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Mitigating methane in dairy cattle: Integrated strategies and the evolving role of precision livestock farming

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Abstract: Modern dairy farming faces the dual challenge of meeting global food demands while mitigating its environmental impact, particularly greenhouse gas (GHG) emissions, such as methane (CH_4), a potent contributor to climate change. This review explores the role of Precision Livestock Farming (PLF) technologies in monitoring and reducing CH_4 emissions from dairy cattle. We evaluate state-of-the-art methods, including direct monitoring (e.g. respiratory chambers, GreenFeed systems) and indirect approaches (e.g. infrared milk spectroscopy, AI-driven analytics), alongside mitigation strategies such as nutritional optimisation, genetic selection, and ruminal additives. PLF emerges as a transformative tool, integrating real-time data on animal health, feed efficiency, and environmental conditions to optimise management practices and reduce emissions per unit of milk produced. By synthesising current research, we highlight the potential of PLF to reconcile productivity with sustainability, offering scalable solutions for the dairy sector. Critical gaps in real-time CH_4 monitoring and farm-level implementation are identified, underscoring the need for further innovation. This review provides a roadmap for aligning dairy production with global climate goals while ensuring food security for the growing population.

Keywords: emission monitoring; mitigation strategies; rumen fermentation; ruminant emissions; sustainability

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GREENHOUSE GAS EMISSIONS IN DAIRY CATTLE PRODUCTION: A GLOBAL PERSPECTIVE

The global human population is projected to reach 10 billion by 2050, creating unprecedented demands for food production that are intensifying pressure on agricultural systems and natural resources (von Soosten et al. 2020). As livestock production expands to meet growing protein needs, its environmental impacts have become increasingly urgent, particularly greenhouse gas (GHG) emissions from ruminant systems. Within this landscape, dairy farming represents a significant but addressable contributor to climate change through multiple pathways, including feed production, manure management, and most notably, enteric methane (CH_4) formation (Rotz 2018). The methane exceptional warming potential, 84 times greater than that of carbon dioxide (CO_2) over 20 years (Myhre et al. 2013), and its substantial role in near-term climate change have made it a priority for global action, as evidenced by the Global Methane Pledge's commitment by over 160 countries to reduce anthropogenic CH_4 emissions by 30% before 2030 (Global Methane Pledge 2021). Although the top CO_2-emitting countries do not fully overlap with the leading methane (CH_4) emitters from livestock (Figure 1), methane remains a critical climate concern, particularly in regions like the EU, where enteric fermentation from cattle alone accounts for 38% of total anthropogenic methane emissions (European Environment Agency & European Commission 2025). This underscores the outsised role of livestock in climate change and emphasises the need for targeted mitigation strategies. This is particularly critical because cattle (dairy and non-dairy) production systems contribute to over 70% of total livestock-related CH_4 emissions (Figure 2), with the primary source being enteric fermentation, the microbial breakdown of organic matter in the rumen and hindgut (Wattiaux et al. 2019). Notably, this process is a major emissions driver in both dairy and non-dairy systems (Figure 3), emphasising the broad relevance of mitigation efforts across ruminant production.

This review examines the current understanding of CH_4 emissions from dairy production, evaluates established and emerging mitigation strategies, and explores how Precision Livestock Farming (PLF) technologies can enhance emission reduction efforts. The principles discussed extend beyond dairy cattle to other ruminant systems, including beef production, sheep, and goats, making these insights broadly relevant for sustainable livestock agriculture. By synthesising research across these areas, we aim to identify practical, scalable solutions that can help align animal protein production with climate stabilisation goals while maintaining food security in an era of global population growth.

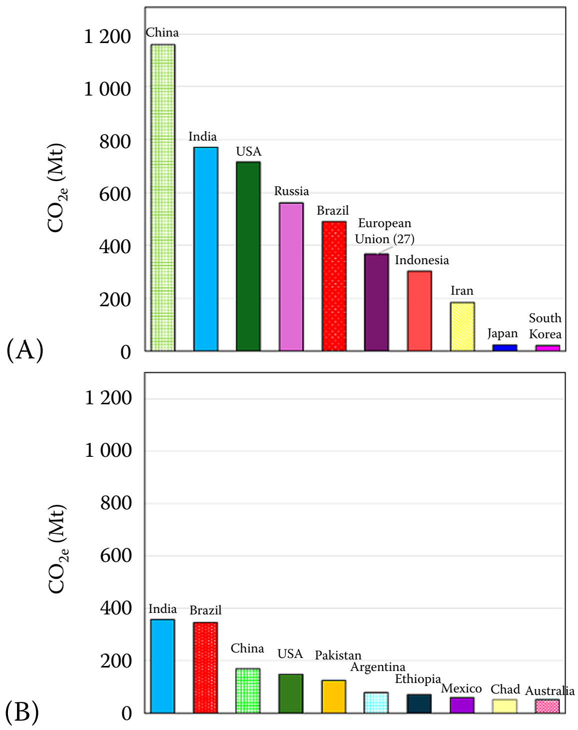

Figure 1. Worldwide top 10 emitters in 2022 for total CH_4 (A) and Livestock (B)
Adapted from WRI (Friedrich et al. 2023)

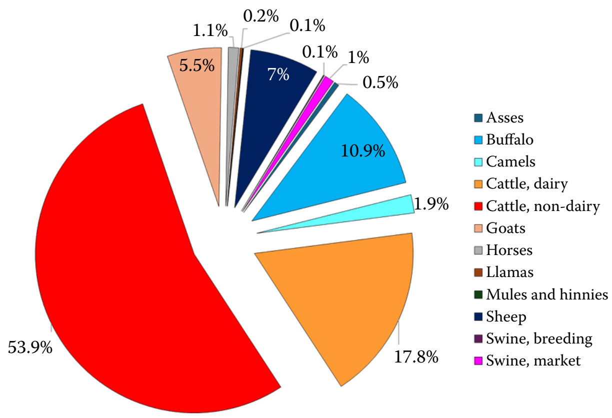

Figure 2. Worldwide total CH_4 emissions by livestock species and categories estimated by FAO for the year 2022 (data from FAOSTAT 2025)

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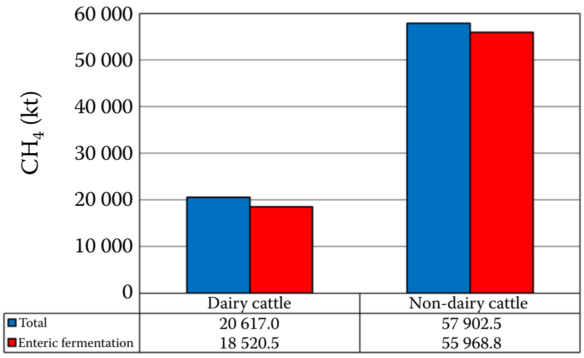

Figure 3. Total methane emissions and enteric-origin methane emissions estimated by FAO for 2022 in dairy and non-dairy cattle (FAOSTAT 2025)

ENTERIC METHANOGENESIS IN RUMINANTS: THE ENVIRONMENTAL–NUTRITIONAL PARADOX

The unique ruminant digestion system, which upgrades low-value feedstuffs into high-quality protein, is intrinsically linked to enteric methanogenesis. This microbial process, essential for efficient fibre degradation, results in the inevitable production of the potent greenhouse gas CH_4. Consequently, a fundamental tension exists between using ruminants to achieve global food security and mitigating their impact on climate change.

The rumen is a symbiotic bioreactor where microbial fermentation breaks down ingested feed, primarily converting carbohydrates into volatile fatty acids (VFAs), the ruminant's primary energy source, and microbial protein, which becomes the animal's primary source of amino acids. This anaerobic process is crucial for the ruminant's ability to upcycle low-quality forage.

A critical consequence of this fermentation is the production of metabolic H_2 (hydrogen). The type of volatile fatty acid (VFA) produced in the rumen directly influences hydrogen (H_2) dynamics, which in turn governs methanogenesis. Acetate and butyrate production belongs among net generators of H_2, whereas propionate synthesis acts as an H_2 sink. Since H_2 accumulation is toxic to many fermentative microbes, the rumen ecosystem depends on methanogenic archaea to maintain metabolic balance. These archaea remove the excess H_2 by using it to reduce CO_2 to CH_4, making methanogenesis an indispensable process for sustaining the overall fermentation efficiency (Hungate 1966). The balance of VFA production directly determines the theoretical potential for methane emission, making it a key target for nutritional mitigation strategies.

The archaea comprise 2–4% of rumen microbiota (Waters et al. 2025), of which an overwhelming majority (90%) are methanogens, predominantly *Methanobrevibacter* spp. (Danielsson et al. 2017). These microorganisms are fundamental to the rumen function by acting as the primary H_2 sink, using the H_2 produced during carbohydrate fermentation to reduce CO_2 to CH_4 via the reaction: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$. As CH_4 is eructated and represents an energy loss of 2–12% for the animal, this process directly links ruminant production to greenhouse gas emissions, accounting for approximately 14.5% of all the GHG (Ghassemi Nejad et al. 2024).

The relationship between dietary fibre and CH_4 production in ruminants is fundamentally linked to shifts in rumen fermentation pathways (Janssen 2010; Bannink et al. 2011) and microbial ecology. High-fibre diets promote acetogenic fermentation, which generates H_2 (e.g. $C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$), thereby increasing substrate availability for methanogens. Conversely, high-concentrate diets shift fermentation towards propionogenesis, which consumes H_2 (e.g. $C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O$), thus competitively reducing its availability for CH_4 production.

Microbial communities adapt dynamically to these dietary changes: fibrolytic bacteria (e.g. *Fibrobacter succinogenes*) and other acetate producers increase in high-fibre conditions, while starch-rich diets select for amylolytic bacteria (e.g. *Streptococcus bovis*) and propionate-generating pathways (e.g. via succinate or acrylate routes) (Morgavi et al. 2010). Additionally, methanogen populations (e.g. *Methanobrevibacter*) decline when fibre is reduced, further suppressing CH_4 (Hook et al. 2010). However, leveraging this dietary principle for mitigation involves a critical trade-off, as low-fibre diets risk causing acidosis and impairing the overall rumen health, highlighting the importance of balanced nutritional strategies (Beauchemin et al. 2020).

Therefore, while ruminal methanogenesis is an intrinsic outcome of the symbiosis that allows ruminants to upgrade low-quality feed, it necessitates targeted nutritional strategies to balance production efficiency with climate objectives.

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STRATEGIES FOR METHANE REDUCTION IN DAIRY CATTLE: PRINCIPLES AND EVIDENCE FROM RUMINANT RESEARCH

Despite the paradox mentioned above, the available evidence suggests that strategies to reduce CH_4 emissions in dairy cattle do not inherently conflict with improved productivity. From a theoretical standpoint, a reduction in CH_4 emission represents a lower loss of dietary energy through eructation. This saved energy could potentially be redirected toward production, meaning that strategies that enhance feed efficiency often lead to both improved productivity and reduced CH_4 yield (Lovendahl et al. 2018). The purpose of this item is to provide a general overview of possible strategies to reduce CH_4 emissions. For comprehensive reviews on the topic, we recommend Hristov et al. (2013), Beauchemin et al. (2020), or Almeida et al. (2021).

Nutritional strategies that enhance propionate production in the rumen

As explained before, the higher the proportion of propionate in the rumen, the lower the CH_4 emitted. In this sense, higher non-fibre carbohydrate (NFC) content in the diets promotes propionate synthesis, diverting H_2 away from CH_4 production (Janssen 2010; Bannink et al. 2011). However, it is well-known that high NFC diets pose a risk of acidosis, which is greater when diets are low in forage-derived fibre (NASEM 2021). In a meta-analysis of 73 studies, Herliatika et al. (2024) demonstrated that increasing dietary starch in cattle mitigates enteric CH_4 production by two ways of action: (*i*) altering rumen protozoa populations [key H_2 producers according to Lewis et al. (2020)] and (*ii*) shifting the rumen fermentation profile toward propionate at the expense of acetate.

While modulating the carbohydrate composition is one effective approach, modifying the dietary lipid content represents another major avenue for reducing enteric methane. Indeed, changes in the ration content and the addition of lipids to dairy cow diets, although changing the fermentation profile toward acetate formation (Szumacher-Strabel et al. 2002), have been shown to reduce CH_4 emissions, concurrently altering the fatty acid profile in milk and demonstrating a positive correlation between these parameters (van Lingen et al. 2014).

It is generally accepted that providing highly digestible forages enhances efficient ruminal fermentation and reduces CH_4 emissions (Eugene et al. 2021). Forage maturity directly increases enteric CH_4 production through nutritional quality decline. As plants mature, the secondary cell wall development elevates lignin content and reduces digestibility, simultaneously depressing intake and energy availability while enhancing methanogenesis per feed unit (Thompson and Rowntree 2020). These structural changes simultaneously lower forage intake and energy availability, promoting greater methanogenesis per unit of ingested feed. Archimede et al. (2011) reported that cattle fed warm-season legumes produced the lowest CH_4 emissions per unit intake, followed by cool-season legumes and temperate (C3) grasses, with tropical (C4) grasses yielding the highest emissions. Wims et al. (2010) and Munoz et al. (2016), working with dairy cows grazing high or low pre-grazing herbage mass, found that low herbage mass swards improved grass quality and reduced CH_4 emissions per cow, per unit of milk, and kilogram of dry matter intake due to higher forage quality. In beef cattle, Dini et al. (2018) demonstrated that grazing on high-quality pastures reduced enteric CH_4 emissions by approximately 15% compared to low-quality pastures across seasons, aligning with observations in dairy herds. In contrast, their earlier work with grazing dairy cattle (Dini et al. 2012) found no significant differences in milk yield or CH_4 production between legume-rich and grass-rich pastures. The authors attributed this result to the high herbage allowance that enabled selective grazing by cows, highlighting the ability of grazing ruminants to improve the chemical composition of their diet through selective foraging. Additionally, certain plant components, such as tannins, can influence CH_4 emissions. In a grazing study with heifers, Alecrim et al. (2024) demonstrated that incorporating tannin-rich legumes into grasslands is a strategy for mitigation by efficiency. In fact, although these authors did not observe a reduction in the total CH_4 emitted per animal, this approach effectively lowered the carbon footprint of beef production by drastically reducing methane emissions per kilogram of weight gain.

Genetic enhancement of forage species through traditional breeding techniques or genetic modi-

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fication can lead to important gains in nutritional quality (Capstaff and Miller 2018; Pereira et al. 2022). This field has grown rapidly in recent years, as advances in molecular sciences and biotechnology now provide powerful tools to uncover the molecular mechanisms behind key traits in forage species, facilitating breeding strategies and tools for creating and implementing enhanced genetic solutions (Bryan et al. 2024).

Ruminal additives

Significant research efforts in recent years have focused on identifying natural inhibitors and developing synthetic analogues to suppress CH_4 generation, with many products marketed as efficiency enhancers now claiming emission-reducing effects. Recent publications include reviews and guidelines for identifying and selecting emission-reducing additives (Durmic et al. 2025) and properly evaluating CH_4-mitigating additives in dairy cows (Hristov et al. 2025). Among emerging compounds, 3-nitrooxypropanol (3-NOP), which inhibits the enzyme methyl-coenzyme M reductase responsible for CH_4 formation, demonstrates a proven mitigation potential (studies report up to 30% CH_4 reduction), though some evidence suggests it may reduce production (Pupo et al. 2025). Since NDF reduces 3-NOP effectiveness, the compound works better in intensive systems where diets contain more concentrates than fibre (Kebreab et al. 2023; Xuan et al. 2024). Among natural additives, the most frequently studied have been tannins, saponins, essential oils, and seaweeds. Tannins showed the greatest effect (Almeida et al. 2021), while essential oils demonstrated positive effects when used in long-term studies (Belanche et al. 2020). The outcomes depend on phytochemical combinations, dosages, and basal diet composition (Beauchemin et al. 2020).

While some studies show no effects using essential oils (Benchaar and Hassanat 2025), others report a clear CH_4 reduction using blends of essential oils and tannins in *in vitro* (Rossi et al. 2022) and *in vivo* studies (Minutti et al. 2025). Seaweeds like *Asparagopsis taxiformis*, containing bromoform as the main active compound, have also been studied, showing favourable results (Glasson et al. 2022). Natural compounds remain promising, especially when combined with other strategies. Still, challenges persist in identifying specific mitigants, optimising doses and synergies (Flachowsky and Lebzien 2012), and elucidating microbial mechanisms beyond the confirmed effects (Belanche et al. 2025).

Genetic selection of the animals for higher production efficiency

Methane emissions in dairy cows can be reduced through genetic selection, using either direct or indirect genetic traits (Wall et al. 2010). Direct genetic traits are individual and specifically related to CH_4 emissions, whereas indirect genetic traits are related to the herd performance. Because genetic improvements are both permanent and cumulative, they represent a particularly promising long-term strategy for mitigating greenhouse gas emissions from ruminant production systems.

Selecting programmes for higher feed efficiency has been demonstrated to be useful to choose to emit less CH_4, in both dairy and beef cattle (Lovendahl et al. 2018; Olijhoek et al. 2018; Dini et al. 2019; Jenkins et al. 2024). De Haas et al. (2011) demonstrated that genetic selection could reduce cattle CH_4 emissions by 11–26% over a decade, a strategy with the potential for synergistic effects when integrated with feed additives, pasture management, and precision farming technologies. A recent large-scale Dutch study (7 139 cows across 68 farms) using automated "sniffer" sensors for CH_4 measurements revealed moderate heritability of CH_4 concentration and weak genetic correlations with production traits, suggesting the breeding for CH_4 mitigation could complement productivity goals (van Breukelen et al. 2025). Selection programs targeting rumen microbiome-associated traits are also promising (Mizrahi et al. 2021). Wall et al. (2010) proposed genetic selection for fitness traits (health, fertility, longevity) as a CH_4 mitigation tool. In dairy systems, increasing the cow longevity from 3 to 3.5 lactations reduces heifer replacement numbers, shrinking the herd's carbon footprint without compromising the production, a whole-herd genetic strategy rather than an individual-efficiency metric. This author estimated that this approach would lead to a decrease in CH_4 emission by 0.55% in milking cows and 18.87% in young stock, with a mean total decrease by 4.42% in the UK.

Herd management

We cannot overlook the numerous management measures that aim to optimise the production process, which, as a byproduct, also reduce CH_4 emissions. It is important to remember that low-producing animals or those in maintenance, though emitting less, continue to release CH_4. Furthermore, Goopy et al. (2020) found that feeding cattle below maintenance levels increases CH_4 production per unit of feed intake, suggesting a counterproductive effect on emission reduction strategies.

Reducing unproductive periods (e.g. rearing, dry cows), improving reproductive performance, enhancing herd health, and minimising stress are herd tools that directly contribute to lowering CH_4 emissions by improving feed-to-product conversion efficiency (Pulina et al. 2017).

For instance, in a study conducted on Scottish dairy farms, Ferguson et al. (2024) reported that improving reproductive efficiency and reducing disease incidence could decrease total GHG emissions by 5–12%, and this magnitude was dependent on the baseline management conditions. Beauchemin et al. (2020) reached similar conclusions after reviewing 50 years of studies on methanogenesis in ruminants. These authors, however, caution that it is also unclear whether a decrease in CH_4 production leads to a consistent and sustained improvement in animal performance over time, information that will be necessary for producers to adopt. This information will also require further research on animal health, reproduction, product quality, cost-benefit ratio, safety, and consumer acceptance. At the same time, precision feeding, the practice of tailoring diets to individual animals, can minimise nutrient waste and associated emissions, although its implementation remains challenging in extensive production systems (Chase and Fortina 2023).

Manure and slurry management

Greenhouse gas emissions from ruminant manure and slurry depend on their composition, storage conditions, treatments, and soil distribution methods. Moreover, the management of manure and slurry can be independent of the dairy production efficiency and can be applied despite the farming performance.

Storage conditions, such as temperature and duration, are critical, as demonstrated by Cardenas et al. (2021). These authors reported that temperature and storage duration are critically interlinked in controlling methane emissions. While the long storage in warm summers led to high emissions, the same long duration in cold winters resulted in negligible release. The key mechanism is a temperature threshold of ~14 °C. Storage below this point permanently suppresses the manure methane potential, making the long-term cold storage an effective mitigation strategy where the factor of time works to prevent, rather than to cause, emissions. Therefore, they suggest that the yearly temperature sum should be monitored because the winter temperature influences the onset of methane emissions from slurry storage during the warm seasons. This agrees with Balde et al. (2016), suggesting anticipating the slurry pit management in late summer or early autumn to mitigate CH_4 emission. Another strategy to decrease CH_4 emissions from slurry includes reducing the manure liquid-phase or slurry volume in sump pits during high-temperature seasons (Balde et al. 2016). Higher CH_4 emissions were observed in covered slurry storage pits, probably due to an increased slurry temperature as compared to uncovered basins (Vechi et al. 2023).

Different treatments, physical, chemical and microbiological ones, can be applied to change the manure and slurry composition and consequently mitigate CH_4 emissions. Treatments aiming to decrease organic matter or methanogenesis in slurry and manure, such as anaerobic digestion, acidification, or composting, contribute to reducing the storage and field release of CH_4. Slurry chemical amendments can be used to decrease methanogen activity in slurry and significantly reduce CH_4 emissions during slurry storage. For instance, Sommer et al. (2017) proposed to reduce methane emissions by 68% using the sulphuric acid treatment and decreasing slurry pH to 5.5. Finally, the distribution methods of manure and slurry can lead to a variation in GHG emissions from the soil. However, according to Sherman et al. (2021), unlike other GHGs, CH_4 emissions are not influenced by manure and slurry distribution techniques but vary with soil moisture and temperature. Precision agriculture methods can be used to optimise the distribution of manure and slurry in the fields according to soil organic matter and fertility.

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Manure management practices also play a crucial role: strategies such as frequent manure removal from pens, solid-liquid separation, slurry acidification, and anaerobic digestion can significantly mitigate CH_4 emissions. For example, acidifying cattle slurry can reduce CH_4 emissions by up to 60% (Petersen et al. 2013). The authors suggest this practice is best suited for intensive production systems, where they identify the greatest potential for reducing methane emissions. In addition to acidification, anaerobic digestion, depending on the conditions of humidity, temperature, and organic matter, allows biogas recovery and cuts emissions from storage by 40–80% depending on the system efficiency (Montes et al. 2013). These practices, while variable in applicability across systems, highlight that improvements in the herd and manure management represent effective, often complementary pathways to nutritional mitigation strategies.

It is known that feeding practices influence the potential CH_4 emissions of manure. High-forage diets increase the manure organic matter content, leading to a potentially higher CH_4 emission compared to high-concentrate systems. In fact, the concentration of non-digestible neutral detergent fibre (NDF) by *in situ* incubation has been proposed as one method to estimate CH_4 emissions from dairy cow manure (Huhtanen et al. 2021). Furthermore, evidence from tropical forage grasses links the low nitrogen content in forage to reduced CH_4 emissions from manure, an effect attributed to the suppression of methanogens under low N availability (Leitner et al. 2021).

Several research studies previously reviewed by Owen and Silver (2015) demonstrate that methane emissions from slurry and manure are underestimated by the most widely used estimation systems, such as the IPCC used to monitor national methane emissions. Therefore, on-site monitoring of methane emissions is fundamental to assessing the efficacy of nutritional, animal management, and manure management to mitigate emissions of methane. Monitoring sensors applied to flux chambers and wind tunnels can be used to measure CH_4 emissions from barns, manure collection platforms, slurry storage basins, or in the field (Ding et al. 2016; Figure 4). Moreover, considering that methane emissions are highly influenced by slurry physicochemical conditions, monitoring slurry temperature and pH in slurry basins could be a cost-effective measure to program slurry treatments throughout the warm season, when the environmental conditions are favourable for methanogen activity.

METHANE MONITORING TECHNOLOGIES: FROM ANIMAL TO FARM LEVELS

Various methods exist to monitor and quantify CH_4 emissions in dairy cows, each with distinct applications, advantages, and limitations. However, selecting the appropriate methodology requires more than only choosing a measurement technique, but also it demands alignment with the study objectives. The optimal approach will differ depending on whether the data will be used for farm management decisions, feed evaluation, additive efficacy testing, or genetic selection. The intended application dictates the most suitable methodology. The first consideration should be whether direct animal measurements are required. There exist multiple *in vitro* methods that eliminate animal use, avoiding welfare concerns while reducing costs compared to *in vivo* approaches.

These techniques are particularly useful for preliminary assessments, such as initial feedstuff evaluations, additive screenings, or dose-response trials. *In vitro* approaches frequently allow deeper mechanistic studies, as researchers can fully control experimental conditions, including fermentation, substrate use, and digestive transit. However,

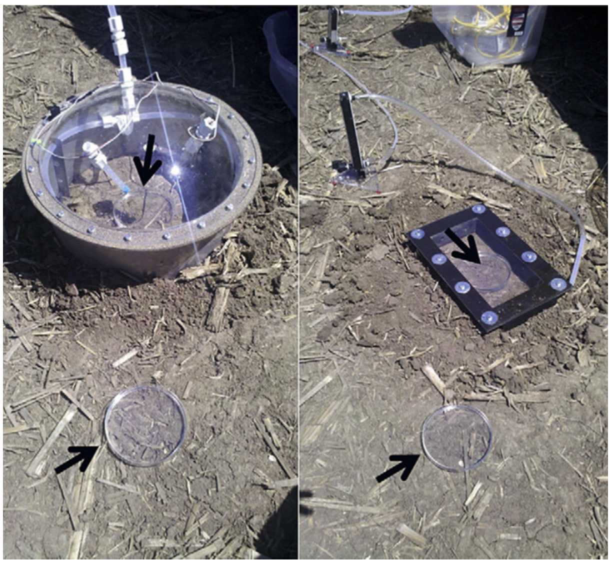

Figure 4. Experimental flux chamber and wind tunnel (extracted from Parker et al. 2013)

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in vivo validation remains essential for conclusive results in later stages of research or product development. However, *in vivo* validation remains essential for conclusive results, despite the well-documented challenges of scaling reference methods like respiration chambers and the SF_6 tracer technique for practical, continuous on-farm use (Tedeschi et al. 2022).

For *in vivo* studies, methodologies can be broadly categorised as direct or indirect quantification approaches (Huhtanen et al. 2015). Direct quantification approaches measure the physical gas emissions from the animal, typically through breath analysis or chamber confinement. In contrast, indirect approaches estimate emissions through models based on proxies like milk mid-infrared (MIR) spectra or animal performance data. Three direct methods have been predominantly recognised as the most appropriate for regulatory and scientific purposes: the respiration chambers, the sulphur hexafluoride tracer technique, and the GreenFeed system (Thompson and Rowntree 2020; Hristov et al. 2025).

Respiration chambers, historically used in ruminant experiments for energy metabolism and nutrient utilisation studies, are regarded as the gold standard for quantifying emissions (Huhtanen et al. 2015; Ghassemi Nejad et al. 2024). The method involves housing animals in sealed chambers (Figure 5) where gas concentrations (e.g. CH_4, CO_2) are precisely monitored by comparing inlet and outlet air compositions. Accurate measurements require the proper instrument calibration and account for differences between incoming and outgoing gas concentrations, because air extraction rates and chamber piping systems can influence the precision of the results (Arceo-Castillo et al. 2019). The main limitation is related to the artificial environment and restricted movement imposed on animals, which may not accurately represent natural production settings. This raises concerns about biological validity, especially for extrapolations in grazing conditions. Furthermore, the necessity for animal acclimation and training introduces additional variables that could compromise data extrapolation to real-world scenarios. Consequently,

Figure 5. Chambers of the ILVO Ruminant Respiration Facility

(A) Four of the six chambers; (B) Inside view of a chamber made of polypropylene mounted on a stainless-steel frame; (C) Cow tied in the chamber (extracted from: De Campeneere and Peiren 2014)

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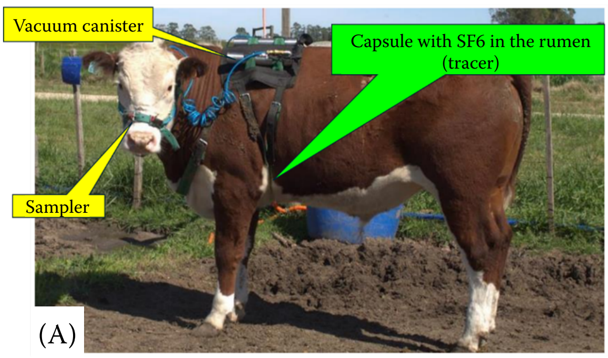
while respiration chambers provide highly precise data under controlled conditions, the artificial environment introduces a degree of systematic uncertainty when these measurements are extrapolated to predict emissions in commercial, free-moving herds. This limitation necessitates a cautious interpretation of absolute emission values for on-farm inventory purposes.

The sulphur hexafluoride (SF_6) tracer technique (Johnson et al. 1994) quantifies enteric CH_4 emissions by placing a slow-release capsule of SF_6 in the rumen, which disperses at a known rate. A sampling device worn by the animal continuously draws air from the muzzle into a canister over 3–6 days, capturing both CH_4 and SF_6 (Figure 6). By analysing the ratio of these gases in the collected sample and referencing the predetermined SF_6 release rate, total CH_4 production can be accurately estimated. This portable, low-cost system is suitable for both grazing and confined animals, offering practical advantages in diverse settings. It has been adopted in several regions for its non-invasive nature and reliability in field studies (Della Rosa et al. 2021). However, this method relies on labour-intensive custom-built sampling systems to assemble from heterogeneous components. The equipment requires continuous monitoring to prevent animal dislodgment, further increasing the operational demands of data collection and analysis. Additionally, it is less reliable for assessing daily emission patterns and involves the use of trained animals. Therefore, while the SF_6 technique provides valuable field-based data, the cumulative effect of these operational demands can introduce a non-trivial degree of measurement uncertainty. This underscores a limitation for its application in generating the highly consistent, granular data required to formulate specific, on-farm mitigation strategies.

The GreenFeed system completes the trio of established measurement approaches. This automated technology, first developed by Zimmerman (1993) and later upgraded in 2012 (Zimmerman and Zimmerman 2012), quantifies enteric CH_4 emissions during ruminant feeding through controlled airflow sampling. The system captures real-time data, typically requiring ~50 samples over two weeks for reliable estimates. Unlike respiration chambers, it allows animals to move freely, but measurements are restricted to trained animals visiting the unit (Hammond et al. 2016). A key limitation is its reliance on concentrate-based rewards to attract animals, which means emissions are sampled only during supplemental feeding and not during forage-only diets. The system's hardware and data processing are vendor-specific (C-Lock Inc., Rapid City, South Dakota, USA), which could



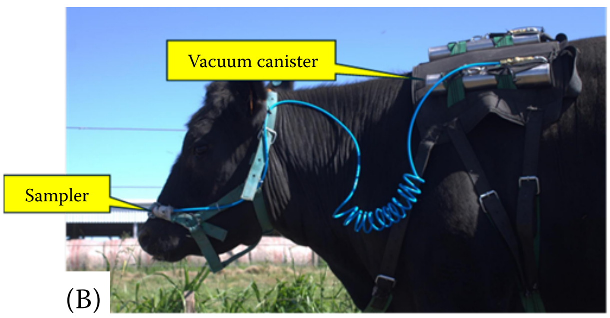


Figure 6. Using the SF_6 tracer method in the IPAV (Veterinary Faculty, UdelaR, Uruguay, images from the authors)

(A) How the system works: a capsule placed in the rumen releases SF_6 at a known rate (in green), and a sampling device in the muzzle of the animal continuously draws exhaled air from the muzzle of the animal into a vacuum canister for 3–6 days (in yellow); (B) Detail of the vacuum canister and the sampler; (C) Milking cow on pasture during a measurement period

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limit customisation and raw data access if necessary. While studies have demonstrated that the GreenFeed system provides accurate estimates of emission rates (McGinn et al. 2021), this accuracy is confined to the specific conditions of measurement. The combination of voluntary animal interaction, potential site-specific interference, and the sampling of emissions primarily during supplemental feeding bouts introduces a significant uncertainty regarding the representativeness of these measurements for the total daily methane production of the herd under natural conditions.

A comprehensive review by Della Rosa et al. (2021) analysing approximately 400 publications from 1995–2018 found that respiration chambers were the predominant technique (55% of studies), followed by the SF_6 tracer method (38%), with GreenFeed systems representing just 7% of studies. However, these proportions will likely shift in future analyses given the increasing adoption of GreenFeed systems by the global research community, with installations continuing to grow due to their advantages for long-term CH_4 monitoring in production environments. This historical reliance on methods with significant trade-offs between precision (chambers) and real-world applicability (SF_6) underscores a key uncertainty in the existing literature: the challenge of generating datasets that are both highly precise and directly representative of commercial farm conditions.

Portable analysers like "sniffers" have been developed to measure emissions in real-time at the feed bunk (Garnsworthy et al. 2012). While practical for on-farm use, these systems are prone to significant inaccuracies. Unpredictable cow head movements, variations in the feed trough design, and inconsistent sampling point placement can all introduce substantial measurement uncertainty, raising questions about their reliability for precise quantification.

The field is rapidly evolving, with new devices in permanent development. For instance, the ZELP device, a field-deployable system using near-infrared sensors on a face mask to analyse exhaled breath, demonstrated a strong positive correlation (r = 0.912, P < 0.05) with gold-standard respiration chamber measurements (Coetzee and Bica 2025). While promising, its practical implementation depends on the consistent wearing of the mask by the animal, a variable that must be accounted for. Similarly, hand-held laser detectors are another portable method, noted for being relatively inexpensive and providing immediate results (Roessler et al. 2018; Kang et al. 2022). However, their measurements are highly sensitive to the operator's distance and angle to the animal, introducing another layer of operational uncertainty.

In summary, while these emerging portable technologies offer compelling advantages for farm-level deployment, their current limitations – chiefly their susceptibility to environmental and behavioural variables – mean that rigorous on-farm validation and a clear understanding of their associated measurement errors are prerequisites for their reliable use in research and mitigation strategy assessment.

The use of artificial intelligence (AI) represents a promising indirect method for determining CH_4 emissions. Recent advances have demonstrated its potential, with estimations being improved by techniques such as support vector regression, random forests, and artificial neural networks that can explore complex, non-linear relationships in data (Ghassemi Nejad et al. 2024). However, the robustness of these models is heavily contingent on the quality, volume, and representativeness of the input data used for training. A key limitation and a source of uncertainty are the "black box" nature of some complex models, which can make it difficult to interpret the underlying physiological drivers of the predicted emissions. Furthermore, models trained on data from one production system or breed may not generalise well to others, creating a significant challenge for the broad farm-level implementation without extensive, and costly, revalidation.

Another indirect method for monitoring CH_4 emissions in dairy cattle integrates mid-infrared spectroscopy and milk fatty acid analysis (Engelke et al. 2018) with rumen volatile fatty acid profiles and microbiome characterisation (Bilton et al. 2025). This combined approach facilitates large-scale CH_4 quantification and could optimise breeding strategies for CH_4 reduction through genetic selection. The established relationships between milk fatty acid profiles and CH_4 emission levels (van Lingen et al. 2014) support the validity of these proxy measurements. However, a significant source of uncertainty stems from the confounding influence of other factors on these proxies. Key variables such as diet composition, energy balance, and health status can directly alter milk fatty acid profiles and rumen microbial communities inde-

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pendently of changes in methanogenesis. This can lead to situations where a shift in a proxy variable is misinterpreted as a change in CH_4 production, thereby compromising the accuracy of animal phenotyping for genetic selection programs.

In conclusion, the selection of a CH_4 monitoring method is not a search for a universal optimum, but a strategic decision that must align the inherent strengths and limitations of the method with the specific objectives and constraints of the intended application, from fundamental research to on-farm management.

PRECISION LIVESTOCK FARMING AS A STRATEGIC TOOL FOR METHANE MITIGATION IN DAIRY SYSTEMS

The application of process engineering principles to livestock production management represents a transformative modern approach, systematically capturing the key operational parameters and efficiency metrics that define PLF (Tuyttens et al. 2022). These technologies enable farmers to enhance operational efficiency while simultaneously addressing environmental concerns, safeguarding livelihoods, and improving animal health and welfare. Amid growing economic and environmental pressures in livestock production, PLF systems provide farmers with advanced tools to monitor animals more effectively, optimise welfare, and extend productive lifespans through smart technological solutions (Norton et al. 2019).

The most common PLF technologies employed on farms include the use of sensors as rumen monitoring boluses (Tuyttens et al. 2022), oestrus detectors, in-line milk analysers, and automated lameness sensors (Ferguson et al. 2024), alongside environmental monitors (e.g. thermometers, acoustic sensors, cameras) tracking housing conditions. These on-farm tools enable real-time tracking of animal physiology, health, and environmental factors, allowing the recording of large amounts of data and information about animals and their management to optimise management decisions (Tuyttens et al. 2022). The data can be used to adjust farm conditions and management in a short period, for example by adjusting feed rations and preventing metabolic diseases (rumen boluses), changing ventilation systems and adjusting ventilation slats (thermometers, airflow sensors), milking (robotic systems) and reproductive management (animal movement and temperature sensors) (Norton et al. 2019).

While PLF systems provide measurable improvements to livestock management, their implementation requires the careful risk assessment. Concerns include direct animal welfare impacts, such as health complications from sensor malfunctions or prolonged device exposure, and operational challenges like erroneous decisions caused by data misinterpretation. A significant secondary effect is the potential decline in husbandry skills and reduced human oversight as over-dependence on automated systems diminishes hands-on animal care practices. Based on this, the effective implementation of PLF systems requires continuous attention by the livestock breeder and careful selection of suitable PLF technologies (Tuyttens et al. 2022).

The PLF technologies were primarily developed for reproductive and health monitoring, but they also offer a strategic potential for CH_4 mitigation in dairy systems due to their core features: real-time monitoring, automation, and data analytics. A range of PLF tools is currently utilised, including sensors that monitor behavioural and physiological parameters (activity, rumination, temperature, body condition), automated feeders for precision nutrition, and AI-based models capable of interpreting complex data streams for timely decision-making (Jacobs and Siegford 2012; Spoliansky et al. 2016; Strapak et al. 2021). Among these, rumen boluses have proven to be particularly valuable for the continuous monitoring of ruminal pH, temperature, and activity levels, providing critical insights into the animal's metabolic status (Studer et al. 2023; Vladimirov et al. 2023; Vakulya et al. 2024; Weir et al. 2024). These devices enable early detection of subacute ruminal acidosis and related disorders, which, if left unmanaged, can result in significant productivity losses and increased environmental impact (Voulgarakis et al. 2024; Pfrombeck et al. 2025). Furthermore, insights from bolus data support dietary adjustments that improve rumen stability and reduce CH_4 emissions associated with inefficient fermentation. For example, deviations from the optimal pH range have been associated with milk production losses of 6.8% (low pH) and 14.08% (high pH) (Hanusovsky et al. 2018) and therefore, the use of rumen sensors can help to lower the CH_4 emis-

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sion intensity (i.e. CH_4 per kg of milk, fat or protein produced). Boluses have also been used to evaluate drinking behaviour, revealing that high ambient temperatures increase the water intake frequency, particularly after feeding and milking (Hanusovsky et al. 2017), which can adjust strategies for managing the heat stress that reduces feed efficiency. Although slight sensor drift and inter-system variability are limitations (Studer et al. 2023; Weir et al. 2024), these technologies remain reliable for long-term data collection.

In parallel, PLF tools such as motion and rumination sensors enhance reproductive efficiency by accurately detecting oestrus and calving, thereby reducing open days and improving productivity (Stevenson et al. 2014; Mayo et al. 2019; Strapak et al. 2021). Health monitoring systems, including automated body condition scoring (Fischer et al. 2015; Spoliansky et al. 2016) and infrared thermography for early mastitis and lameness detection (Zaninelli et al. 2018; Korelidou et al. 2024), further support the herd management efficiency. Collectively, although CH_4 mitigation is not the primary function of these systems, their application in optimising health, nutrition, and productivity aligns with sustainability goals by reducing CH_4 emissions per unit of milk produced. Ferguson et al. (2024) modelled the potential emission reductions using the PLF technologies available to farms and concluded that sensors used to improve fertility had the largest reduction potential to reduce the emissions expressed as kg CO_2 equivalent. In line with this, McNicol et al. (2024) demonstrated that the adoption of PLF technologies, specifically automatic weighing platforms, oestrus detection sensors, and health monitoring sensors, led to significant reductions in both total emissions (kg CO_2e) and product emissions (kg CO_2e/kg deadweight) in Scottish beef systems. The greatest reduction in total emissions was observed with weighing platforms in grazing systems (6.8%) and health sensors in housed systems (6.1%). In terms of product emissions, health sensors achieved the largest decrease (12% in housed systems and 10.5% in grazing systems). These findings suggest that PLF technologies can serve as an effective greenhouse gas mitigation strategy in dairy production systems.

To critically assess the role of PLF in methane mitigation, it is essential to distinguish between its current indirect contributions and its future potential for direct management. Currently, PLF technologies contribute to methane emission mitigation primarily through indirect pathways. For example, by improving animal health and fertility, shortening time to slaughter, and increasing feed efficiency, all of which reduce CH_4 emissions per unit of product (Papakonstantinou et al. 2024).

In contrast, the development of PLF for direct methane measurement and mitigation is an ongoing research frontier. Direct measurement of CH_4 at the individual animal level on farms is possible using several new PLF tools, but these approaches still require further validation, cost reduction, and integration before they can deliver the routine emission mitigation on farms. Established direct methods (breathing chambers, SF_6 tracers) remain the reference standards but they are not practical for continuous monitoring on farms (Tedeschi et al. 2022). Practical systems on farms that provide near real-time measurements include automated sampling devices at head/feeding stations (e.g. GreenFeed) that capture exhaled air during voluntary visits and estimate individual enteric CH_4 fluxes, handheld/vehicle-mounted laser methane detectors (LMD/TDLAS) that detect breath vapours or emissions from barns, and fixed or mobile cavity ring-mode/dual-comb/open-path spectrometers that, when combined with wind/dispersion modelling, can quantify CH_4 fluxes in a barn or across the entire farm (McGinn et al. 2021). Each approach has its trade-offs in terms of accuracy, temporal resolution, animal coverage, and cost: GreenFeed and similar head-gate systems provide validated individual estimates, but sufficient animal visits and calibration are required to extrapolate to 24-hour emissions; LMD and mobile CRDS/TDLAS devices show promise for rapid screening measurements and farm-level flux estimation, but they require standardised protocols and quantification of uncertainty; open-path dual-comb systems and fixed CRDS systems show a potential for continuous whole-farm monitoring, but remain relatively expensive and require advanced data processing (Hristov et al. 2015). Crucially, however, these are not yet standard PLF tools for routine mitigation. Their widespread adoption faces significant hurdles, including the need for rigorous validation against gold-standard methods, the development of algorithms to convert spot measurements into reliable daily fluxes, substantial cost reduction, and farm trials dem-

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onstrating that real-time data can be effectively translated into management actions that reduce methane (USDA 2024).

Therefore, while PLF could evolve into a direct methane monitoring tool, it currently functions most effectively as an indirect mitigation strategy. The critical challenge is to balance accuracy, animal welfare, and affordability to ensure the practical adoption. According to Kaur et al. (2023), future efforts should prioritise developing affordable, interoperable sensors and robust data integration. Ultimately, the transformation of animal agriculture toward greater sustainability will depend on merging these technological advancements with robust biological models to create closed-loop systems that not only monitor but also actively manage methane emissions.

CONCLUDING REMARKS

Over the past decades, numerous strategies to mitigate CH_4 emissions in dairy farming have been investigated. Both direct and indirect approaches, ranging from nutritional interventions and genetic selection to improved herd management, can enhance farm sustainability by optimising animal productivity and health, reducing CH_4 output. These approaches can enhance sustainability, but their effectiveness depends on precise implementation, a challenge where PLF could play a pivotal role. The PLF technologies offer tools to optimise these strategies on-farm, delivering direct benefits in productivity, while also enhancing farmers' decision-making and product traceability. Indirectly, PLF adoption can reduce the carbon footprint of livestock production and improve socio-economic outcomes. However, critical gaps remain, particularly in capitalising on PLF for real-time CH_4 monitoring, a key hurdle for targeted mitigation. For instance, automated CH_4 sensors paired with AI-driven analytics could provide actionable insights while reducing labour demands, but such solutions require further research and on-farm validation. To maximise the impact, future efforts must prioritise developing accessible, reliable PLF systems tailored to CH_4 measurement and farm-level decision support. Bridging this gap will be essential to translate mitigation strategies into practical, scalable solutions that align environmental goals with farm profitability and animal welfare.

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Conflict of interest

The authors declare no conflict of interest.

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