

The Path to Net-Zero in Dairy Production: Are Pronounced Decreases in Enteric Methane Achievable?

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Keywords

dairy cows, greenhouse gases, methane, mitigation, net-zero emissions, ruminants

Abstract

Achieving net-zero greenhouse gas (GHG) emissions in dairy production will require >50% reduction in enteric methane (CH₄) emissions together with elimination of emissions from feed production, additional carbon sequestration, reduction in manure emissions, anaerobic digestion of manure, and decreased reliance on fossil fuel energy. Over past decades, improved production efficiency has reduced GHG intensity of milk production (i.e., emissions per unit of milk) in the United States, but this trend can continue only if cows are bred for increased efficiency. Genetic selection of low-CH₄-producing animals, diet reformulation, use of feed additives, and vaccination show tremendous potential for enteric CH₄ mitigation; however, few mitigation strategies are currently available, and added cost without increased revenue is a major barrier to implementation. Complete elimination of CH₄ emissions from dairying is likely not possible without negatively affecting milk production; thus, offsets and removals of other GHGs will be needed to achieve net-zero milk production.

1. INTRODUCTION

Globally, the agriculture sector contributed 7.5 Gt (14%) of carbon dioxide equivalent (CO₂e) to the 53 Gt CO₂e total greenhouse gas (GHG) emissions in 2021, with an additional 3.1 Gt CO₂e from land-use changes associated with agriculture (1).¹ The US agriculture sector produced 0.60 Gt CO₂e (9% of national GHG emissions) in 2021, representing a 9% increase compared to 1990 levels (2). The primary GHGs emitted, apart from CO₂, are CH₄ and N₂O, with agricultural sources accounting for 58% and 52% of global emissions, respectively (3). Enteric fermentation and manure management contributed 31% of the total anthropogenic CH₄ emissions globally (3). In the United States, enteric CH₄ emissions accounted for 26% of total anthropogenic CH₄ emissions, whereas agricultural soils accounted for 73% of total N₂O emissions (2). Unfortunately, atmospheric CH₄ levels are increasing at an accelerating rate, primarily because of rising emissions from agriculture, waste, and fossil fuels, highlighting the need for stronger mitigation measures (4). For this reason, 155 countries have committed to the Global Methane Pledge (<https://www.globalmethanepledge.org>), aiming collectively to reduce CH₄ emissions 30% from 2020 levels by 2030.

To achieve global net-zero GHG emissions, all CO₂ emissions must be eliminated or offset by durably stored CO₂ removals. Non-CO₂ GHG emissions also must be eliminated or offset. Emissions from the electricity and fossil fuel sectors are expected to reach net-zero before 2050, and some activities, such as land-use change, are projected to see reductions of more than 125% by 2050. Various agricultural and food-related industries have also pledged to achieve net-zero GHG emissions within the next 20 to 30 years. The US dairy industry has set the goal of achieving GHG neutrality by 2050 (5, 6), and the US beef industry has a goal of climate neutrality by 2040 (7). In scenarios that achieve Paris Agreement temperature goals, the Intergovernmental Panel on Climate Change (IPCC) (8) anticipates that non-CO₂ emissions from agriculture will not reach net zero by 2050 but likely will be cut by ~50% with the remaining non-CO₂ GHG offset. Our objective here is to determine pathways to achieving net-zero emissions in primary dairy production in the United States, with a particular focus on enteric CH₄ production, which contributes the most to agricultural non-CO₂ emissions.

2. NET-ZERO

The concept of net-zero originated from the realization that global warming from CO₂ emissions is cumulative and that reducing CO₂ emissions by 80% would still cause temperatures to keep rising, just at a slower rate (9). The concept of net-zero GHG emissions includes CO₂, CH₄, and N₂O but excludes nongaseous emissions such as aerosols (10). Inclusion of CH₄ and N₂O emissions, which have shorter lifetimes than CO₂, complicates the concept of net-zero. To define net-zero across multiple gases, a metric of equivalence must be used to convert the non-CO₂ emissions to CO₂e, if CO₂ removal from the atmosphere (and its permanent storage) is used to offset non-CO₂ emissions. Typically, the global warming potential of the gas over a 100-year period after the emission (GWP100) is used. However, the resulting temperature outcome of scenarios with net-zero CO₂e emissions defined with GWP100 is not analogous to that from net-zero CO₂ emissions. This is because GWP100 equivalence provides an accurate analog of warming impacts only for GHGs with lifetimes over 100 years (e.g., N₂O), which excludes CH₄, with a lifetime of approximately 12 years (11). Depending on how much of each gas is eliminated and how much is offset, net-zero scenarios defined by GWP100 can theoretically result in rising or declining temperatures (e.g., 12). Typical Paris Agreement-compliant scenarios from the literature show a

¹ Values of CO₂e emissions from the literature may use differing values for GWP100 in their calculation.

declining temperature once net-zero GHG emissions are reached (e.g., 13), which is not always essential to achieving the Paris temperature goal (14). Lynch et al. (15, p. 1) demonstrate what this means for agriculture and its unique mix of GHG emissions and conclude that “conventional reporting of aggregated CO₂e emission rates is highly ambiguous and does not straightforwardly reflect historical or anticipated contributions to global temperature change.” This ambiguity can be avoided if long- and short-lived GHGs are examined separately rather than together (16) and only long-lived gases form the net-zero target. This is because long-lived GHGs must reach net-zero emissions to limit global warming to below a threshold temperature. Short-lived GHGs must decline but need not reach net-zero.

The IPCC (8) presents illustrative scenarios that achieve the Paris Agreement’s goal of limiting warming to 1.5°C. In the most ambitious scenario, CO₂ emissions reach net-zero around 2050 and become net negative after that, whereas CH₄ reduces by approximately 50% by 2050 and thereafter declines at a gradual rate. N₂O reduces by only approximately 30% (8; scenario WG1 SPM). In this ambitious scenario, the amount of warming caused by CO₂ by 2100 compared to 1900 is approximately 1°C, and the combined warming from all non-CO₂ GHG is less than half a degree. A similar scenario shown by Cain et al. (17) demonstrates that between 2020 and 2100, the contribution of CO₂ to global warming increases until a peak in 2050 (when net-zero is achieved) and then decreases back to 2020 warming levels. CH₄’s contribution to global warming in 2100 declines by approximately 0.14°C from its peak in 2020, because its effect on radiative forcing and warming scales with its annual emission rate. Hence, reducing global CH₄ emissions means lower levels of warming from atmospheric CH₄. Because N₂O has a lifetime of well over a century, on these timescales, N₂O acts cumulatively and causes an additional 0.06°C of warming by 2100 compared to 2020.

Even in the most ambitious scenarios, globally there will still be CH₄ and N₂O emissions, whereas there will be net-zero or net-negative CO₂ emissions. Levels of global warming could be held constant at 1.5°C if future CO₂ emissions are limited to the 1.5°C remaining carbon budget [estimated to be in the region of 400–650 Gt CO₂ from the beginning of 2020 by IPCC (8; scenario AR6 WG1 SPM)], while non-CO₂ emissions decline as per the illustrative scenario above. Less ambitious reduction of non-CO₂ emissions would mean a smaller remaining CO₂ budget to end up with the same temperature outcome.

Based on net-zero agreements, each sector must eliminate or store its CO₂ emissions. However, how net-zero for all GHGs should be applied to any particular sector is not clear. In dairy production, where CH₄ and N₂O emissions are dominant, what should be the target for emission reductions of these gases? One option is to align with the IPCC-assessed scenarios. For example, New Zealand has a target of 24–47% reduction for biogenic CH₄ emissions (and net zero for all other gases) from 2020 levels by 2050 (18).

A key question is what the dairy production sector should look like in a net-zero world. Must it fulfill some definition of net-zero? Could forestation contribute CO₂ removals to the sector? To answer these questions, we need clear definitions of terms. Declarations and targets must provide clear definitions of terms such as climate neutrality, GHG neutrality, and net-zero to ensure clarity and transparency as we strive to reduce environmental harm.

In this review, we define net-zero GHG emissions using the GWP100 metric across emissions of CO₂, CH₄, and N₂O, the key GHGs from agricultural systems. Values of CO₂e are 27 for CH₄ and 273 for N₂O, as per the IPCC’s Sixth Assessment Report (19). In the literature, where net-zero for dairying is not defined explicitly, we assume this definition. Typical net-zero scenarios for dairying use CO₂ sequestration or removals to offset any CH₄ and N₂O emissions that cannot be eliminated. Such scenarios would result in a peak in contribution to global warming when net-zero

is first reached, followed by a decline for as long as CH₄ emissions are balanced by CO₂ removals based on GWP100.

3. EMISSIONS FROM DAIRYING

Farm-based emissions constitute 68–75% of the supply chain emissions of producing milk in the United States, estimated using a life-cycle approach (20, 21). In a study of 20 representative farms in each of 6 regions of the United States, GHG intensity (i.e., footprint) averaged 1.04 (from 0.69 to 1.45 kg) CO₂e/kg of milk corrected to 4% fat and 3.5% protein (22). Variability among farms was due mainly to milk production per cow, diet composition, and manure-handling practices. Farms with the lowest GHG per kilogram of milk were those with greater milk production per cow, smaller grazing operations with little or no long-term storage of manure, and those that used anaerobic digesters. In contrast, long-term liquid manure storage (i.e., large lagoons or retention ponds), especially in the warmer regions of the country, increased GHG per kilogram of milk.

Enteric CH₄ accounts for 35–56% of the GHGs associated with milk production and is affected by farm size, feed type and quality, and management practices (20, 21, 22, 23). Manure emissions of CH₄ and N₂O typically vary from 20% to 33% of GHG intensity of milk production and depend upon the type of housing, manure storage, and handling (20, 22, 23). In addition, N₂O, CH₄, and CO₂ are emitted from feed production, which includes emissions during manufacturing of purchased feeds, inputs used for cropping and pastures (i.e., fertilizers, pesticides, herbicides, lime, plastics, and so forth), and soil-based emissions from the application of organic and inorganic fertilizers. Feed production emissions average 26% for US dairy farms but range from 10% to 60% of the GHG emissions from milk production (20, 22, 23). Emissions from feed production are typically less for grazing systems due to fewer resource inputs and manufactured feeds, whereas enteric CH₄ emissions tend to be greater for these farms due to elevated fiber concentrations in the diets of the cows. The final component of the GHG intensity of milk is CO₂ from energy used on the farm. However, on-farm energy use typically comprises less than 15% of GHG intensity of milk (20, 22, 23).

4. ACHIEVING NET-ZERO DAIRYING

4.1. The GHG Reductions Required

The US dairy industry has set an ambitious goal of achieving net-zero GHG emissions by 2050, although specific reduction targets for the various gases have not yet been established (5, 6). The World Wildlife Fund (24) presented a path toward net-zero dairy emissions in the United States that assumes a 60–65% decrease in enteric CH₄ along with complete elimination of CO₂ and N₂O emissions from feed production, additional carbon sequestration in soils, a >90% reduction in CH₄ and N₂O emissions from manure, a 60% decrease in fossil fuel energy use, and anaerobic digestion of manure. The Canadian dairy industry's plan for achieving net-zero emissions by 2050 is based on a 50% decrease in emissions and 50% offset via removals, with enteric CH₄ emissions from livestock declining by approximately one-third (25).

Veltman et al. (26) conducted a life cycle–based analysis of three simulated dairy farms in the United States. Excluding the use of feed additives to reduce CH₄ emissions and carbon sequestration, they calculated that dairy farms could reduce emissions by 31–46%. Using additives that are commercially available or may soon be available could reduce emissions from milk production by a further 4–20% (27). The best-case scenario is that approximately two-thirds of emissions may be reduced through avoided emissions and one-third will need to be compensated for through carbon sequestration or other carbon removal technologies.

Offsetting CH₄ emissions with CO₂ removals to achieve net-zero GHG emissions will lead to a peak and decline in the sector's contribution to global warming, using any standard metric including GWP100 (1, 28). Temperature outcomes will depend on the mix of emissions and removals. This is because most metrics, including GWP100, are not based on the warming caused by an emission, and therefore exchanging them on this basis is not temperature neutral.

Net-zero GHG emission scenarios for dairy production require offsetting of continued CH₄ and N₂O emissions with CO₂ removals. This raises the question of whether maintenance of such removals over time is feasible. There is finite land available for tree planting, and soil carbon sequestration will saturate over time (29). An interesting case study (30) considers the tree planting required to offset CH₄ emissions from a herd of cattle. Offsetting the CH₄ emissions based on GWP100 leads to a set area of forest being planted every year. In the short term, the CO₂ absorbed from tree planting does not offset the warming from the CH₄ emissions. Only after 100 years is the warming neutralized, and after that there is net cooling, with the tree planting overcompensating for the CH₄ emissions. Offsetting based on a warming equivalence method called GWP* (31) leads to a large area of trees being planted at the start, as a one-off. Year on year, the CO₂ removals cancel out the warming from the cattle's CH₄ emissions fairly closely. However, the New Zealand Parliamentary Commissioner for the Environment (30) also shows that if CH₄ emissions from New Zealand's livestock were nearly halved, approximately 4 million hectares of land would need to be afforested to counter the warming, which is the same area of land currently used for sheep farming in New Zealand.

If the primary goal for net-zero strategies is to combat global warming, then levels of global warming from mitigation strategies must be calculated to evaluate whether strategies are likely to work. This would mean not relying solely on net-zero GHG emissions. Without explicit targets and reporting for CH₄ emissions, effects of mitigation strategies on global warming cannot be evaluated (10). Achieving net-zero GHG emissions from dairying will require an ambitious reduction in emissions from all sources, but particularly from enteric CH₄ emissions. A short summary of the GHG mitigation opportunities is given below.

4.2. Animal Husbandry

Improving milk production per cow has cut GHG emissions per kilogram of milk by more than 50% in the past 80 years. Improved productivity has occurred through improvements in genetics, nutrition, and management, including management of health, reproduction, feeding, and milking. By increasing milk per cow, less feed is needed per kilogram of milk, and thus, less CH₄ is produced per kilogram of milk. Naranjo et al. (32) showed that over the last 50 years the California dairy sector reduced GHG intensity of milk by 47% (from 2.11 to 1.12 kg CO₂e/kg milk).

4.3. Manure Management

Manure GHG emissions can be lowered substantially by implementing alternative management and storage strategies. One effective method is the use of anaerobic digesters, especially in confinement setups where liquid manures are common. These digesters work by breaking down the manure in an oxygen-free environment, which not only helps in managing waste but also reduces emissions of harmful gases by capturing them. Anaerobic digesters cut GHG emissions by 23–53%, depending upon the specific conditions and design of the digester, the level of technical support available, and the skill and experience of the operator handling the system (33). By optimizing these factors, the effectiveness of anaerobic digesters in mitigating GHG emissions can be maximized.

4.4. Soil Management

This strategy involves closely matching plant nitrogen needs with inputs to minimize the risk of losses to the environment, while improving soil health and carbon sequestration. Some examples include improved nutrient management and more efficient use of fertilizers, reduced tillage, use of cover crops, greater use of perennial forages, increased use of legumes in rotations, erosion control, organic soil amendments, and management of grazing intensity and timing (34). Carbon sequestration is an essential part of a dairy net-zero strategy; however, the maximum achievable rate of carbon sequestration in arable lands is highly contested (29).

4.5. Energy Efficiency

Replacement of fossil fuel-based energy with renewable sources is key to decreasing energy-based CO₂ emissions. Additionally, upgrading to more energy-efficient technologies in milk processing (milking and cooling) can reduce energy consumption and lead to reductions in GHGs. These technologies include improvements in milk refrigeration, lighting, heating, and other processing operations.

4.6. Anti-Methanogenic Strategies

The use of strategies specifically aimed at altering rumen fermentation in a manner that reduces CH₄ production in the cow rumen is a critical element of a net-zero strategy and is discussed in greater detail below.

5. ENTERIC METHANE MITIGATION

Recent reviews provide an in-depth analysis of innovative approaches for mitigating CH₄ emissions, with emphasis on opportunities and barriers to their implementation in a range of ruminant production systems (e.g., 1, 35, 36). The amount of CH₄ a ruminant animal produces is primarily a function of dry matter intake (DMI), with variability caused by the chemical composition of the diet, the inherent rumen microbial population of the animal, and the animal's physiology and genetics. Mitigation approaches can be broadly classified as (a) improved production efficiency, (b) genetic selection, (c) feed and diet management, and (d) rumen fermentation manipulation.

5.1. Improved Production Efficiency

Over the past 100 years, farms have selected and managed cows to produce more milk. Because cows produce more milk, they also eat more feed per day. However, the output of milk per unit of feed input, or feed conversion efficiency, has increased, because a smaller portion of the ingested food is used for maintenance of body functions and a greater portion is used for milk production. Likewise, as cows eat more, they also produce more CH₄ per day, but the portion associated with maintenance is diluted out so CH₄ emissions per unit of milk decrease.

Capper and colleagues (37) showed the importance of increased productivity for decreasing GHG emissions in a series of life cycle analyses. In 2007, compared to 1943, the US dairy sector produced 340% more milk per cow so that total milk production was 60% greater using 64% fewer cows; this resulted in a 63% smaller GHG intensity of milk. Capper et al. (38) demonstrated that if bovine somatotropin were used across the United States, the dairy herd could be reduced by 8% and CO₂e emissions would decrease by 6%. In contrast, if all cows were managed in organic operations, 25% more cows would be needed, emitting 13% more CO₂e. Finally, Capper (39), using FAO data (40), illustrated the relationship between productivity and GHG emissions across continents. Dairy cattle in North America produced 9,000 kg milk/year, with a GHG intensity of 1.3 kg CO₂e/kg milk, and as milk production dropped to a low of 250 kg/year in sub-Saharan

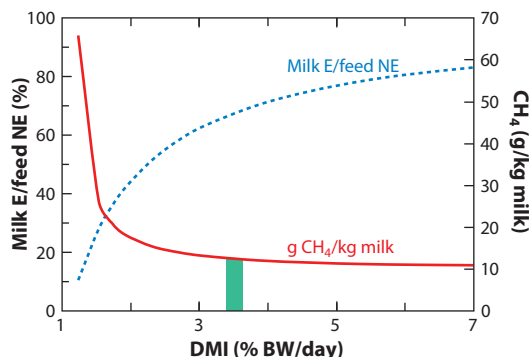


Figure 1

Projections for efficiency and CH₄ emissions as cows eat more and produce more FPC milk. The dashed blue line represents milk E output/feed NE consumed, the solid red line represents intensity (g CH₄/kg FPC milk), and the histogram indicates the current average for the US dairy industry. Abbreviations: BW, body weight; DMI, dry matter intake; E, energy; FPC, fat- and protein-corrected; NE, net energy.

Africa, the GHG intensity increased to 7.6 kg CO₂e/kg milk. However, other factors, such as economic and social sustainability, and even religion, must be considered before all global regions are encouraged to adopt North American practices.

Whereas increased production up to ~10,000 kg/cow/year decreases the GHG intensity of milk, increases in milk production beyond that will not necessarily continue to decrease GHG intensity. The dilution of maintenance phenomenon has its biggest effect at lower levels of production. As milk production per cow increases in the future, the benefits of feed efficiency will diminish (41). This trend also applies to the relationship between milk per cow and CH₄ per kilogram of milk.

If milk production per cow continues to increase in the future as it has in the past 20 years, production in the United States should average approximately 15,000 kg/cow/year by 2050. In fact, some have suggested milk yield will increase faster in the future, perhaps reaching 25,000 kg/cow/year in 2050 (42). US milk production currently (as of 2024) averages ~11,000 kg/cow/year; cows eat approximately 3.5% of body weight (BW); and using the National Academies of Science, Engineering, and Medicine (NASEM) (43) model, enteric CH₄ emissions are predicted at ~12 g/kg milk. Assuming cow size will stay the same but milk production (on a fat- and protein-corrected basis) increases up to 25,000 kg/cow, cows would eat 7% of BW on average, and CH₄ intensity would drop to 10.4 g/kg milk. As shown in **Figure 1**, most of the benefit of increased production has occurred already.

To further complicate projections of cow productivity on CH₄ emissions per unit of milk, we must consider that both cow body size and the maintenance requirement per kilogram of BW have increased in the past 50 years and likely will continue to increase unless genetic trends turn. In 1970, the maintenance requirement per unit of metabolic BW (BW expressed as kg^{0.75}) was calculated as 0.072. The NASEM (43) increased this value to 0.10. If the maintenance coefficient continues to increase, CH₄ emissions per unit of milk might be not be lower in the future than they are today. To meet net-zero goals, a focus on breeding specifically for more efficient cows that emit less CH₄ per unit of milk is needed.

5.2. Genetic Selection

Genetic progress depends on selection intensity and the generation interval. Genomics has enabled greater selection intensity and, with modern reproductive technologies, a shorter generation

interval, which has been reduced to only 2 years for Holstein bulls and 4 years for cows (44). Thus, genetic progress could occur by 2050, given that genetic variation exists for CH₄ emissions and it is a heritable trait. CH₄ was measured in 575 Danish cows (using sniffers) and calculated to be 9.2 g/kg milk with a genetic standard deviation of 0.8 g/kg milk and heritability of 0.1 to 0.5 depending on lactation stage (45). Van Breukelen et al. (46) measured CH₄ emissions for 822 cows using a Greenfeed system and for 1,800 cows using sniffers and found a high genetic correlation with both measurement systems and heritability of 0.3 for mean weekly emissions. Ramirez-Agudelo and Kebreab (unpublished data) assembled a data set of dairy cows and found an average of 20 g CH₄/kg DMI with standard deviation of 2.1 to 2.7 g CH₄/kg DMI. New Zealand researchers could achieve a 12% variance in CH₄ yield in ewes in a decade-long selective breeding study (47). If CH₄ was the sole focus of genetic selection, scientists obtained more measurements to improve trait reliability, and genetic variation does not diminish with time, then perhaps a 50% reduction in CH₄ intensity would be possible in 10 years. A more likely scenario is that CH₄ would be part of a multi-trait index, and a drop in CH₄ per unit of milk of 20–30% could be achieved by 2050. However, because CH₄ is produced during fiber fermentation, the relationship between selection for low CH₄ and fiber digestion must be thoroughly examined. The strongest argument for a thriving dairy sector is that cows convert human-inedible cellulosic material into high-quality human-edible foods. In a study of 130 lactating Holstein cows, the 5 lowest CH₄ emitters had impaired fiber digestion compared to the 5 highest CH₄ emitters (48). These differences can be attributed largely to variation within the rumen microbiome of individual animals, which influences the rate of feed degradation and fermentation pathways. Additionally, host animal characteristics, such as the retention time of feed particles in the rumen, play an important role. Various factors further affect rumen function efficiency, including saliva production, chewing and rumination activities, feeding patterns, total feed intake, and rumen volume, which collectively influence the outflow of rumen contents. Munger & Kreuzer (49) highlighted that CH₄ emission traits in animals might not be consistent over time, suggesting a complex interaction between an animal's genotype and its diet. This interaction indicates that effective selection for low CH₄ emissions in dairy cows requires careful consideration of their diets.

5.3. Feed and Diet Management

DMI is the main driver of CH₄ production in the rumen; the amount of CH₄ produced per kilogram of feed consumed (i.e., CH₄ yield) depends upon the chemical composition and digestibility of the feed. Diets high in fiber (i.e., cellulose, hemicellulose, lignin) promote CH₄ production, whereas diets high in starch and water-soluble carbohydrates (sugars, pectins, and soluble compounds), such as those fed in early lactation, result in less CH₄ yield. Therefore, incorporating grain into dairy diets to increase starch concentration leads to a rumen fermentation with a high molar proportion of propionate relative to acetate. Propionate formation results in a net uptake of H₂ and is associated with decreased CH₄ production. In contrast, forage-based diets are high in fiber and are characterized by a rumen fermentation with a high molar proportion of acetate relative to propionate, which is associated with increased CH₄ production. Additionally, concentrate feeding decreases rumen pH, which inhibits the growth of methanogens and protozoa. However, feeding higher concentrate diets is not usually promoted as a CH₄ mitigation strategy because grain cultivation increases emissions of CO₂ and N₂O from the manufacture and use of inorganic nitrogen-based fertilizers and because conversion of pasture land to cropland causes a loss in soil carbon.

Lipids are often supplemented to dairy cow diets to increase energy density or increase milk production. Fat supplementation (excluding rumen-inert fats) of up to 6% of dietary DMI also

linearly decreases CH₄, measured as g/day, g/kg DMI, and g/kg milk (50). The mechanism whereby lipids reduce methanogenesis is complex: Lipids are largely unfermentable (except for the glycerol moiety). Thus, replacing carbohydrates with lipids decreases fermentable organic matter intake, they exert toxicity against methanogens and protozoa, biohydrogenation of unsaturated fatty acids (FAs) serves as a minor sink of electrons, and rumen fermentation is shifted to promote the production of propionate (36). Fats with high concentrations of C12:0 and C18:3 or other polyunsaturated FAs are most effective (50), and oils are more effective than oilseeds. Based on meta-analyses, each percentage of added fat results in a 3–5% decrease in CH₄ production compared with a basal diet containing approximately 2% fat (50, 51, 52). Fat supplementation of >6% of dietary dry matter (DM) tends to decrease milk yield and negatively affect DMI and fiber digestibility (50), with these adverse effects being most pronounced for high-fiber diets. Thus, fat supplementation of dairy diets should be limited to a maximum of 4% added fat (6% total fat), with an expected CH₄ mitigation potential of 12–20%.

Altering species, chemical composition, and digestibility of forages may also alter CH₄ emissions. Harvesting forage at an earlier stage of maturity to decrease neutral detergent fiber concentration (% DM) and increase digestibility promotes DMI and milk production. Although the CH₄ produced per kilogram of DMI may increase, CH₄ per kilogram of milk typically decreases (36, 53). The potential CH₄ per kilogram of DM differs among forage species; however, these differences are typically small (<10%) and depend upon the relative differences in digestibility and chemical composition (36). For example, whole cereal, sorghum, and maize forages can elevate dietary starch compared to grasses and legume forages and decrease methanogenesis. Additionally, legumes contain various concentrations of secondary compounds (e.g., condensed tannins, saponins, polyphenols) that are associated with decreased CH₄ production.

Many prediction models consider a range of nutritional factors that influence CH₄ production in dairy cows. Appuhamy et al. (54) used an extensive data set for lactating dairy cows to evaluate 38 of these models. The highest-ranked model for North America estimated CH₄ as a function of DMI, digestible neutral detergent fiber (dNDF), and FA:

$$\text{Methane(Mcal/day)} = 0.294 \times \text{DMI} - 0.347 \times \text{FA} + 0.0409 \times \text{dNDF},$$

where DMI is in kg/day and FA and dNDF are in % of dietary DM.

Using this equation, one could expect that diet reformulation with emphasis on lipid supplementation has an expected CH₄ mitigation potential of 15–20% in dairy cows.

5.4. Rumen Manipulation

Manipulating the rumen fermentation process using exogenous compounds offers tremendous potential for CH₄ mitigation. During the rumen fermentation process, complex carbohydrates such as cellulose, hemicellulose, and starch are degraded by the rumen microbiota to hexoses and pentoses, which are further metabolized mainly to volatile fatty acids, CO₂, and CH₄. This complex process relies on the concerted action of the rumen microbiome to generate metabolites that are used by the animal and rumen methanogens that primarily convert excess CO₂ and H₂ into CH₄. Mitigation approaches that are based on naturally derived and synthetic compounds target the microbiome directly or the rumen fermentation process itself in a manner that decreases CH₄ production.

5.4.1. 3-Nitroxypropanol. The most extensively studied CH₄ inhibitor is the feed additive 3-nitrooxypropanol (3-NOP; commercial name Bovaer®; DSM Nutritional Products). 3-NOP decreases CH₄ production by targeting methyl-coenzyme M reductase, the enzyme that catalyzes the last step of methanogenesis in methanogenic archaea (55). Adding low concentrations of

3-NOP to diets decreases enteric CH₄ emissions by 20–40% in dairy and beef cattle fed mixed diets and by 40–80% in feedlot cattle fed high-grain diets (56). The effectiveness of 3-NOP is dose dependent and is inversely affected by increasing dietary concentration of fiber (57). 3-NOP must be added directly to a total mixed diet; thus, in its present form, it is not applicable to grazing cattle.

The use of 3-NOP has not resulted in consistent improvements in animal performance (56, 58, 59), which is a major barrier to its widespread use by farmers. However, van Gastelen et al. (60) reported a notable exception, where a year-long trial demonstrated a 6.5% increase in milk yield following 3-NOP supplementation. This improvement was associated more closely with the animals' diet rather than the duration of supplementation, suggesting diet plays a crucial role in the efficacy of 3-NOP. Regulatory officials in many countries have deemed the safety risks of using 3-NOP to be low (61). As of June 2024, 3-NOP has been approved for use in 59 countries, including the United States, Canada, and the European Union.

5.4.2. Halogenated compounds. Among the most promising strategies for reducing CH₄ emissions from livestock is the use of halogenated compounds, especially those that contain bromoform, such as the macroalga *Asparagopsis taxiformis*. Bromoform inhibits methyl-coenzyme M reductase that catalyzes the last step of methanogenesis in methanogenic archaea, and inhibition of other methyl group transfer steps in methanogenesis is also possible (36). In vivo studies with beef cattle (62, 63) fed diets supplemented with bromoform-containing macroalgae report up to 98% less CH₄. However, only a few studies have been conducted feeding *Asparagopsis* spp. to dairy cows; these studies were short term and reported decreased DMI and milk production when CH₄ reduction exceeded 30–40% (64, 65). Additional long-term dairy cow studies are urgently needed to evaluate the CH₄ mitigation effects of *Asparagopsis*. The potential of wide-scale adoption of *Asparagopsis* for CH₄ mitigation may also be limited by the challenges of growing this red seaweed at scale, as production costs are high and stabilizing the bioactive compounds postharvest is difficult. Furthermore, the CO₂e emissions from growing, harvesting, processing (drying), storing, and transporting *Asparagopsis* on a large scale may partially offset the reduction in CO₂e emissions associated with decreased CH₄ emissions.

Synthetic forms of bromoform and other halogens are also of interest, and research to determine if they could be administered as feed additives or via a slow-release bolus in the rumen is ongoing. When administered to dairy cows, iodoform reduced CH₄ emissions by up to 66%; however, DMI and milk production were also reduced substantially (66). Although the initial studies with halogenated compounds are promising, further research is needed to refine their application and safety. Given the limited number of studies published to date, a major limitation to regulatory approval and widescale adoption of *Asparagopsis* and synthetic halogenated compounds is the uncertainty as to whether bromoform or related residues accumulate in animal tissues.

5.4.3. Nitrate. Supplementing diets with calcium nitrate decreased CH₄ from dairy cattle by an average of 13–17%, depending upon the metric used to express CH₄ (35). Nitrate acts as an electron sink in the rumen; the reduction of nitrate to nitrite and then ammonium consumes H₂, which reduces H₂ available for CH₄ formation. Nitrate can be used to replace urea in the diet as a source of nonprotein nitrogen, although nitrate is typically more expensive. The main limitation to adoption of nitrate feeding is the potential risk of nitrate poisoning, which can be fatal (67). Gradual introduction of nitrate to the diet of animals over several weeks can reduce the risk of toxicity.

5.4.4. Monensin. Monensin is an ionophore feed additive used to enhance feed efficiency in beef and dairy cattle production. Ionophores inhibit gram-positive bacteria and favor propionate production, while decreasing ruminal proteolysis and ammonia synthesis. Monensin has been shown to reduce methanogenesis by limiting the availability of H₂ and formate, the substrates for methanogens (36). A recent meta-analysis of 13 dairy cow studies reported that monensin at

a dosage of 19–26 mg/kg of diet DM was inversely related to CH₄ emissions (CH₄ reduction: 8–33 g/day, 2–8%), with the mitigation effect partially explained by the significant decrease in DMI that also occurred (68). Outside this range, the response was not significant (68). A meta-analysis of beef cattle studies concluded that monensin had an anti-methanogenic effect when included at between 32 and 44 mg/kg of diet DM, mainly in high-forage diets offered for ad libitum intake, with the effect being greatest during the first 79 days of supplementation (69). Overall, the scope of using monensin to help achieve net-zero GHG emissions is relatively limited, as the US dairy industry already uses ionophores extensively.

5.4.5. Vaccines. Administering vaccines to target methanogens in ruminants, particularly those on pasture, is a promising strategy for mitigating CH₄ production (70). A vaccine targeting rumen methanogens aims to generate antibodies that impair methanogen metabolism, thereby reducing CH₄ production while favoring propionate production. This approach involves the delivery of antibodies into the rumen via saliva that interact with methanogens (71–74). An anti-methanogenic vaccine must have broad specificity against methanogens commonly found in the rumen to be effective, and cross-reactive antigens for diverse rumen methanogens are crucial (75). Recent development in vaccine technology following the COVID-19 pandemic has opened doors for a new generation of vaccines that can potentially be developed to reduce enteric CH₄ emissions. Several start-up companies have raised capital in pursuit of anti-methanogenic vaccines, and rapid development of such vaccines is expected in the near future.

5.4.6. Plant secondary compounds. Plant secondary compounds have been studied extensively for their potential to reduce enteric CH₄ emissions in livestock, with varying degrees of effectiveness influenced by source, type, molecular weight, and the specific methanogenic community in the animal's rumen. Tannins, for instance, were shown to linearly decrease CH₄ yield by 3.65% for every 10 g/kg DM addition, although this was also accompanied by a 2.6% decrease in organic matter digestibility per 10 g/kg DM addition, highlighting the need for a careful balance between reducing emissions and maintaining diet digestibility (76). Essential oils present a variable and less conclusive effect on CH₄ production in vivo, despite promising in vitro results. Their effectiveness varies based on type and concentration, and concerns about their impact on digestion and animal product quality remain (36, 77). Although some plant secondary compounds show potential for reducing CH₄ emissions in livestock, further research is necessary to optimize their use in animal diets for CH₄ mitigation.

5.5. Opportunities for Combined Strategies

A combination of mitigation strategies is likely needed to obtain the >50% decrease in CH₄ required to achieve net-zero dairying. Theoretically, combining strategies that differ in mode of action may achieve additive or synergistic mitigation effects. Few combinations have been tested to date. Zhang et al. (78) fed beef cattle high-forage diets supplemented with 3-NOP and 5% canola oil and reported that the combination decreased CH₄ yield by 51% compared with the control, whereas individually the decrease in CH₄ yield was 32% and 27% for 3-NOP and oil, respectively. In contrast, Maigaard et al. (79) explored combinations of dietary fat, nitrate, and 3-NOP in dairy diets and reported that no combination of additives reduced CH₄ yield to a greater extent than what was achieved by supplementation of the most effective additive alone. Furthermore, supplementation of combinations of these additives negatively affected production parameters. The number of labs equipped to measure CH₄ is expanding rapidly, and the number of researchers and granting agencies interested in CH₄ mitigation has grown. We expect that soon studies will be forthcoming to test combinations of the strategies mentioned above.

6. ENCOURAGING ADOPTION

Dairy farms, which operate with narrow profit margins, are hesitant to adopt CH₄ mitigation practices that increase production costs without generating additional revenue. Although milk production is not expected to increase as a result of CH₄ mitigation in most cases, opportunities will exist for farmers to diversify their income by participating in carbon offset markets and branded low-GHG products. Financial incentives from governments and companies seeking to reduce emissions from their value chain (e.g., Scope 3 emissions) may help farmers make the shift toward low-CH₄ milk production. Other barriers to adoption include the limited access to new feed additives due to the slow regulatory approval process. Animal and consumer safety may preclude the use of some feed additives. Many mitigation strategies have been evaluated only at the research scale, and on a short-term basis, so long-term effects on animal health, reproduction, and performance are unknown. Consumer acceptance also must be considered, particularly for the use of synthetic feed additives. Few strategies are available for organic and grazing dairy production systems, although the situation may change in the future with the development of breeding approaches, vaccines, new feed additives, and early-life interventions that alter the rumen microbiome in a manner that decreases CH₄ production.

7. WILL MITIGATION NEGATIVELY AFFECT ANIMAL PRODUCTION AND HEALTH?

The energy lost as CH₄ represents 5–7% of the gross energy consumed by dairy cows (36), so one might speculate that reducing this energy loss would increase animal productivity. This speculation assumes that the reduction in CH₄ is not accompanied by decreases in DMI and digestibility, and that the energy spared would not be lost to the atmosphere as H₂ gas but would be captured in the form of an energy precursor (e.g., propionate) that could be used for milk synthesis (80, 81). Decreases in CH₄ production greater than 80% have been achieved in beef cattle fed high-grain diets supplemented with *Asparagopsis* (62) or 3-NOP (82) without negative effects on productivity, but this has not always been the case with dairy cows. Most dairy studies with diets supplemented with 3-NOP report moderate decreases (20–40%) in CH₄ with no change in milk production (56), but studies in which CH₄ yield was decreased by 30% or more using *Asparagopsis* report reduced DMI and milk production (63–65). Ungerfeld et al.'s (81) meta-analysis reported that inhibition of methanogenesis by 50% or more using inhibitors was associated with lower DMI. The decrease in DMI could be due to several factors including palatability of inhibitors, the satiating effects of increased propionate production, increased accumulation of H₂, and potential impairment of rumen fermentation. The effects of pronounced CH₄ inhibition on DMI and rumen fermentation require greater study to ensure animal production is not negatively affected when implementing mitigation practices.

8. FUTURE NEEDS

Decreasing enteric CH₄ by >50% is critical for net-zero dairy production and will have direct effects on slowing the warming of our climate. Although significant advancement has been made in recent years to understand the microbial, physiological, and genetic factors that control CH₄ production in the rumen, more investment from government, philanthropy, and the private sector is urgently needed. Few mitigation solutions are currently available for dairy farmers to implement today, and many barriers prevent widespread adoption. In particular, more investment is needed to progress the development of new feed additives, vaccines, delivery systems for grazing cattle, and genetic selection programs. Long-term studies over multiple lactations that evaluate the effects of CH₄ inhibitors on milk production, health, and reproduction are critical

to encourage adoption by dairy producers, but these studies are extremely costly. Macroalgae and synthetic halogenated compounds show tremendous promise but require extensive evaluation before they can be used with confidence. Investment into the fundamentals of rumen biochemistry, microbiology, physiology, genetics, immunology, and nutrition is needed such that the development of CH₄ mitigation tools is based on scientifically sound principles. Policy incentives will significantly bolster the availability of technologies. Frank et al. (83) demonstrated that the adoption and mitigation potential of technologies related to livestock would see a substantial increase if carbon pricing reached or exceeded \$100/t CO₂e, indicating the strong influence of economic mechanisms on environmental practices. Strategies and targets from the dairy industry should specify separate targets for each GHG, or at minimum specify CH₄ targets separately from the long-lived gases so that temperature impacts can be evaluated accurately.

9. CONCLUSION

Governments and industry have set ambitious goals to reach net-zero GHG emissions by 2050. Offsetting CH₄ emissions from the dairy sector with CO₂ removals and storage (based on GWP100) to achieve net-zero emissions will lead to a peak and then continuous decline in global warming from the sector. Achieving this target is challenging for the dairy sector, primarily because dairy farming results in mainly non-CO₂ GHG emissions, which are technically difficult to eliminate or offset. Typical net-zero GHG emissions for dairy production that achieve the Paris Agreement temperature goals will require a minimum of a 50% reduction in enteric CH₄ without negative effects on cow productivity or health. Although continued improvements in production efficiency of dairy cows can be highly effective in reducing GHG intensity of milk in low- and middle-income countries, GHG reductions to 2050 are projected to be minimal in the United States as the dairy industry approaches a biological threshold GHG intensity of milk. Aggressive adoption of CH₄ mitigation strategies, including breeding cows for low CH₄ production, formulation of low CH₄ diets, use of CH₄-inhibiting feed supplements and additives, and other emerging technologies, will be needed. Whether CH₄ reductions are additive when multiple mitigation strategies are applied is not known. Complete elimination of enteric CH₄ emissions from dairy cows may not be possible without negatively affecting milk production; thus, offsets and removals of other GHGs will be needed to achieve net-zero milk production.

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