentation and manure, N_2O emitted from soils, crop residues, manure, and fertilizers, and CO_2 generated from soil processes, fuel combustion, on-farm energy consumption, and the production of agricultural inputs (Le, 2018). Although these sources are often analyzed independently, interactions between them can influence the total amount of emissions (Rotz, 2018). Feed management plays a key role in reducing enteric CH_4 production, which is the largest single contributor to GHG emissions on dairy farms (Boadi et al., 2004; Le, 2018). According to a life cycle assessment by McGeough et al. (2012), 64% of emissions originate from lactating cows, 20% from dry cows and pregnant heifers, and 10% from animals less than one year old.

Extensive efforts have been made to measure GHG emissions from individual sources on dairy farms; however, monitoring and simultaneously quantifying all emissions from an entire farm or production system is both technically challenging and prohibitively expensive. As a result, the use of modeling approaches is necessary to estimate and evaluate GHG emissions from dairy production systems. These models can range from simple emission factor calculations to highly detailed process-level simulations (Rotz, 2018). Identifying effective mitigation strategies is crucial to reducing farm-level emissions, especially as agricultural production continues to intensify (Chianese et al., 2009). Dairy farming plays a significant role in driving climate change, largely because of CH_4 released through enteric fermentation and N_2O generated during manure management. However, implementing sustainable practices such as optimized grazing systems and soil conservation strategies can enhance carbon sequestration, partially offsetting these emissions and highlighting the sector's potential contribution to reducing its environmental footprint (Neethirajan, 2024).

The different livestock related activities and their contribution to existing GHG pool are described in Figure 2.

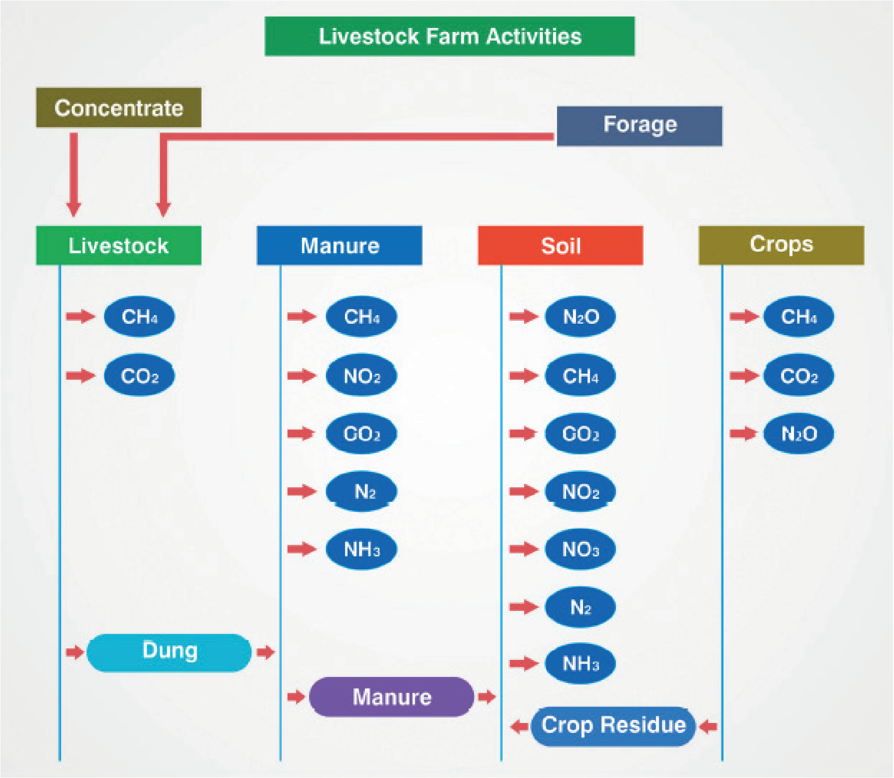


Figure 2. Pictorial representation of different livestock related activities and their contribution to GHG pool (Jose et al., 2016)

3. Emission Sources

The primary GHGs emitted from agriculture are CH_4, CO_2, and N_2O. These gases vary in their global warming potential, or their capacity to retain heat in the atmosphere. CH_4 is approximately 20 times more potent than CO_2, while N_2O is nearly 300 times more effective at trapping heat. Together, CH_4 and N_2O account for more than 95% of total agricultural GHG emissions. CO_2 is primarily released through soil cultivation, electricity consumption, and fuel combustion; CH_4 originates from enteric fermentation and manure decomposition; and N_2O is emitted during the breakdown of fertilizers, manure, and crop residues (Le, 2018). Many of these emission pathways are regulated by microbial processes, which are influenced by the optimal temperature range of the specific microorganisms involved (Chianese et al., 2009).

The various sources of GHGs from livestock farms are described in Figure 3.

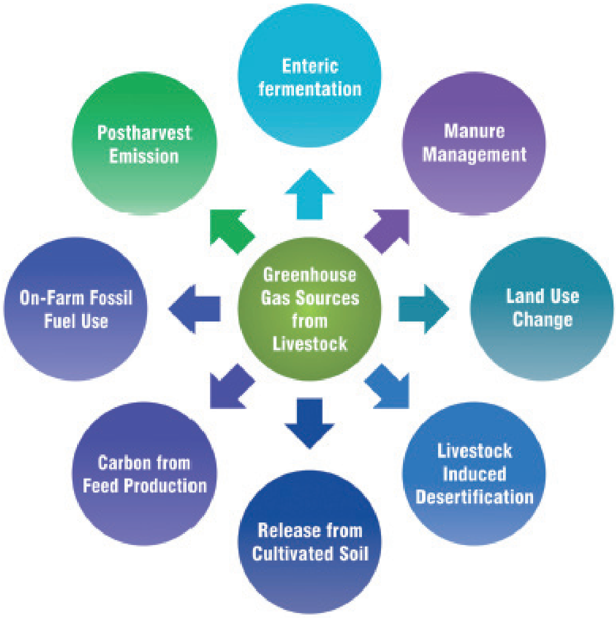


Figure 3. Different sources of GHGs from livestock farms (Jose et al., 2016)

3.1. Methane (CH4)

CH_4 is the second most important GHG after CO_2 and absorbs significantly more energy than CO_2. Over a 100-year time horizon, its global warming potential is approximately 28 times higher than that of CO_2. In addition, CH_4 contributes to indirect climate effects as a precursor to ozone, another potent GHG (Króliczewska et al., 2023). The primary source of CH_4 emissions is the anaerobic decomposition of organic matter. Interestingly, recent studies suggest that plants may also release small amounts of CH_4, although the exact mechanisms behind this process remain unclear (Chianese et al., 2009).

CH_4, one of the most potent GHGs, is a significant byproduct of ruminant digestion and manure management (Neethirajan, 2024). Methanogenesis is a key component of the global carbon cycle, contributing to both CO_2 and CH_4 emissions and thus shaping the overall carbon footprint (CF) of GHG–emitting systems (Ozlu et al., 2022). Domesticated ruminants including cattle, sheep, and goats naturally produce CH_4 during digestion, with cattle and dairy cows accounting for nearly 72% of total CH_4 emissions from the sector in 2020 (Króliczewska et al., 2023), while buffalo and small ruminants accounted for 8.7% and 6.7%, respectively. Ruminants are unable to digest cellulose on their own; however, rumen microorganisms break down cellulose from forage, releasing hydrogen as a byproduct. Symbiotic enteric methanogens utilize this hydrogen to reduce CO_2 to CH_4, preventing hydrogen accumulation (Chianese et al., 2009). Lactating cows emit roughly twice as much CH_4 as dry cows or heifers, primarily due to their higher feed intake, although diet composition and body size also play a role (Chianese et al., 2009). Consequently, researchers and livestock breeders worldwide are actively seeking strategies to simultaneously enhance animal productivity and mitigate CH_4 emissions, particularly from ruminants (Króliczewska et al., 2023). Additionally, manure applied to cropland surfaces can serve as an additional emission source (Sherlock et al., 2002).

In ruminant production systems, CH_4 represents the primary GHG emitted, with enteric fermentation in the rumen being the main contributor (Crosson et al., 2011). This process, driven by methanogenic archaea in the ruminant stomach, facilitates the breakdown of ingested feed but simultaneously produces CH_4 as a byproduct, which is mostly expelled into the atmosphere through eructation. As this mechanism is a fundamental aspect of ruminant physiology, it constitutes a consistent and largely unavoidable emission source within livestock systems (Polymeni et al., 2024). The overall CH_4 balance in agricultural systems is determined by the interplay between methanogenesis (CH_4 production) and methanotrophy (CH_4 oxidation). The relative strength of these processes dictates whether net CH_4 emissions are positive or negative. While methanogens are the microorganisms responsible for CH_4 production, methanotrophs are bacteria that oxidize and utilize CH_4 as an energy source (Bhattacharyya et al., 2020).

The amount of CH_4 generated by ruminants is influenced by multiple factors, such as animal species and body size, feed digestibility, and the intake of dry matter, total carbohydrates, and digestible carbohydrates (Chianese et al., 2009). Among these factors, feed quality plays a particularly critical role: diets high in fiber, especially cellulose, tend to increase CH_4 emissions. In addition to enteric fermentation, N_2O is released during manure decomposition. When manure is stored in liquid systems, the organic material is subjected to anaerobic microbial activity, resulting in GHG emissions (Jose et al., 2016). During storage, CH_4 is produced through pathways similar to those in the rumen, as microbial cellulose degradation creates substrates for methanogenesis (Monteny et al., 2001; Chianese et al., 2009). Therefore, strategies to mitigate CH_4 emissions must focus on reducing CH_4 generation without disrupting hydrogen removal, which is essential for maintaining efficient digestion (Clark et al., 2011).

3.2. Carbon Dioxide (CO_2)

CO_2 is the primary GHG emitted from soils, originating from the decomposition of active organic matter that accumulates carbon through crop residues, roots, and root exudates, and is broken down by soil microorganisms (Ozlu et al., 2022). CO_2 enters agricultural systems via photosynthesis and is subsequently released through the respiration of plants (both shoots and roots), animals, and microorganisms decomposing organic matter from manure and crop residues (Chianese et al., 2009). In addition, CO_2 emissions in agricultural practices are largely linked to the use of fossil fuels in farm machinery and equipment, where combustion generates substantial amounts of CO_2 into the atmosphere (Polymeni et al., 2024).

Both livestock and manure management are notable sources of CO_2 emissions on dairy farms. CO_2 is naturally released through animal respiration, forming a crucial component of the carbon cycle that begins with the photosynthetic fixation of carbon by plants. When animals consume plant-derived feed, much of the carbon captured by crops is returned to the atmosphere as CO_2 through respiration (Kirchgessner et al., 1991). Additionally, long-term manure storage can contribute significantly to CO_2 emissions, with production levels largely influenced by aerobic microbial activity. Solid manure stored in piles allows for greater oxygen penetration, which enhances microbial respiration and results in higher CO_2 emissions compared to high-moisture manure stored under anaerobic conditions in tanks. Research indicates that tillage systems and crop management practices can strongly influence carbon sequestration in agricultural soils (Chianese et al., 2009). Moreover, farming practices directly and indirectly affect CO_2 emissions by altering soil health and structure. For instance, the use of both organic and inorganic fertilizers has been identified as a significant source of GHG emissions in agricultural systems (Ozlu et al., 2022).

CO_2 emissions tend to increase with higher temperatures, reaching their peak during the summer, while decreasing at lower temperatures and falling to their lowest levels in snow-covered winter periods, indicating higher CFs during the growing season (Ozlu et al., 2022). In addition to temperature, soil moisture has been identified as a key factor influencing CO_2 emissions. Other important drivers of CO_2 release from soil to the atmosphere include soil pH, temperature, and management practices such as tillage, drainage, fertilization methods, crop rotation, crop type, residue management, and the use of soil amendments (Bhattacharyya et al., 2020).

3.3. Nitrous Oxide (N_2O)

N_2O is a significant GHG, even at low concentrations, due to its much higher global warming potential compared to CH_4 and CO_2, and it also contributes to stratospheric ozone depletion (Ozlu et al., 2022). N_2O emissions occur primarily through two microbial pathways: nitrification and denitrification (Bhattacharyya et al., 2020). Nitrification is an aerobic process in which ammonium (NH_4^+) is oxidized to nitrate (NO_3^-), with N_2O and N_2O produced as intermediate compounds. Therefore, N_2O emissions are influenced by both nitrification and denitrification processes. Denitrification can act as either a source or a sink for N_2O, as it is an intermediate product in the reduction pathway (Chianese et al., 2009; Soussana et al., 2010).

Recently, the agricultural sector has promoted the replacement of chemical inputs with organic or biodynamic growing methods. The use of chemical fertilizers in agriculture has been shown to increase GHG emissions, particularly N_2O, thereby exacerbating climate change concerns. Consequently, agricultural practices need to be reviewed and adapted to become more environmentally sustainable (Ozlu et al., 2022). N_2O emissions are closely associated with the wetting of dry soils and the application of nitrogen via manure or fertilizers (Chianese et al., 2009). These emissions may originate directly from stored manure, organic or inorganic fertilizers applied to soil, or nitrogen deposition by grazing animals (Crosson et al., 2011). In most agricultural soils, the biogenic formation of N_2O is enhanced by increased availability of mineral nitrogen, which stimulates both nitrification and denitrification. Therefore, the addition of nitrogen through fertilizers, manures, or other nitrogen-rich wastes generally promotes N_2O emissions, with the magnitude influenced by soil conditions at the time of application (Soussana et al., 2010). N_2O emissions from manure depend on its nitrogen and carbon content, the duration of storage, and the type of treatment (Jose et al., 2016).

N_2O emissions from livestock systems are generally low but not negligible. Annual emissions from manure storage are typically between 0 and 0.1 kg N_2O per cubic meter of stored manure, with most emissions arising from stacked solid manure or slurry with a surface crust or other conditions that encourage aerobic microbial activity. In contrast, liquid or slurry manure without a crust generally produces minimal N_2O emissions.

Livestock housing also contributes to N_2O release, primarily from manure on barn floors, with average annual emissions estimated at around 0.3 kg N_2O per livestock unit (Chianese et al., 2009). When nitrogen fertilizers are applied to soils, particularly for crops with high nitrogen requirements, they undergo complex microbial transformations. During nitrification, soil microorganisms convert ammonia-based fertilizers to nitrate (NO_3^-) under aerobic conditions, releasing N_2O as a byproduct. Under anaerobic conditions, denitrification further reduces nitrate to gaseous forms, including N_2O. As agricultural production expands to meet rising global food demand, the use of synthetic fertilizers has increased significantly, contributing to elevated soil N_2O emissions (Polymeni et al., 2024). These emissions are often concentrated in localized "hot spots," such as urine patches or areas with fertilizer granules and crop residues, even when nutrient applications are evenly distributed (Flechard et al., 2007).

4. Enteric Fermentation

Enteric fermentation is a complex biological process that cannot be fully described by a single equation. To predict CH_4 emissions from ruminants across different diets, models have been developed that simulate nutrient digestion, absorption, and passage through the rumen and hindgut (Ellis et al., 2001). This process is a significant contributor to GHG emissions in milk production, accounting for roughly 37% of total anthropogenic CH_4 emissions (Rotz and Thoma, 2017). These emissions are inevitable, as they result from the normal digestive processes of dairy cows. The quantity and composition of farm animals, particularly those not used for milk production, influence enteric CH_4 emissions; a higher proportion of non-lactating animals leads to greater GHG emissions per litre of milk produced. Additionally, the type of feed, the physiological state of the animals, and their level of production all significantly affect the amount of enteric CH_4 generated (Singaravadivelan et al., 2023).

CH_4 is generated during enteric fermentation as a byproduct of carbohydrate breakdown by methanogenic microorganisms in the rumen. The produced CH_4 is released by the animal primarily through eructation, contributing to GHG emissions (Jose et al., 2016). Estimates of enteric CH_4 from livestock are generally based on average daily feed intake, expressed as gross energy (GE; MJ/d), and corresponding CH_4 conversion rates. In livestock reporting, cattle are typically categorized into dairy cows and other types, with the latter further classified by sex, age, and feeding regimen (Crosson et al., 2011). One nutritional strategy with the potential to reduce enteric CH_4 emissions is partially replacing grass silage with maize silage in the diet. Dijkstra et al. (2018) reported that substituting 50% of grass silage with maize silage in a diet consisting of approximately 70% grass silage and 30% concentrates can decrease enteric CH_4 production by around 8%. At the individual animal level, this strategy provides a practical approach for mitigating GHG emissions.

Enteric CH_4 mitigation has been extensively studied, and several well-established strategies have been developed for practical use on farms. These include the supplementation of ionophores, incorporation of dietary lipids, improvement of forage quality, and increased inclusion of grains in ruminant diets (Boadi et al., 2004). For instance, feeding monensin an ionophore has been shown to lower enteric CH_4 emissions by approximately 20% in dairy cattle (Sauer et al., 1998). These mitigation approaches work primarily by inhibiting methanogenic archaea or by redirecting hydrogen ions away from methanogenesis pathways, thereby reducing CH_4 formation (Boadi et al., 2004).

Enteric fermentation and urinary nitrogen are the primary sources of CH_4 and N_2O emissions in ruminant systems (Waghorn, 2008). Enteric CH_4 contributes approximately 78–86% of total CH_4 emissions, with the remainder originating from manure management (McGeough et al., 2012). The model developed by Mills et al. (2003), which represents enteric CH_4 production as a function of metabolizable energy intake and the starch-to-fiber ratio, has proven effective for predicting CH_4 emissions across a wide range of forage-based diets (Stackhouse-Lawson et al., 2012). In addition to CH_4, cattle also produce enteric N_2O as part of their normal nitrogen metabolism (Hamilton et al., 2010).

5. Carbon Footprint (CF)

More specifically, the CF quantifies the total amount of GHGs produced both directly and indirectly through agricultural activities or throughout the entire life cycle of a product. It provides a comprehensive measure encompassing all GHG emissions linked to production, including CO_2, CH_4, and N_2O, originating from sources such as fuel use, livestock rearing, fertilizer application, and the decomposition of crop residues (Polymeni et al., 2024).

The emission sources from agricultural and dairy farming drained peatlands and their potential impacts on dairy products are illustrated in Figure 3.

The farming stage plays a critical role in determining the CF of most food products, as approximately 70–90% of total emissions occur before the products leave the farm gate (Hermansen and Kristensen, 2011). Evaluating agricultural CFs can serve as a valuable tool for managing farming practices to mitigate GHG emissions and, consequently, climate change. However, efforts to reduce GHG emissions should be implemented while ensuring that soil health and quality are maintained or enhanced (Ozlu et al., 2022).

To determine whether dairy cow nutrition can significantly reduce the CF, it is first necessary to define what constitutes the CF and clarify what is considered a "meaningful" reduction. Subsequently, the potential impact of implementing GHG mitigation strategies related to animal nutrition must be evaluated. The primary GHGs contributing to CF on dairy farms are CH_4 originating from enteric fermentation and manure management and N_2O resulting from manure handling and feed production. Since nutritional interventions are expected to mainly influence ruminal fermentation, this analysis focuses on strategies for mitigating enteric CH_4 in relation to CF (Hristov et al., 2013).

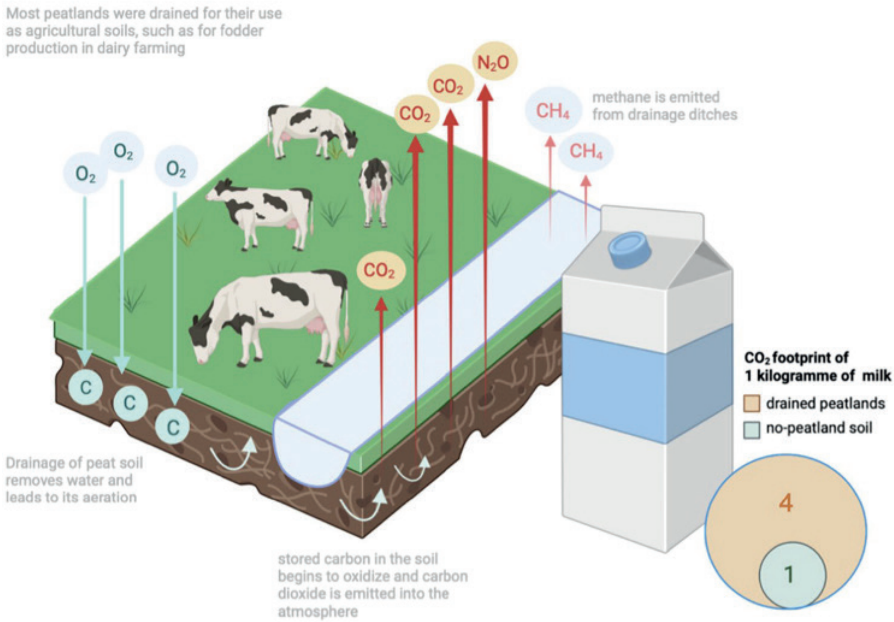
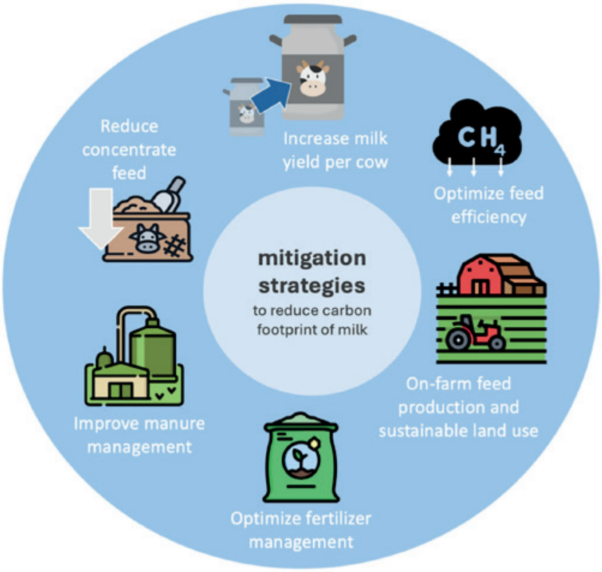


Figure 4. Sources of emissions from drained peatlands used for agriculture and dairy farming and their potential influence on the CF of milk (Müller et al., 2025)

Increasing milk yield, optimizing diets and feed efficiency, as well as improving manure and land management, are frequently highlighted as key strategies for mitigating the CF of milk production (Figure 4).



Figre 4. Widely adopted strategies for mitigating the carbon footprint associated with milk production (Müller et al., 2025)

According to Sahu and Agarwal (2021), the dairy industry represents a significant source of anthropogenic GHG emissions when assessed through CF analysis. Studies conducted under different international standards and methodologies consistently identify enteric CH_4 as the primary contributor to emissions, followed by manure management and fertilizer production. Recommended strategies for reducing these emissions include providing balanced feed rations, minimizing the use of nitrogen-based fertilizers, and adopting alternative energy sources such as biogas. Ibidhi and Calsamiglia (2020) estimated the GHG emissions and CF of twelve dairy farms in Spain, reporting that CH_4 emissions were the largest component of total GHG emissions, with an average CF of 0.84 kg CO_2e per kilogram of milk produced. Their findings indicated that management-based interventions were more effective than dietary modifications, achieving up to a 27.5% reduction in the CF. Hermansen and Kristensen (2011) observed that the CF per kilogram of milk declines substantially as milk production per cow increases, particularly up to 3,000–4,000 kg per cow per year. The higher CF at lower yields was primarily attributed to reduced feed efficiency in such systems, where a greater proportion of feed is allocated to non-productive uses such as maintenance, replacement stock, and draught power.

6. Mitigation Strategies for GHG Emission

6.1. Housing

Livestock housing management plays a significant role in influencing both CH_4 and N_2O emissions. CH_4 output varies across production stages; for example, emissions from farrowing units are typically lower than those from fattening units because they are cleaned approximately every 27 days compared to 90–100 days in fattening houses (Sommer et al., 2009). In straw-flow housing systems, improved litter aeration can result in higher temperatures, which may increase CH_4 emissions. Nevertheless, implementing daily scraping practices has been shown to reduce CH_4 emissions by up to 50% (Philippe et al., 2007).

The design of animal housing facilities is an important factor when evaluating emissions from livestock operations (Chianese et al., 2009). In freestall barns, emissions from housing typically account for less than 5% of total farm emissions. By contrast, systems such as slatted floors or bedded pack facilities effectively combine housing with long-term manure storage, resulting in substantially higher emissions (Rotz and Thoma, 2017). Emission levels also depend on the manure management system employed. In freestall barns, manure is generally removed every few hours or at least once daily through scraping or flushing, which limits the time available for CH_4 and N_2O formation, thereby keeping emissions relatively low (Rotz, 2018).

Freewalk housing systems represent an important step toward sustainable dairy farming by providing cows with a more natural, welfare-oriented living environment. Compared to conventional stall-based housing, cows in freewalk systems show reduced incidences of health problems such as lameness and mastitis. From an environmental perspective, these systems support natural cow behavior, which results in more even manure distribution and improved management, ultimately helping to lower ammonia emissions. Additionally, the installation of cooling systems in bedding areas can slow the decomposition of organic matter, thereby reducing CH_4 and ammonia emissions. The integration of automated bedding management technologies further enhances farm hygiene and supports emission mitigation by maintaining a clean, controlled environment for the animals (Neethirajan, 2024).

The adoption of renewable energy sources in farm operations plays a vital role in lowering GHG emissions and enhancing agricultural sustainability, not only by reducing carbon output but also by improving energy independence (Ayaz et al., 2019). Furthermore, the implementation of precision agriculture technologies offers a significant opportunity to both mitigate GHG emissions and boost overall farm productivity (Balafoutis et al., 2017). In terms of animal management, strategies for reducing GHG emissions generally include improving animal productivity and health, shortening the time to puberty, reducing days on feed, and selecting animals with greater fertility through genetic improvement (Hristov et al., 2013). Enhancing per-animal production is another effective approach, as Gerber et al. (2011) reported that although higher milk yield per cow increases total emissions per animal, it simultaneously lowers GHG emissions per kilogram of fat-corrected milk.

6.2. Feeding Management

The inclusion of concentrates in cattle diets can be an effective strategy to reduce nitrogen losses, as they lower ruminal pH and alter rumen activity (Klevenhusen et al., 2011). Another approach to mitigating nitrogen excretion involves reducing the overall protein intake of cattle. To ensure a minimum intake of 14% dry matter, oilseed meals can be incorporated to balance crude protein levels when legumes are not included in the forage component of the ration (Beauchemin et al., 2008). A primary objective of grassland management is to enhance the nutritional quality of forage consumed by grazing ruminants. Since CH_4 production is strongly associated with fiber digestion in the rumen, decreasing the fiber content of forages is expected to lower CH_4 emissions (Clark et al., 2011).

The implementation of the Total Mixed Ration (TMR) system or the use of ration formulation software can significantly enhance nutrient management, minimize dietary nitrogen surpluses, and ensure that energy requirements are properly balanced for different animal groups particularly monogastrics across various production stages (Basely and Hayton, 2007). Diets containing higher levels of concentrates, greater proportions of legumes, tannin-rich forages, or elevated lipid concentrations have all been associated with a reduction in CH_4 emissions when expressed per kilogram of dry matter intake (Clark et al., 2011). In a comprehensive review, Hristov et al. (2013) recommended feed management practices for mitigating GHG emissions, including the use of tannins, lipids, increased grain proportions, high-quality forage, and processed feeds. Tannins plant-derived bioactive compounds have gained recognition for their ability to reduce enteric CH_4 emissions in dairy cattle by binding to rumen proteins, thereby reducing protein degradation and subsequent ammonia production. However, their inclusion must be carefully managed to prevent potential negative effects on feed intake and nutrient utilization (Neethirajan, 2024). Fat supplementation in ruminant diets not only lowers CH_4 emissions but has also been shown to decrease ammonia (NH_3) emissions from fresh manure by approximately 14% (Machmüller et al., 2003). Nevertheless, since fat and grain levels in North American dairy rations are already high, further increases have limited potential for additional GHG reduction (Lee and Sumner, 2014). Moreover, excessive dietary protein contributes to elevated nitrogen excretion and ammonia emissions. Optimizing protein levels to meet but not exceed the physiological requirements of cattle can help mitigate CH_4 production and reduce the environmental burden associated with nitrogen losses (Neethirajan, 2024).

An effective alternative for reducing farm GHG emissions is the use of high-quality forages, which are less expensive than grain and require less fuel for cultivation, thereby potentially lowering production costs and net emissions (Johnson et al., 1996). Diets with higher fiber content increase acetate production in the rumen, which is associated with greater CH_4 output. Incorporating grain into a forage-based diet and selecting forages with lower fiber content increases starch intake and decreases fiber intake, leading to lower ruminal pH and a shift in fermentation toward propionate rather than acetate, ultimately reducing CH_4 emissions (Burbi, 2014). Conversely, feeding diets high in cellulosic material has been shown to increase enteric CH_4 emissions (Króliczewska et al., 2023). In pasture-based systems, grazing on younger pastures, especially those containing legume-grass mixtures with lower fiber content, increases the rate of passage and consequently reduces CH_4 production (Robertson and Waghorn, 2002).

Feeding rations with lower fiber and higher energy content can significantly influence enteric fermentation; however, excessive reductions in fiber may compromise the economic and physiological benefits of proper rumination. The inclusion of concentrates lowers ruminal pH, which in turn decreases CH_4 production. High-fiber dried grains, such as barley, contain more fiber compared to maize or wheat and therefore have a lower capacity to reduce ruminal pH and CH_4 emissions, though they are generally more affordable (Chianese et al., 2009). Lee et al. (2004) reported that enteric CH_4 emissions can be significantly reduced when diets contain a high proportion of white clover, but under practical conditions where white clover typically comprises less than 20% of the diet, the effect is negligible. Silage quality defined by its fermentation profile and nutrient composition plays a crucial role in shaping ruminal fermentation dynamics. Thus, improving silage production and management practices is essential for minimizing the environmental footprint of dairy farming (Neethirajan, 2024). Moreover, incorporating fat supplements into cattle diets can lower total GHG emissions by approximately 8–14% (Petersen et al., 2013). Finally, efforts to reduce energy and water consumption not only contribute to emission reduction but also promote sustainable and cost-effective farm management (Pretty et al., 2018).

6.3. Grazing and Pasture Management

Grasslands represent the natural climax vegetation in regions where rainfall is insufficient to support forest growth. In contrast, in areas with higher precipitation, grasslands are not the dominant climax vegetation and tend to be more productive. Rangelands, which are found on every continent, are characterized by low-growing vegetation shaped by temperature and moisture limitations (Soussana et al., 2010). Livestock play a crucial role in maintaining these grassland ecosystems, thereby preventing land-use changes that could lead to increased carbon emissions. Moreover, they may contribute to soil carbon sequestration: studies on temperate, unfertilized grasslands where cattle are reared without supplemental feed or fertilizers indicate that the carbon sequestered in the soil can offset their CH_4 and N_2O emissions (Garnett, 2009). Thus, the carbon sequestration potential of grasslands and rangelands offers an opportunity to partially mitigate GHG emissions from the livestock sector (Soussana et al., 2010).

Grazing livestock, especially those consuming legume-based pastures, excrete a greater proportion of ruminal ammonia (NH_3) as urea in their urine (Arelovich et al., 2003). This ammonia originates from the breakdown of non-protein nitrogen during digestion. Once excreted, the nitrogen in urine is transformed into nitrate (NO_3^-) through soil nitrification processes, which can then be converted to N_2O via denitrification. This biochemical pathway explains the strong link between urine deposition by grazing ruminants and elevated N_2O emissions (Menneer et al., 2005).

The implementation of rotational grazing affects both the duration and intensity of grazing. Specifically, relocating animals every 1–2 days can significantly influence CH_4 and N_2O emissions. Shortening grazing periods offers multiple benefits: it encourages animals to feed on younger, lower-fiber pasture, potentially reducing CH_4 emissions by up to 22%; additionally, when combined with decreased fertilizer application, it limits nitrogen availability in the pasture, thereby reducing N_2O emissions by up to 10% (DeRamus et al., 2003; Schils et al., 2006). Furthermore, lowering grazing density helps prevent overgrazing and soil compaction, supporting overall pasture health (Saggar et al., 2007).

6.4. Manure Storage and Treatment

Livestock manure represents both an asset and a challenge in agricultural systems. It provides essential nutrients to the soil; globally, approximately 22% of applied nitrogen and 38% of phosphate originate from animal manure, with over half contributed by beef cattle (Garnett, 2009). However, manure also accounts for up to 10% of total GHG emissions from livestock worldwide (Symeon et al., 2025). Typically, manure is excreted in slurry form, and separators can be employed to partition solids from liquids, enabling separate storage and handling. When manure is deposited on open lots, it dries and forms solid material. These solids may be stored in stacks without treatment or periodically turned to encourage composting (Rotz, 2018).

Anaerobic conditions in liquid or slurry manure favor CH_4 production, while N_2O emissions remain low unless a crust develops on the surface. Particles of bedding and undigested feed can rise to the surface, forming a crust in which alternating aerobic and anaerobic conditions facilitate incomplete denitrification, leading to N_2O formation (Rotz, 2018). Manure contains considerable amounts of inorganic nitrogen, microbially available carbon, and water, making it a valuable resource if managed correctly. At the same time, these components serve as substrates for microbial generation of CH_4 and N_2O, two potent GHGs contributing to climate change (Symeon et al., 2025). The magnitude of emissions from manure storage and treatment is influenced by the quantity produced, its carbon and nitrogen content, the proportion decomposing anaerobically, and the storage duration, temperature, and method. Generally, liquid (primarily anaerobic) systems emit more CH_4, whereas solid systems tend to produce more N_2O (Crosson et al., 2011).

Manure management is a key aspect of farm nutrient budgeting and is closely linked to fertilizer application. Livestock manure consists primarily of organic material and water. In anaerobic environments, the organic fraction of cattle manure is decomposed by facultative and anaerobic bacteria, resulting in the production of CH_4, CO_2, and stabilized organic matter as byproducts. On-farm GHG emissions are influenced by manure management practices, the volume of manure produced, and whether the manure is in solid or liquid form (Singaravadivelan et al., 2023). Manure is produced daily by farm animals, with composition and quantity varying according to animal type, production stage, production system, and diet. For instance, a cow typically generates around 29 kg of manure per day. Manure can be classified based on its dry matter content into liquid, slurry, and solid forms. The main nutrients contained in manure include carbon (C), nitrogen (N), phosphorus (P), sulfur (S), and potassium (K), the concentrations of which depend heavily on the animal's diet and physiological characteristics (Symeon et al., 2025).

There are several strategies available to mitigate manure-related emissions. Manure not only represents a significant portion of GHG emissions from dairy farms, but it also contains a large fraction of nutrients from feed. For instance, only about one-third of the nitrogen in feed is incorporated into the protein of animal products, while the remainder is excreted in urine and manure (Kirchgessner et al., 1994). Consequently, the energy content in manure can be harnessed through biogas production for electricity generation instead of being released into the atmosphere.

Recommended manure management practices include reducing dietary protein, separating solids, acidifying manure, matching application rates to crop needs based on soil and manure testing, and avoiding spreading during late fall, winter, or adverse weather conditions such as heat, wind, or rain (Hristov et al., 2013). Treatment methods for solid and liquid manure significantly influence emission rates: low temperatures, aeration, and composting help reduce CH_4 emissions, while adding straw, using covers, and treating solid and liquid fractions separately can minimize N_2O losses. Furthermore, the frequency of manure removal, the type of bedding, the floor design, and regular flushing and cleaning of housing units all contribute to reducing CH_4 and N_2O emissions from livestock facilities (Burbi et al., 2016).

It is crucial to note that controlling gaseous emissions from manure depends on regulating the compost pile's temperature and maintaining a balance between aerobic and anaerobic conditions. Compaction can reduce ammonia (NH3) emissions by up to 90% and, to a lesser extent, N_2O emissions by approximately 30%. CH_4 emissions are generally lower during colder months but may increase substantially in warmer periods (Chadwick, 2005). Adding water can decrease the free air space by 20–60%. Separating the liquid and solid fractions of manure offers several advantages for storage management. Storing these fractions separately enables better control of factors influencing emissions, such as temperature, moisture content, aeration, and covering. Additionally, separation can enhance slurry storage capacity and result in fractions with higher nutrient concentrations. However, the reduction of ammonia and CH_4 emissions particularly from the solid fraction is most effective when slurry separation is combined with lower storage temperatures and solid-cover solutions. Storing the liquid fraction under anaerobic conditions prevents the nitrification of NH3 to nitrate (NO3−), thereby minimizing denitrification processes that produce N_2O (Fangueiro et al., 2008).

6.5. Manure Application to Soil

When applying manure to soils, careful consideration of both timing and application rates is essential to prevent excessive nitrogen input. Different application techniques have also been shown to help reduce soil emissions (Burbi et al., 2016). Manure can either be injected beneath the soil surface or incorporated into the soil immediately after application through tillage. Incorporating manure into the soil minimizes emissions during application and can be estimated using an emission factor or process-based simulation for any manure remaining on the surface (Rotz et al., 2011). In general, adding nitrogen from fertilizers, manure, or other readily mineralizable sources stimulates N_2O emissions, with the magnitude influenced by prevailing soil conditions. N_2O losses under anaerobic conditions are typically more significant than those from nitrification under aerobic conditions (Skiba and Smith, 2000). Soil N_2O emissions often occur in localized 'hot spots' such as urine patches or fertilizer and residue particles, even when manure and fertilizers are applied diffusely (Flechard et al., 2007). CH_4 emissions from well-drained grassland soils, however, are generally negligible (Hendriks et al., 2007).

GHG emission processes continue after both manure and inorganic fertilizers are incorporated into the soil. Three key processes influence GHG emissions from cropland and pasture: oxidation, nitrification, and denitrification (Rotz, 2018). In most soil conditions, atmospheric CH_4 is oxidized to CO_2, thereby acting as a net sink for CH_4 (Boeckx et al., 1997). A review of published data for crops commonly grown on dairy farms indicated an average annual CH_4 absorption of approximately 1.5 kg CH_4 per hectare (Chianese et al., 2009).

6.6. Disease Control

Animal health plays a crucial role in determining how efficiently animals utilize resources such as feed and water. Poor health typically leads to increased resource inputs, including medications, while reducing productivity. Consequently, there is a direct positive relationship between good animal health and production efficiency, which is expected to result in lower GHG emissions (Kyriazakis et al., 2024).

Mastitis has been identified as a condition that can increase GHG emissions in the dairy sector, primarily due to reduced production and higher rates of involuntary culling. Lowering somatic cell count (SCC), an indicator of mastitis, from 800,000 to 50,000 cells/ml has the potential to decrease GHG emission intensity by 3.7% (Gülzari et al., 2018). Additionally, a reduction of 18% in subclinical mastitis and 17% in clinical mastitis (CM) incidence was shown to reduce herd-level GHG emissions by 2.5%. However, there remains a significant knowledge gap regarding how different animal health conditions affect feed intake and utilization, which limits accurate estimation of GHG emissions from feed conversion (Mackenzie and Kyriazakis, 2021).

6.7. Genetic Selection

Genetic improvement in livestock represents a highly effective approach, producing permanent and cumulative enhancements in performance (Wall et al., 2010). One key strategy involves selecting or genetically adapting breeds that are better suited to heat stress. Breeds that sustain productivity under warmer conditions and exhibit traits such as heat tolerance and disease resistance may provide viable pathways for climate change adaptation (Neethirajan, 2024). Reducing GHG emissions in livestock production offers clear societal benefits by helping to mitigate the impacts of climate change. However, these benefits will only materialize if producers themselves perceive tangible advantages. For genomic selection strategies designed to enhance feed efficiency and decrease CH_4 emissions to be widely adopted, the economic incentives for farmers must be evident. In the past decade, genomic advancements have facilitated more precise selection of animals for improved feed efficiency and lower GHG emissions, as identifying these traits at the genotypic level is relatively cost-effective (Hailu, 2018).

Animal selection is inherently a long-term process, and choosing animals with lower CH_4 emissions represents a promising strategy for the future (Króliczewska et al., 2023). In dairy cattle, a slightly different approach has focused on selecting animals with reduced residual feed intake, as lower feed consumption generally results in decreased enteric CH4 emissions due to the direct correlation between feed intake and CH_4 production (Clark et al., 2011). Consequently, improving the productivity of low-producing animals tends to have a relatively greater impact on reducing emissions, whereas enhancing productivity in high-producing animals has a smaller effect (Króliczewska et al., 2023). Genetic selection has also led to physiological modifications that influence the rumen, feeding behavior, rumen outputs, and overall body composition of livestock (Rowe et al., 2013). Conducting a genetic selection program requires the collection of thousands of measurements, ideally on a weekly basis. The complexity of this process is further heightened by the diversity of grazing systems, which vary according to climate, plant species, soil type, and livestock management practices, including continuous grazing, rest-rotation grazing, deferred rotational grazing, and intensive grazing strategies. Therefore, developing reliable biomarkers through animal selection is essential to accurately estimate CH4 production across diverse farm systems (Manzanilla-Pech et al., 2021)

Integrating data from multiple studies and countries can facilitate the creation of an accurate genomic reference database and enable the development of precise genetic parameters for CH_4 traits. Achieving this requires genotyping and phenotyping a sufficiently large population of animals, with the resulting data made publicly accessible (de Haas et al., 2021). Basarab et al. (2013) indicate that improving feed efficiency through selective breeding provides an indirect means of lowering enteric CH_4 emissions in both beef and dairy cattle. In a similar vein, Goddard et al. (2016) show that adopting genomic selection to enhance feed efficiency not only offers economic benefits for the beef industry but also generates environmental advantages for society. Biotechnological approaches, such as genomic selection targeting improved feed efficiency and reduced CH_4 emissions, have substantial potential to achieve these objectives within the livestock sector. For these strategies to be successfully implemented, the economic and environmental benefits must be clearly established, and widespread adoption is crucial (Hailu, 2018).

7. Conclusions

Climate change has profoundly affected nearly all aspects of agriculture, particularly the livestock sector, resulting in significant global environmental and economic challenges. Animal-derived foods generally have a substantially higher carbon footprint compared to plant-based foods, making livestock production a key focus for climate mitigation efforts. As a result, policies targeting GHG reductions from livestock have become increasingly common in recent years. Dairy farming is a major contributor to GHG emissions across the entire life cycle of milk and dairy products. Therefore, reducing emissions from dairy cattle remains a central objective in minimizing the agricultural sector's overall carbon footprint. Potential mitigation strategies include improved feed and barn management, optimized grazing and pasture systems, enhanced manure storage and treatment, efficient manure application, disease prevention, and genetic selection. Given the complexity of dairy farming systems, it is essential to account for emissions at the whole-farm level rather than focusing solely on individual components, as emission reductions in one area may inadvertently increase emissions elsewhere.

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