Some Aspects of Reducing Greenhouse Gas Emissions on Dairy Farms to Mitigate Climate Change – An Overview

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WebLog Open Access Publications
Article ID : wjvsah.2025.j0103
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Abstract

Climate change is the greatest threat to humanity this century. The impact of dairy cows on climate change is currently being intensively discussed. There are several ways to reduce methane, carbon dioxide and nitrous oxide emissions on dairy farms. The aim of this study was to present some aspects of reducing greenhouse gas emissions in dairy farms to mitigate climate change. It has been found that methane emissions from dairy farms could be reduced by using feed additives such as the addition of oilseeds, various oil blends, seaweed, rapeseed cake, grape pomace, increasing the proportion of grains or changing the feed ratio between rough feed and concentrates. Another important tool for reducing greenhouse gas emissions is extending the useful life of dairy cows. The longer the useful life of dairy cows, the fewer animals must be kept as replacements, the lower the feed requirements and the lower the greenhouse gas emissions. Mastitis is a major problem on dairy farms worldwide and many cows do not recover after treatment. This means that many cows must be culled between the first and third lactation. It is noteworthy that the longevity of dairy cows milked with a suitable milking machine such as the "MultiLactor" (Siliconform, Germany) was higher. However, the right milking machine for dairy cows is of great importance on the farm as it ensures a healthy udder and a longer lifespan of the cow, thus reducing greenhouse gas emissions. In addition, technological improvements in herd management and productivity can help reduce methane emissions. A notable, computational methods offer the potential to reduce methane production in dairy cows. This approach is based on molecular dynamics techniques that can be used to develop inhibitors of methane production.

In conclusion, it is important to make dairy farms as climate-friendly as possible to reduce greenhouse gas emissions and to take this into account when designing feeding management, milking technology, animal husbandry and computational methods.

Keywords: Dairy Cow; Feed Additives; Longevity; Milking Machine; Multilactor; Reduce Methane

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Received Date: *22 Sep 2025*
Accepted Date: *30 Sep 2025*
Published Date: *01 Oct 2025*

Citation:
Kaskous S. Some Aspects of Reducing Greenhouse Gas Emissions on Dairy Farms to Mitigate Climate Change – An Overview. WebLog J Vet Sci Anim Husb. wjvsah.2025.j0103. https://doi.org/10.5281/zenodo.17291311

Introduction

Climate change is one of the greatest challenges of the 21st century. It can lead to environmental damage, global food shortages, and poverty [1, 2]. However, the climate system is warming and the increase in global average temperature is largely due to the strong contribution of greenhouse gas emissions from human activities [3]. According to a recent study, agriculture is a major source of methane (CH_4) and nitrous oxide (N_2O) emissions [4], accounting for approximately 18.4% of emissions and contributing significantly to human-caused greenhouse gas emissions [5, 6] (Figure 1).

However, emissions from livestock farming and manure contribute about 5.8% to total greenhouse gas emissions in the agricultural sector [7] and the relationship between global temperature and the concentration of greenhouse gases in the atmosphere is well established [3]. By 2050, the world's population will grow to around ten billion people [8]. Given our planet's limited resources, feeding these people will pose an enormous challenge. The question is: Where should food be produced and how can global warming be counteracted at the same time? [2]. This question was discussed at the world food forum in Mexico in May 2023. Researchers estimate that large-scale production of artificial meat and the use of insects as a protein source could only cover 20 to 30 percent of global demand. To compensate for the protein deficiency, intensive meat and milk production is necessary. However, the intensive production and accumulation of greenhouse gases in the atmosphere contribute to global climate change [9]. There is clear evidence of greenhouse gas emissions from the dairy sector and their impact on climate change [10-15]. Astuti et al.

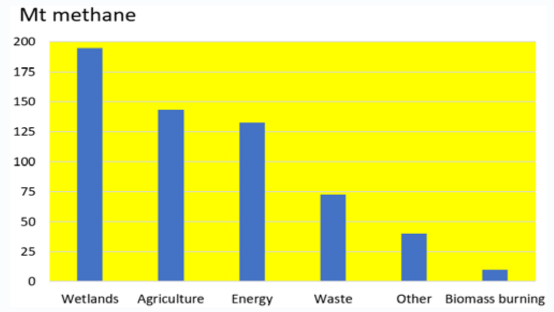

Figure 1: Methane emission sources in million tons (Mt) (Adapted from the International Energy Agency [5].

[15] also found that dairy farming contributes significantly to the accumulation of climate-damaging gases. Therefore, animal protein must be produced in a more climate-friendly and sustainable manner and used more productively in the food chain.

On the other hand, climate change poses unprecedented challenges to the dairy sector. Rising temperatures, weather variability, and the increasing frequency of extreme weather events are changing traditional agricultural practices and forcing farmers to adapt to a new reality [16]. It is noteworthy that the livestock sector is responsible for about 30% of global greenhouse gas emissions [17]. However, enteric fermentation produces methane (CH_4), feed production (including processing, transport, and storage) produces carbon dioxide (CO_2) and nitrous oxide (N_2O), and manure management produces methane (CH_4) and nitrous oxide (N_2O), all of which contribute significantly to emissions [4, 18, 19]. In addition, there are greenhouse gas emissions that arise from the rearing of replacement animals [20]. It is also noted that methane from the gut is responsible for about 35–55% of total agricultural emissions [21]. The following figure (Figure 2) clearly shows the fermentation of methane processes and their excretion by the body of cows [22].

Due to this situation, several studies are currently being conducted to investigate how to reduce gas emissions, particularly enteric methane emissions from ruminants [3, 13, 23]. According to these studies, dairy farms can make an important contribution to improving the efficiency and sustainability of modern agriculture, which in turn could have a positive impact on climate change [24]. For long-term milk production, it is necessary to investigate feeding, breeding, husbandry, milking techniques, and management strategies to reduce methane emissions [25-28]. There are several ways to reduce methane, carbon dioxide and nitrous oxide emissions on dairy farms. This study addresses some aspects of reducing greenhouse gas emissions on dairy farms to mitigate climate change.

The Influence of Some Feed Additives or Change in Feed Ration on Reducing methane Emissions in Dairy Cows

Feeding is known to contribute to the release of methane gas in dairy cows, as it is produced during the digestion of high-fiber food [13, 18, 29-31]. This means that the rumen environment can influence methanogen production [27, 31, 32]. However, the composition and quantity of these fermentation gases are primarily influenced by many factors, such as nutrient composition, microbial population dynamics and the general health of the animal, all of which affect performance and production [31. Various measures and approaches have been tested to reduce methane emissions on dairy farms. These

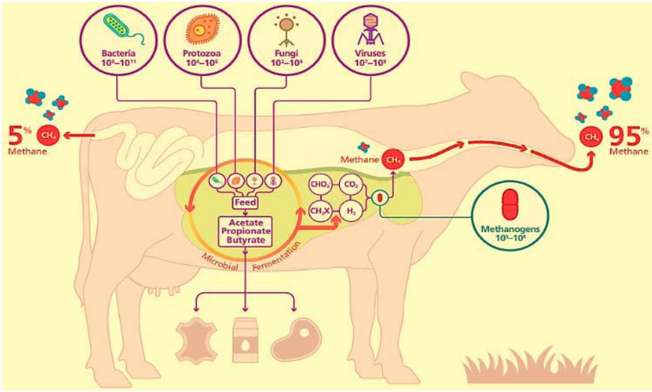

Figure 2: Fermentation processes, their products, and microbial factors in dairy cows. Abbreviations: CO_2 = carbon dioxide; H_2 = hydrogen; CHO_2 = methanal; CH_3X = methoxy compounds or methylamines; CH_4 = methane. According to Belanger and Pilling [22] with some modifications.

include the development of anti-methane feed additives (AMFAs), which can reduce methane emissions in the gut to varying degrees by targeting methanogens, alternative electron acceptors, or the rumen environment [33-37]. Previous research on the use of phytonutrients and bioactive components as feed additives is of particular importance given current regulations on antibiotics and antimicrobials and the low methane production during rumen fermentation [38-40].

The following table (1) shows some examples of reduced methane emissions in dairy farms after the use of feed additives or the change in the feed ratio between rough feed and concentrate.

The table (1) shows that methane production on dairy farms can be reduced by using certain supplementary feed or by changing the feed ratio between rough feed and concentrate.

Alabi et al. [43] showed that the combination of essential oil blends with fumaric acid reduced methane emissions by up to 86% and increased propionate concentration by 9.5%, indicating significant changes in the composition of the rumen microbiome. Various essential oils from natural herbs or extracts of tropical plants, especially garlic, lemon, and mangosteen peels, when ingested, provide phytochemicals in the form of total polyphenols such as condensed tannins (CTs), saponins (SPs), curcumin, quercetin, and other anthocyanins, which are thought to reduce methane production in the digestive tract of ruminants [47]. Phupaboon et al. [48] found that feed supplements containing essential oils of plant origin can be used as feed enhancers for ruminants to increase fermentation efficiency and as feed additives to suppress methanogen populations while reducing methane production. However, dietary fats and oils are known to reduce methane production in the intestine [17, 49]. and simultaneously modulate the rumen microbiome [50]. In a study by Bayat et al. [51], the addition of sunflower oil (50 g/kg dry matter) was more effective in reducing intestinal methane production in high-feed diets than in low-feed diets (feed to concentrate ratio; feed to concentrate ratio 65:35 *vs.* 35:65). In addition, several researchers have investigated the use of rapeseed cake (a by-product of the petroleum industry) as a feed ingredient with high residual oil content and low enteric methane production without negative effects on feed intake [22, 52]. Bayat et al. [53] found that the addition of vegetable oils or oilseeds to the diet can increase feed efficiency and increase the nutritional value of fatty acids in milk, in addition to reducing methane production. Patra [54] found that using the oil

Table 1: The use of supplementary feed or changing the feed ratio between rough feed and concentrate to reduce methane emissions on dairy farms.

The procedure and application	Animal Nr.	Supplementary feed	Methane reduction	Impact on milk production	Authors
Use of three product-based strategies		Increasing feeding level, decreasing grass maturity, and decreasing dietary forage-to-concentrate ratio	decreased CH_4 per unit meat or milk by on average 12%	Increased animal productivity by a median of 17%	[17]
Comparison with or without concentrate in the ration	30 dairy cows	Introduction of concentrates into the feed ration.	By using concentrated feed in the ration, methane production was reduced from 7.26 to 6.42% of gross energy intake.	With concentrate in the ration, milk yield (FPCM) increased from 24.9 to 33.7 kg/day	[25]
Change in the roughage-concentrate ratio.	16 Holstein dairy cows	More forage in the ration	Increasing the R:C ratio from 47:53 to 68:32 increased CH4 emission from 538 to 648 g/cow per day	Milk yield is not changed	[41]
Addition of three oilseeds to the feed ration	16 dairy cows	Addition of sunflower seeds, flaxseeds, and Canola seeds	Decreased methane production 13%	Milk yield not affected by oilseed treatments	[42]
Addition of essential oil mixture and fumaric acid to the mixed ration	Black Angus beef cows	Different oil blends were used	Reduction of gas volume from 181 to 144 ml/g dry mass and reduction of methane content from 7.69 to 4.01 mg/g dry mass	Not specified	[43]
Inhibiting methane formation with seaweed	Dairy Cows	The use of the algae Asparagopsis taxiformis or Asparagopsis armata in feed	Methanogenesis was inhibited by up to 98%.	Not specified	[44]
Addition of rapeseed cake to the feed ration	8 Red cows	Addition of 19.2% rapeseed cake to the dry matter	Reduced methane production from 14.6 g/kg milk to 12.3 g/kg milk.	Increase in milk yield from 37.5 to 41.5 kg/day.	[45]
Addition of seaweed to the feed ration	Brahman-Angus cross steers	Addition of 0.20% of the organic matter intake of Asparagopsis/Taxiformis to the grain-rich ration.	Reduction of methane emissions from 12.5 g/kg to 1.0 g/kg dry matter intake.	Not specified	[46]

CH4: Methane, FPCM: Fat-Protein corrected milk, R:C: rough: concentrate

as a dietary supplement can also provide significant benefits against methane formation. There is evidence that oils and fats can prevent methane formation by replacing fermentable organic matter in the diet and bio-hydrogenating unsaturated fatty acids. This reduces the number of methanogens and protozoa present in the rumen. It is generally accepted that the presence of feed additives containing essential plant oils has a significant impact on the development of methane production [55, 56]. It has been observed that changing feed composition contributes to reducing methane emissions from dairy farms [30. For example, increasing the grain content in the feed lowers rumen pH and increases propionate production. Consequently, methane production decreases [13]. However, a high-energy diet reduces methane production per unit of milk (energy-corrected milk) [57]. This mechanism can be explained physiologically. By increasing propionate and decreasing acetate and butyrate in the rumen, the hydrogen equivalents that would otherwise be used for methanogenesis can be reduced.

It is noteworthy that some feed additives may be effective *in vitro* but not in animals. The use of *naringin* and *chitosan* had a positive effect on fermentation *in vitro*. Propionic acid production increased, while acetate and methane production decreased by 12% and 31%, respectively. However, *in vivo* results showed that neither the administration of *chitosan* and *naringin*, individually or in combination, directly into the rumen had a positive effect on rumen fermentation nor on intestinal methane production 58]. In addition, studies have examined the effects of *seaweed* on methane emissions. The laboratory study showed that 20 g of *Asparagopsis taxiformis*/kg feed with the mentioned *algae* almost eliminated CH4 formation without negatively affecting the digestibility of the feed 46, 59, 60]. Further studies have shown that when dairy cows were fed 1% *Asparagopsis armata*, a 67% reduction in methane was observed and no residues were found in the milk. In addition, trials with tied cattle showed that the addition of 0.2% organic feed in the form of dried *Asparagopsis* reduced methane emissions by up to 98% and increased weight gain by 42% without affecting feed intake or rumen function [46]. Stefenoni et al. [61] found that reductions in methane production (55-80%) were observed in dairy cows fed 0.5 percent dry matter of *Asparagopsis taxiformis*. Similar results have shown that the inclusion of *Asparagopsis armata* in the diet of dairy cows during milk production reduces intestinal methane emissions by more than 50 percent [62]. However, it must be emphasized that feeding with *Asparagopsin* can cause changes in the rumen mucosa [63]. Recent studies have shown that feed containing different amounts and mixtures of seaweed reduces methane emissions in dairy cows [64] (Table 2).

Zhang et al. [65] found that feed containing *condensed tannins* (CT) reduced methane (CH4) emissions and improved milk production. Based on the observations, *L. bicolor* CT significantly reduced CH4 and ammonia nitrogen production while maintaining dry matter digestibility *in vitro*. However, *L. bicolor* CT can effectively improve rumen fermentation and reduce CH4 production.

Interestingly, it has been observed that longer rumination times reduce methane emissions and methane content in milk [13]. Beauchemin et al. [42] indicate that replacing grass silage with maize

Table 2: Dry matter feed intake (kg/day), milk yield, and methane emissions of Holstein dairy cows fed diets containing different amounts and mixtures of seaweed according to Reynolds et al. [64] with some modifications.

Parameters	Treatment groups[2]				SEM
	Control	AN:FV:AT	AN:FV	FV:AN	
Number of cows	10	10	10	10	
DMI[1]	22.6	22.9	24.3	23.7	0.684
Milk yield kg/d	31.5	33.0	31.4	33.1	1.40
ECM Kg/d	35.9	37.4	34.4	35.3	1.76
CH4 g/kg	459[a]	417[b]	452[ab]	435[ab]	17.0
CH4 g/Kg DMI	20.91[a]	18.42[b]	18.72[ab]	18.57[b]	1.065
CH4 g/Kg ECM	13.36[ab]	11.44[b]	14.21[a]	13.20[ab]	1.09

1 DMI: Dry matter feed intake, 2 Treatment diets: Control, no seaweed; AN: FV:AT = Ascophyllum nodosum (AN), Fucus vesiculosus (FV), and Asparagopsis taxiformis (AT) at 5:45:50 and 1.5 g/kg diet DM; AN: FV at 90:10 and 6.5 g/kg diet DM; FV:AN at 90:10 and 17.5 g/kg diet DM.

a, b Treatment means with different superscripts tend to be different at P < 0.08 based on paired t-tests; SEM: Standard error; ECM: Energy Corrected Milk; CH4: Methane.

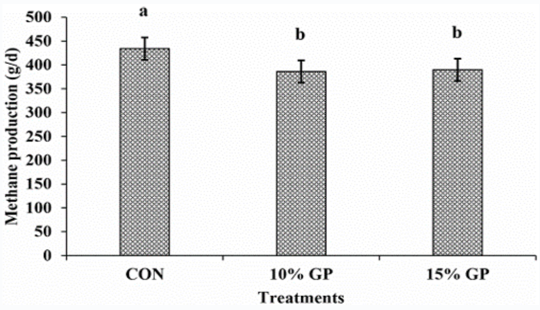

Figure 3: Methane production (CH_4) of multiparous Holstein dairy cows (n = 24, 205 ± 39 day in milk) with different grape pomace treatments. CON = Feed with a total mixed ration without grape pomace; 10% GP = Add 10% grape pomace on a dry matter basis; and 15% GP = Add 15% grape pomace on a dry matter basis. The letter differences a and b were significant (P<0.05). Error bars represent ±SEM [70].

silage promotes the fermentation of propionate instead of acetate in the rumen and thus reduces methane production in dairy cows. When maize silage completely replaced grass silage in the diet of dairy cows, a reduction in methane emissions of 8 to 11 percent was observed [66]. However, due to its high biomass production and high content of fermentable carbohydrates, maize is one of the most important high-yield feeds in ruminant feeding [67, 68]. In this context, it is important to select good maize varieties that improve feed digestibility and reduce intestinal methane emissions, in line with global efforts to combat climate change [69]. A study by Parnian-Khajehdizaj and Moharramnejad [2] found that a specific maize variety (TWC647) improved fermentation efficiency and reduced environmental pollution in the laboratory. The results of Akter et al. [70] showed interesting results that the addition of grape pomace reduced methane emissions and improved milk quality in dairy cows (Figure 3).

However, grape pomace has been reported to reduce methane emissions from cattle *in vitro* [71, 72] and *in vivo* [73, 74]. The above results are due to the fact that the lipid and tannin content of grape pomace has anti-methanogenic [75] and immunomodulatory effects [76]. This means that tannins in grape pomace can negatively affect neutral detergent fiber (NDF) digestion and rumen degradation by altering microbial proteins in the rumen, thus reducing microbial activity and methane production [77]. Therefore, the addition of grape pomace to dairy cow feed can make an excellent contribution to achieving the goal of methane reduction [70].

Considering the above findings, to meet future feed additive needs, the livestock industry needs to develop natural feed additives that improve nutrient efficiency, provide alternatives to antibiotics, and reduce methane emissions from ruminants.

The Impact of Milking Technology on Reducing Methane Emissions in Dairy Cows

At first glance, milking machines seem to have nothing to do with climate protection. However, milking is an essential part of dairy farming to improve milk production and quality. If the milking machine settings and the design of the teat liner are suitable for all dairy cows on the farm [78], the udder condition remains healthy and the cows stay on the farm for a long time, as sick cows with severe mastitis are replaced from the farm. The longer cows are kept on the farm, the fewer cows need to be kept for reproduction, the less feed is needed and the lower the greenhouse gas emissions [25, 79-81]. The research results showed that improved animal health not only led to higher milk productivity but also to a significant reduction in greenhouse gas emission [24]. However, health welfare and longevity have a significant impact on the amount of greenhouse gas emissions per kg of milk produced [82-84]. In this context, increasing individual cow production is often cited to reduce methane emissions by reducing maintenance requirements [85]. This means that lower greenhouse gas emissions are associated with a longer longevity of dairy cows on the farm [25, 86]. Von Soosten et al. [84 reported in a model that cows with five to eight lactations reduced their emissions per kilogram of milk by approximately 40% compared to cows slaughtered after their first lactation. Similarly, Vellingo and de Vries [82] showed that extending the lifespan of cows from two to six years reduced greenhouse gas emissions per kilogram of fat-protein-modified (FPCM) milk by 14-19%. However, good health can increase the longevity of cows, which has a positive impact on the environment [87] To increase life longevity, it is important to understand the biological causes of increased parity [88]. In general, a longer lifespan of dairy cows can lead to lower greenhouse gas emissions per unit of product because cows produce more milk over their lifetime, require fewer cow replacements [80], and cause fewer emissions by raising younger cows [89, 90]. Thus, increased milk production and the absence of health problems such as metabolic disorders, lameness or mastitis reduce the risk of culling and greenhouse gas emissions [91]. However, efforts to increase the longevity of dairy cows have so far failed because increased number of lactation and milk production increase the risk of health problems, culling of cows or death of animals on farms [86, 88, 92]. In practice, it has been shown that higher milk yield per cow leads to a shorter productive lifespan and, at the same time, an increased replacement rate [25]. Therefore, dairy cows' longevity has decreased in most high milk-producing countries over time [86, 92]. This means that dairy cows have no real physiological performance potential, as the average slaughter age is significantly below their maximum milk production in the 4th or 5th lactations [24, 91, 93]. It is important to know that increased life expectancy is an indicator of the welfare of animals on the farm [94]. Beaudeau et al. [95] found that udder diseases have the greatest direct influence on the risk of culling. Several lines of evidence indicate that the culling rate due to clinical and subclinical mastitis ranges between 20 and 40% of the dairy cow population [93, 96]. The authors assume an average loss of two to three Liters of milk per cow per day due to production diseases. These mastitis problems also occur in industrialized countries [93. Studies by Betschold et al. [97] showed that mastitis pathogens were detected in 19% of milk quarter samples in southern Germany (Bavaria) between 2023 and 2024.

The main reason for the short longevity of most cows is that farmers do not use the right milking machines to keep their cows healthy. One of the most promising solutions to address these challenges is the introduction of appropriate milking technologies to maintain udder health [98]. In view of the research results of various studies showing that the premium milking machine "MutiLactor" (Siliconform, Germany) contributes to the fight against climate change [78, 99, 100]. With this milking system, cows can enter the parlour voluntarily and ruminate during milking. They behave calmly and contentedly. This demonstrates that the milking machine is very well suited for lactating cows (Figure 4).

An interesting comparison of the milk parameter results of seven Bavarian dairy farms using a suitable milking machine (MultiLactor)

Figure 4: MultiLactor milking machine during milking in a tandem milking parlour according to Kaskous [100].

Table 3: Milk parameter results from seven dairy farms with the average milk parameters for the whole of Bavaria.

Parameter	Milk yield kg/year	Fat %	Protein %	SCC 1000 Cells/ml	Lactation number
Bavaria Dairy cows*	8797	4.17	3.53	208	3.1
7 Dairy farms**	9296	4.28	3.57	123	3.7

* Milk parameters of dairy cows in the state of Bavaria, Germany, according to LKV Bayern in 2024. ** Dairy farms use the MultiLactor milking system (Siliconform, Germany).

with the average milk parameters of all Bavarian dairy farms showed that the seven dairy farms not only increased their milk production but also improved milk quality and extended the longevity of the dairy animals [100, 101] (Table 3).

However, it should be noted that milking is not only about the well-being and health of the cows, but also about the functional reliability and efficiency of the milking machine [102]. This reduces stress and improves overall animal health. Consequently, healthier cows are more productive and produce more milk, which is crucial in times of extreme environmental stress. Therefore, extending the productive lifespan of dairy cows is an effective way to reduce climate impacts and improve the profitability of milk production [25]. This means that milking technologies can play an important role in mitigating the impacts of climate change by improving the efficiency of milk production, reducing emissions, and improving resource use. Finally, appropriate milking systems can increase the efficiency of the milking process and contribute to improving animal health and welfare, thereby reducing greenhouse gas emissions on dairy farms.

The Impact of Dairy Husbandry and Management in Dairy Farms on Reducing Methane Emissions

There are many opportunities in this sector to contribute to climate protection by reducing emissions. A reduction in disease and parasite prevalence on dairy farms would in principle lead to a reduction in emission intensity, as healthier animals are more productive and thus cause fewer emissions per unit of production [1, 24]. However, good management is particularly important during the transition period of lactation, as metabolic disorders during this phase pose a significant risk for productivity and economic losses, as well as an increase in greenhouse gas emissions [24]. This means that poor health and welfare of dairy cows on farms are associated with behavioural and metabolic changes that can lead to increased greenhouse gas emissions 12]. It is important to note that the emission intensity of milk production is lowest in developed countries (between 1.3 and 1.4 kg CO_2 equivalent per kg of fat- and protein-corrected milk). In contrast, higher emission intensities are observed in developing countries such as South Asia, sub-Saharan Africa, West Asia, and North Africa (between 4.1 and 6.7 kg CO_2 equivalent per kg of fat- and protein-corrected milk) [1]. In addition, there are numerous opportunities to reduce greenhouse gas emissions from the dairy industry. For example, measures to promote the construction of biogas plants on dairy farms to process manure and prevent its discharge into waterways are crucial for reducing methane emissions [103]. This means that by using technologies such as anaerobic digestion, which converts manure into biogas, methane emissions can be reduced and renewable energy can be generated. Interestingly, reports from China indicate an increased focus on technological innovations in animal feed, which have significant implications for reducing belching and bloating in cows, the two largest sources of methane emissions on dairy farms [103]. In addition, the use of precise feeding techniques that ensure that cows receive right nutrients without overfeeding can reduce methane and nitrous emissions from manure. This means that improvements in herd management and productivity enabled by technologies such as milking technology can help reduce methane emissions per unit of milk produced.

Impact of Breeding on Reducing Greenhouse Gas Emissions

Numerous reports have shown that methane emissions from cattle and sheep can be significantly reduced through breeding programs. However, measurements on a total of 14,000 Dutch cows and the analysis of DNA profiles showed that methane emissions vary by up to 25 percent depending on genetic factors. To achieve this goal, breeding cows and bulls with the lowest methane emissions are selected, considering other relevant traits such as fertility, health, and longevity. Consequently, genetic selection of cows with low methane (CH_4) emissions could be an effective and sustainable strategy to reduce greenhouse gas emissions from dairy cows [104, 105]. However, several studies have shown that the heritability of methane traits in dairy cows is low to moderate, ranging from 0.11 to 0.33 [106, 107]. Manzanilla-Pish et al. [108] reported that animals with lower methane production process feed more efficiently.

How Can Dairy Cows Maintain Their Milk Production While Reducing Greenhouse Gas Emissions in the Face of Climate Change?

Increased global temperatures are affecting the health and productivity of livestock. Cows are particularly sensitive to heat stress, which can lead to reduced milk production, lower fertility rates and increased susceptibility to disease. Farmers must find ways to mitigate these impacts to maintain productivity [109]. However, climate change is exacerbating water scarcity and poses a challenge to the production of fodder crops and the health of livestock, particularly in developing countries [109]. Nevertheless, heat stress affects the longevity of dairy cows and the profitability of the farm. Physiological, when high temperatures and humidity overwhelm a cow's natural cooling mechanisms, resulting in reduced productivity, fertility, and overall health [110-112]. Due to long summers and high temperatures, heat stress in cows is difficult to manage in many countries. Therefore, maintaining dairy farm profitability and herd welfare is crucial under such conditions. As a result, dairy cows suffer from the following problems [93, 110-114]:

- Reduced milk production: Cows suffering from heat stress eat less and experience physiological and hormonal changes, leading

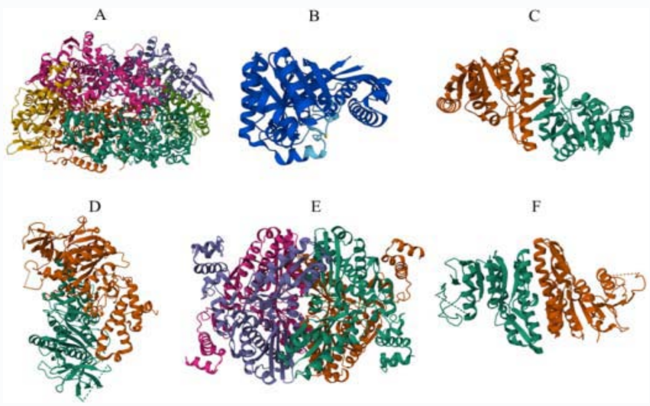

Figure 5: Three-dimensional ribbon structure of target molecules for the discovery of methanogenesis inhibitors. (A) Methyl-CoA reductase M (Methanothermobacter thermautotrophicus) [119]; (B) Predicted structure of 4-(β-D-ribofuranosyl) aminobenzene-5'-phosphate synthase [120; (C) Coenzyme F420H2: NADP+ oxidoreductase (FNO) from Archaeoglobus fulgidus [121]; (D) Subunit B of the enzyme A1A0 ATP synthase from Methanosarcina mazei [122]; (E) HMG-CoA reductase from Methanothermococcus thermolithotrophicus [123]; (F) Isopentenyl phosphate kinase from Thermoplasma acidophilum [124].

to lower milk production. Every liter of milk lost means a loss of income.

- Reproductive problems: Heat stress disrupts hormonal balance and makes it difficult for cows to conceive and give birth. This leads to longer calving intervals and a smaller number of calves over their lifetime.

- Health and longevity: Chronic heat stress leads to claw problems, a weakened immune system, and diseases such as mastitis, often resulting in premature slaughter. Each premature slaughter increases the cost of replacing a cow that has not yet reached its peak productivity.

- Costs of herd turnover: Raising or purchasing replacement calves is expensive, and high herd turnover reduces the efficiency of investments such as housing and milking equipment.

- Herd longevity: Healthier cows stay in the herd longer, spreading costs and increasing profits, as well as reducing methane emissions.

Interestingly, direct measurement of CH_4 production in heat-stressed dairy cows usually shows lower values, as feed intake often decreases under heat stress [115]. However, prolonged exposure to a hot environment is expected to increase methane concentrations in dairy cows, highlighting the need to mitigate heat stress and its environmental impacts [115, 116].

Computer-aided Methods for Reducing Methane Emission

Of particular note is the potential use of computational methods to reduce methane production in ruminants. This approach is based on molecular dynamics techniques that can be used to develop inhibitors of methane production [3]. The increased use of computational research techniques, including artificial intelligence, is encouraged to reduce methane production in livestock farming more efficiently and cost-effectively. Methanogens have been observed to possess unique physiological properties, including metabolic pathways that differ from those of other rumen microorganisms. Therefore, inhibition of rumen methane production should not cause disturbances to other rumen microorganisms such as bacteria, fungi and protozoa involved in proper digestion. However, inhibition of rumen methane emissions can lead to changes in hydrogen partial pressure and fermentation parameters in the rumen, which can indirectly affect the composition of the rumen microbiome [117]. Interestingly, several methanogen-specific enzymes were identified that are responsible for the formation of inhibitors [118]. Figure (5) shows the structure of some enzymes that inhibit the process of methane formation.

In addition, this research project investigates identified methanogenic enzymes as potential targets for the development of inhibitors.

Conclusion

- Inclusion of additives in the diet of dairy cows to inhibit methane formation can be economically viable, as it can increase the cow's productivity through improved nutrition while reducing greenhouse gas emissions.

- By optimizing milking technology, greenhouse gas emissions on dairy farms can be reduced because dairy cows stay healthier and their life expectancy on the farm increases.

- Optimal animal husbandry and good management are crucial for udder health and increased milk yield. This increases the lifetime productivity of dairy cows and thus reduces greenhouse gas emissions.

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