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Review Article

A Path Towards Achieving Net Zero in Dairy Farming

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Abstract

Climate change and Global warming due to greenhouse gases increase the need for sustainable livestock production which ultimately demands to find the better solutions to reduce these greenhouse gases, especially methane. Ruminants (Cattle>sheep>goat>buffalo) and their manure contribute to approximately 32% of global anthropogenic methane emissions. Feed management involving diet formulation and precision feeding, rumen manipulation, animal management and other biotechnological strategies need to be applied properly in the dairy farms to reduce the enteric methane emissions. This review paper discusses the various strategies followed to enhance the sustainable dairy farming across the globe. Its main focus on the traditional and emerging potential mitigation techniques like disabling protein binding, methane zapping masks etc. to reduce the methane emission produced by the dairy cows. Additionally, the manuscript reviews the different approaches to mitigate the other greenhouse gases like carbon dioxide and nitrous oxide. In conclusion, there is the foremost need to explore the potentialities of biological approaches with applied research for reducing methane emissions with the aim of achieving net zero in dairy farming.

Keywords: Methane emission; Dairy; Rumen; Diet

Introduction

From ice ages to warm periods, Earth's history has been shaped due to natural climate changes. Distinct climatic zones, across the globe facing formidable environmental challenges to protect their valuable natural resources. Climate is changing because of increased anthropogenic activities which have serious consequences on social and economic development. There are many issues contributing to the climate change which we need to address include deforestation and habitat loss, biodiversity loss, water use and pollution, overfishing, soil health and erosion, and of course, the quarter of all human-caused greenhouse gas emissions that come from food production. Intergovernmental Panel on Climate Change (IPCC) included six gases while defining the term "greenhouse gases" viz., carbon dioxide (CO_2), methane (CH_4), nitrous oxide(N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). The first three are present in the atmosphere and are also produced as a result of agricultural and livestock activities. Global contribution of livestock sector to the greenhouse gas emissions is around 18 percent (7.1 billion tonnes CO_2 equivalent). Thus, it accounts for nine percent of global CO_2, but generates 65 percent of human-related nitrous oxide and 35 percent of methane,which has 310 times and 23 times the Global Warming Potential (GWP) of CO_2 respectively [35].

The concept "Net zero" refers to a state of Earth's atmosphere where the anthropogenic GHGs (greenhouse gases) released into the air are balanced by the removal of an equal amount. Achieving this balance is crucial for sustainable future. The concept is based on the principle of carbon neutrality, backed by a twofold strategy: reducing the existing emissions and enhancing carbon sinks like forests and oceans along with Carbon Capture and Storage (CCS). Reducing emissions involves transitioning to renewable energy sources, boosting energy efficiency, and altering land use practices [29]. The aim is to counterbalance the emitted GHGs by a ton removed or sequestered from the atmosphere. According to FAO 2014, Global GHG emissions by livestock sector consist of enteric fermentation (39%), Manure management (26%), Feed (21%), Land-use change (9%), energy and post-farm (5%) at global level. The management of hydrogen production in the rumen is the most important factor to be considered while developing strategies to control ruminant methane emissions either by inhibiting H_2 liberating reactions or by promoting alternative hydrogen-using reactions or routes for disposing of H_2 during fermentation [15].

The livestock sector contributes significantly to global warming through greenhouse gas (GHG) emissions. At the same time, livestock is an invaluable source of nutrition and livelihood. The global consumption of dairy products like cheese, milk, and butter comprises~14% (high income countries) and ~5% (low to middle income countries) of the total dietary intake [24]. Therefore, climate mitigation policies involving livestock must be designed with extreme care. It is imperative to adopt the novel practices like Circular economy thinking, creating opportunities to reduce dairy industry waste or valorise it through reusing, recycling and recovery operations, incentives for small scale farms collaboration between large-scale farms and industry to achieve the net zero in global dairy.

Background and Global Scenario

The Net zero target on an international level was the first time set by the Paris Climate Accord which is entered into force on 4th November 2016. Paris Accord is to limit the warming to 1.5°C from pre-industrial levels to secure a liveable future for all. According to the data (2015), overall 3.4 percent of all human-induced greenhouse gas emissions were generated along the entire dairy production chain – from cow to grocery store shelf. When it comes to implementation of strategies, we face three major hurdles i.e. a) *Economic* : high investment and additional costs are needed b) *Technological* : difficult to set up on small scale farms c) *Cultural* : willingness of farmers and suppliers to invest is different. Global emission intensity of milk per litre has declined between 2005-2015. However, total emissions from dairy have increased by 18% because of increased global herd size. Methane, being the dairy's primary greenhouse gas, is produced by ruminants as a product of the fermentation of ingested feed. There are two main pathways, through which ruminants emit methane: via midgut fermentation and hindgut fermentation. Midgut fermentation or enteric fermentation solely accounts for 89% of total CH_4 emission from the animal. The methane emission in dairy cow ranges from 151 to 497 g per day. Lactating cows produce more methane (354 g per day) [4]. In other words, more milk leads to more methane emission. At the same time, more efficient cows produce more milk per unit of feed they consume, and thus their methane emissions per unit of milk are lower.

The Global Dairy Platform (GDP) announced the "Pathways to Dairy Net Zero" initiative on 23rd September, 2021. Innovation Sprints (announced at COP26 and COP27) are initiatives led and funded by partners to achieve a specific outcome in agricultural innovation. Programs suchas the Natural Resources Conservation Service (NRCS) Environmental Quality Incentives Program (EQIP), the EPA's RFS Renewable Identification Numbers (RINs) program will enable farmers to make decisions about the mitigation practices. Many countries have made pledged to achieve the net zero by 2050 and started the timeless efforts in the same direction. The measure with the largest potential within the supply chain is to increase carbon storage in the soil, often mentioned as part of 'regenerative farming'. South Africa and Brazil stepped into the regenerative farming. Germany is focusing on practical solutions. For example, cow manure is recovered to efficiently fertilize crops through nutrient recovery. A product from the Netherlands is reported to reduce methane emissions from enteric fermentation by up to 40%.Chile is using biofertilizers to enhance soil productivity and to cut down the emissions. Denmark government is involved in the development of agricultural biogas installations. USAan evolving industry supports new technologies and environmental practices. All of the manure produced by cows either used to fertilize crop or it is dried and used for bedding. Indian Council of Agricultural Research (ICAR) has developed an anti-methanogenic feed supplement 'HaritDhara' (HD), which can cut down cattle methane emissions by 17-20% and can also result in higher milk production.

Mitigation strategies to reduce GHGs produced by livestock sector

Enteric methane amelioration strategies

Around 35% of the on-farm carbon footprint of dairy production is assigned to the methane produced by enteric fermentation, the process which enables ruminants to eat and break down forage feeds into soluble carbohydrates. Depending upon the quality and quantity of ration, about 8-12% of dietary energy is lost in the form of methane in ruminants [37]. Mainly nutritional approaches are implied to reduce enteric methane emission along with other biological approaches.

Dietary manipulation

Energy level in diet and the type of roughage provided affects the extent of methanogenesis significantly. Sugarcane bagasse and paddy straw produced 11% and 4% more methane as compared to that on wheat straw. Urea treatment of straws reduces the methane production by12-15% due to increased propionate production and decreased molar proportion of acetate. Green maize and berseem in the ration also decrease methanogenesis significantly [36]. It has been found that lower hemicellulose content leads to increased methane production.

Concentrates and grains in the diet

Increasing grain mixture in the grazing livestock fed on crop residues may lower methane emission by 20-30%, and that of high yielding cows reduces it by 14-25%. Fermentation of cell wall carbohydrates produces more methane than fermentation of soluble sugars or starch [16]. High grain diets fed at high intake levels are associated with high rates of ruminal digestion and passage that favour higher propionic acid production which ultimately lowers methanogenesis.

Feeding of oils and fats

Free oil act as rumen modifier but cannot be added beyond certain levels. Adding canola oil @4.6% of dry matter intake inhibited methane emission by 32% and decreased methane emissions as a percent of gross energy intake by 21% primarily due to reduced feed intake and lower total tract digestibility of feed, especially the fibre component [3].

Increase digestibility of feed

Feeding of more digestible feeds like legumes improves the digestibility and reduces the methanogenesis by 15-21%. It is found that, pasture-grazing cattle produced 0.23 kg methane per animal per day, requires 7.7 to 8.4% of gross energy to convert into methane. The same cattle fed with a highly digestible, high-grain diet produced only 0.07 kg methane per animal per day, utilizes only 1.9 to 2.2% of the feed energy for conversion of methane. Thus, four times more methane production can be reduced by feeding high digestible diet [10].

Tannins and Saponins

Tannins are polyphenolic compounds of plant origin, generally regarded as inhibitory to the growth of microorganism, which might be due to complexing ability of tannins with the cell wall of bacteria especially methanogens. Tannins also suppress methanogenesis by reducing hydrogen production. Whereas, saponins indirectly reduces methane production by its sterol binding capability - destroys protozoal cell membrane. Alfalfa saponins isolated by ethanol extraction and partial acid hydrolysis decreased protozoal numbers in the rumen of sheep by 34 and 66% at the inclusion levels of 2 and 4% dietary dry matter, respectively [21].

Feeding frequency of the ration

It was observed that low frequency of feeding increased propionate, reduced acetic acid production, increased diurnal fluctuations in ruminal pH that can inhibit methanogenesis.

Alternate hydrogen sink

During the microbial fermentation, cofactors like NADH, NADPH and the sugars are partially oxidized to volatile fatty acids by transferring hydrogen to carbon dioxide and resulting in the formation of methane with the help of methanogenic archaea.

Hydrogen has to be utilized to continue the enteric fermentation, and methanogenesis is one such process which acts as a hydrogen sink. Thus, we need to focus on alternate hydrogen sinks which could replace methane present in the rumen.

- **Propionate enhancers/fumaric acid :** Inclusion of significant amount of fumaric acid in the diet increases total VFA concentration, increased propionate proportion but may cause a drop in pH which might affect feed fermentation adversely. This can be prevented by encapsulating fumaric acid in a shell of hydrogenated vegetable oil. Prevention of fall in pH along with retention ability of inhibiting methanogenesis is achieved [40].
- **Reductive acetogenesis:** The bacteria which are able to convert two moles of carbon dioxide to one mole of acetate, either autotrophically or heterotrophically, can be classified as reductive acetogens. Inoculation with reductive acetogens like Peptostreptococcus productus along with Lactobacillus plantarum 80 inhibited methanogenesis but this effect was reversed within six days. The results of in vitro experiments have shown that Reductive acetogenesis can serve as an alternate hydrogen sink in rumen fermentation, but in vivo experiments have failed so far [41].

Acetogenesis: $4H_2 + 2CO_2 \rightarrow CH_3COOH + 2H_2O \rightarrow \Delta G^{o\prime} = -104.6$ kJMethanogenesis : $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \rightarrow \Delta G^{o\prime} = -135.6$ kJ

The threshold values of archea for hydrogen are almost 10–100 times lower than the acetogens [8] so they normally out-compete the acetogens by keeping the hydrogen concentration below the critical value needed to enable acetogens to persist.

Use of complete feed blocks/total mixed rations

This approach can ensure nutrient balancing leading to better productivity and lowering methane production by 10 percent.

Plant secondary metabolites

A group of chemicals found in plants might able to modify rumen microbial ecosystem for inhibiting methane emission and improving feed utilization.

Ionophores

They are highly lipophilic substances, including lasolacid, salinomycin, naracin, lysocellin associated with the selective reduction of gram positive ruminococci, and the proliferation of gram-negative bacteria with the concurrent shift in the fermentation from acetate to propionate which ultimately decreases methanogenesis [30]. It has been reported that the feeding of 50mg and 100mg rumensin/day/animal increased the propionate production significantly with concurrent decrease in methane production by 14-23% on maintenance, 30-35% in medium milk production and 22-32% on high milk production.

Natural Antimicrobials

Some plant extracts are generally considered as safe for human consumption (FDA, 2004) and these can be employed to modify rumen microbial fermentation. In a recent study at NDRI, Karnal a mixture of herbs was incorporated @10g/day in the ration of lactating cows and recorded 20% reduction in methane emission.

Flavonoids

The degradation products of flavonoids could modify the microbial metabolism in the rumen as they effectively act against gram-positive bacteria [27]. Some studies revealed that inclusion of flavone, myricetin, rutin, kaempferol etc. significantly decrease in vitro methane production.

Nitrate supplementation

Nitrates, as a dietary supplement, containing low concentrations of nitrogen in the ration reduce methane emissions from dairy cows [34]. Nitrate decrease methanogenesis by acting as electron sinks [35].

Halogenated compounds

They were identified as inhibitors of ruminal methane formation over 40 years ago. Asparagopsis taxiformis, a species of red seaweed containing high concentrations of bromoform @0.2% of diet was shown to reduce methane production by 99% [22].

Fungal metabolite

Lovastatin is a secondary metabolite of idiophase of the fungi, which inhibits the key liver enzyme of cholesterol biosynthesis i.e. hydroxymethyl glutaryl coenzyme A (HMG-CoA) reductase. Isoprenoid is a central component in archaeal cell wall and it is an intermediate step in cholesterol synthesis which is supressed by inhibitor of HMG-CoA reductase, thereby disturbing cell wall synthesis in archaeal cell membrane and methanogens population [7].

Microalgae

These are rich in fatty acids C20: 5n-3 (Eicosapentaenoic acid) and C22:6, n-3 (docosahexaenoic acid). In vitro experiments have shown that brown algae (Cystoseria trinodis and Dictyota bartayresii) are potent methane inhibiters *in vitro* [6], reducing acetate concentration and increasing propionate concentration may be due to their unsaturated fatty acid content, in particular C22:6, n-3 [9].

Methanotrophs

Methanotrophic bacteria act as CH4 sinks in nature, so they can be used to reduce methane levels during enteric fermentation by using methane as the sole carbon and energy source (aerobic process) to obtain single-cell proteins (SCP) as feed and food ingredients and biopolymers [19].

Probiotics and other feed additives

Plethora of feed additives for methane inhibition from ruminants have been developed but somemay not be feasible due to various reasons such as their toxic levels, accessibility, and cost. Feed additives such as lipids, essential oils, and plant secondary metabolites along with roughage and concentrates can be used to achieve methane mitigation. Probiotics are potential feed additives that have many beneficial properties. Specific probiotics can be directly fed to the ruminants include Saccharomyces cerevisiae, Enterococcus, Bifidobacterium, Lactobacillus. The addition of Saccharomyces cerevisiae reduced methane by 10% in vitro [28] whereas, inclusion of yeast culture products (YC1, Diamond-V XP, and YC2, A-Max) in a continuous culture system increased DM digestion, protein digestion and propionic acid production [26]. Lemon grass significantly reduced methane yield by 33%.

Other antimethanogenic compounds

Methanobrevibacter and Methanomicrobium have been found in large numbers in the rumen along with small numbers of Methanosarcina [14]. Methanobrevibacter ruminantium and Methanobrevibacter gottschalkii are the major hydrogenotrophic archaea that alone encompass74% of the methanogenic archaeal community in the ruminant stomach [12].

- **3-nitrooxypropanol:** It is a novel inhibitor having anti-methanogenic properties. It acts against archaea in the rumen by interfering with the last enzymatic step of the methanogenesis.
- **Bromochloromethane (BCM):** It has the potential to reduce a considerable amount (around 95%) of methane from the ruminants by hindering the cobamide (containing cobalt in the corrinoid family of macrocyclic complexes) dependent methyltransferase step in the process of methanogenesis through its reaction with vitamin B12 when fed with BCM-Cyclodextrin (1 g/100 kg BW/day).
- **Bromoethane sulphonate (BES):** It is a potent specific inhibitor of methanogenesis because it is a structural analogue of the cofactor mercaptoethanesulfonic acid (coenzyme M, found only in methanogens) used by methanogenic bacteria (Mathison et al. 1998). It has been observed that BES depressed CH4 production by 71% without significantly affecting organic matter digestibility and VFA concentrations in the artificial rumen or rusitec [5].

Defaunation

It is the partial/total elimination of protozoa from the rumen by dietary or chemical agents, reduces ruminal methane production by about 20-50% depending on the diet composition [13].

Immunization

It is claimed that immunization reduces methane production per kilogram of food by 11-23%.It was found that the methanogenic microbes usually take more than 4 weeks to get stabilized and extreme care must be taken to get acceptable and repeatable results. Vaccine may be effective against all prevailing methanogens, probing the new hydrogen utilizing species that can offer a better alternative than previously tested acetogens in rumen. Also, and redesigningand remodelling of enzyme structures can block the active site of methanogens enzyme using chemogenomic.

Genetic selection

The whole genome sequencing of the Methanobrevibacter ruminantium by identified several key genes i.e. 2,200 genes and almost 3 million base pairs along with enzymes which may be potential targets involved in the methanogensis pathway within the cell [20]. It has been found that rumen microbial metagenome of cattle is associated with high methane production [39].

New potential mitigation strategies

Bacteriocins

Bacteriocins are produced as a means of biological control [11] leads to the direct suppressionof methanogens, produced by bacteria. They are target specific in nature with broad spectrum activity, and possibly transferred genetically and manipulate into another organism. They could possibly be delivered as microbial inoculants for in situ production of the bacteriocin in the rumen or in silage [17].

Archaeal viruses

Another possible method of biological control of methanogens is the use of archaeal viruses (bacteriophages) [11]. However, the knowledge regarding them is still limited.

Exogenous enzymes

Currently, cellulase and hemicellulase are used in ruminant diets to improve fibre digestibility, lower the acetate: propionate ratio in the rumen and ultimately reducing methane production. It was observed that there is a reduction in methane production when the animals were supplemented with the fibrolytic enzyme especially with the high-concentrate-based diet [2].

Disabling the protein binding

Methanogens are associated with other ruminal organisms via specific surface proteins. Disabling these proteins or preventing the binding between these proteins and methanogens could disrupt the interactions and upset their normal behaviour. This may prove a promising technique to inhibit methanogenesis due to the uniqueness and commonness of identified enzymes in all methanogens species which can be easily and specifically targeted.

Methane zapping masks

Few companies have designed face masks which cover the nose and not the mouth. These masks then zap, detect, capture and oxidise methane when ruminants release the gas. This process of oxidation turns methane to carbon dioxide and water which reduces global warming potential of methane significantly to less than 1.5% of its original value. However, adoption of this technique will be very low in small scale farms due to lack of technology and their cultural beliefs.

A number of methane inhibitors have been repeatedly tried to decrease enteric methane production. However, each of them often exerts adverse effects either on microbial fermentation or on digestibility of feed. In addition, some of these inhibitors are toxic to animals and/or decrease rumen fermentation [32]. Collaboration of Animal nutritionist with rumen microbiologists and biotechnologists is the need of the hour to work on improving the hydrogen utilization efficiency of acetogens, exploring the archeal diversity within rumen for developing the second generation vaccine that may be effective against all prevailing methanogens, remodelling of enzyme structures, probing the new hydrogen utilizing species and designing of small chemical molecules that can block the active site of methanogens enzyme using chemogenomic.

Major practices to reduce other emissions in achieving net zero

Precision farming

Cropping practices such as cover crop, crop rotation, and use of manure-based fertilizers alongwith precision farming have the potential to significantly reduce GHG emissions. It avoids the soil disturbance and maintains soil health. Incorporation of fertilizers, often resulting in the release of carbon dioxide and nitrous oxide, a GHG that has a global warming potential of 300 times carbon dioxide. Gene-edited seeds for cover crops could enable greater carbon sequestration. The application of precision agricultural tools such as GPS, sensors, and data analytics, dairy farmers can optimize resource use to improve the crop yield thereby reducing emissions [31]. For instance, sensor-based technologies can monitor soil health and moisture levels, enabling more efficient use of fertilizers and irrigation, thereby reducing nitrous oxide emissions from synthetic fertilizers.

Manure management

Novel techniques like Dry manure-based fertilizer (conversion from liquid manure using new technologies), Anaerobic digesters (convert a portion of organic matter of manure into energy) could be applied to fields which can be used to generate electricity (to power the dairy and/or sell to the grid). For example, dairy waste can be used as substrate for ethanol production using yeast, and high-strength effluent streams can be used for methane recovery via anaerobic digestion. Ethanol and methane can then be utilised by the manufacturing plant as a Supplementary fuel supply [1]. In addition, microbes as catalysts can be employed to generate electricity waste streams via bio electrochemical processes.

Artificial intelligence

AI in herd health management, and sensor networks for real-time monitoring ensures promising future of sustainable dairy industry. Optimizing feed through AI contributes to reducing methane emissions, enhances feed efficiency, reduces reliance on fossil fuels by ensuring maximum biogas production with minimum greenhouse gas emissions. AI models are equipped to suggest dietary adjustments that minimize methane production, considering breed-specific responses and the diverse nutritional needs of the herd. This is possible because of AI algorithms which effectively forecast energy needs and integrate renewable energy sources wherever needed [18].

Carbon capture and storage (CCS) technologies

Implementing CCS could play a significant role in reducing the carbon footprint of dairy farming, thereby mitigating the climatic impact of dairy operations [38]. It captures carbon emissions directly from various sources within dairy farms, including manure management systems and energy consumption processes.

Incentives and policy development

It has a crucial role in mitigating emission efforts in the dairy sector [42]. Various policies could be developed to avoided emissions. For example, mutual engagement between municipality and farmers to manage the food waste properly and reducing landfill volume. Various incentives like funding for adopting sustainable practices, tax breaks for implementing green technologies, or technical support for transitioning to low-emission practices could support fordairies transitioning to net zero emissions production.

It is essential to have mutual engagements and collaborations between farmers, industry stakeholders, researchers, and policymakers in funding, developing and adopting new technologies and precision farming tools for driving the net zero concept and achieving substantial emission reductions in dairy farming.

Conclusion and Future Perspective

In practice, farmers generally do not adopt the mitigation technologies that do not attain a minimum sustainable production level or are not economically viable, while reducing methane emissions. Thus, during the initial phase of technology adoption, various policies and incentives should be given to encourage farmers to adopt these mitigation strategies. There are several methods and equipment available for the estimation of methane emission from ruminants. However, all the techniques are not suitable in every condition. For example, SF6 technique is more suitable for grazing studies while respiration chambers and hood systems are only useful for indoor studies. At present, most of the nutritional interventions have been developed and assessed under the intensive system or they are focusing on short-term strategies; therefore, further research should, therefore, focus on both the medium and long- term options to profitably reduce the emission footprint of dairy production systems. Long term research would focus on the rumen manipulation and plant and animal breeding

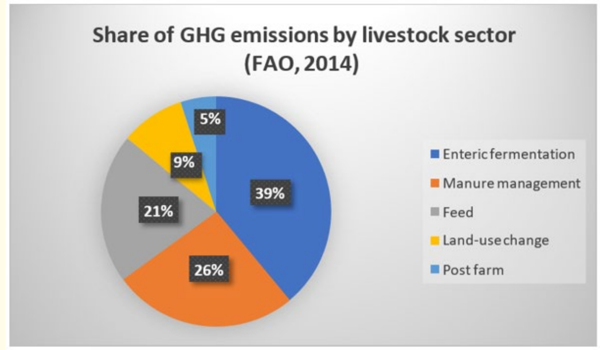

Figure 1: Share of GHG emissions by livestock sector (FAO, 2014).

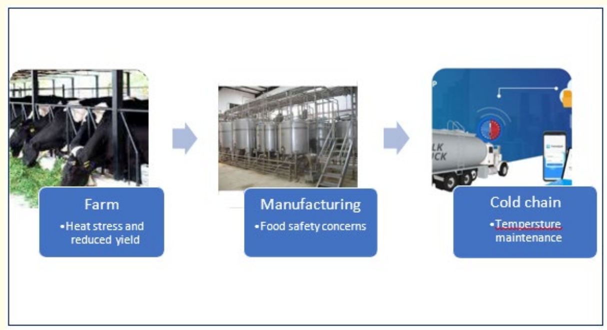

Figure 2: Dairy supply chain affected by climate change [23].

to support the future sustainability and environmental footprint credentials of the livestock system. This comprehensive approach, blending cutting-edge technology with practical farming practices and policy support, paves the way for a more sustainable and environmentally responsible future in dairy farming.

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