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Reducing Methane Emissions from Dairy and Beef Cattle and Ruminant Animals

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Introduction

Agriculture contributes more than 25% of the total greenhouse gases (GHGs) globally, and ruminant livestock animals are one of the largest contributors to these emissions, responsible for an estimated 14% of GHGs worldwide.[1] In 2016, methane emissions from enteric fermentation represented 26% of total CH_4 emissions from anthropogenic activities. Beef cattle are the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71% in 2016.[2]

There is increasing pressure from consumers and governments to reduce the GHG footprint of the beef and dairy industries, with a number of governments enacting aggressive targets for the industry by 2030. These have spurred investment in potential solutions, primarily focusing on the feed input area, that will act to lower methane output and enable dairy and beef producers to operate in a more sustainable fashion. This white paper explores potential solutions to reduce methane emissions from cattle and ruminant animals, as well as highlighting some of the challenges faced.

Enteric Methane Production Mechanism

Ruminant animals have four compartments in their stomach, of which the rumen is the largest, and houses millions of microorganisms. The microorganisms break down plant matter through fermentation to help the animal digest feed. Methane is produced through the conversion of plant matter into hydrogen (H_2) and carbon dioxide (CO2) into CH_4 by methanogens, a type of microbe. The rumen is typically filled with gases, with 45 - 75% CO_2, 20-30% CH_4, 7% N_2, and smaller amounts of O_2, H_2, N_2O, and H_2S.[3] Up to 12% of a ruminant's energy intake can be lost through the enteric methane fermentation process.[4] The amount of CH_4 released depends on the quantity and quality of its feed, the animal's health, genetics, and other environmental factors.

The type of feed animals are given affects the production of CH_4. In fact, feeds with lower hemicellulose content can lead to increased methane production. For example, pasture-raised cows consuming grasses or hay produce more enteric methane compared to fermentable concentrates (e.g. corn silage). Increasing the

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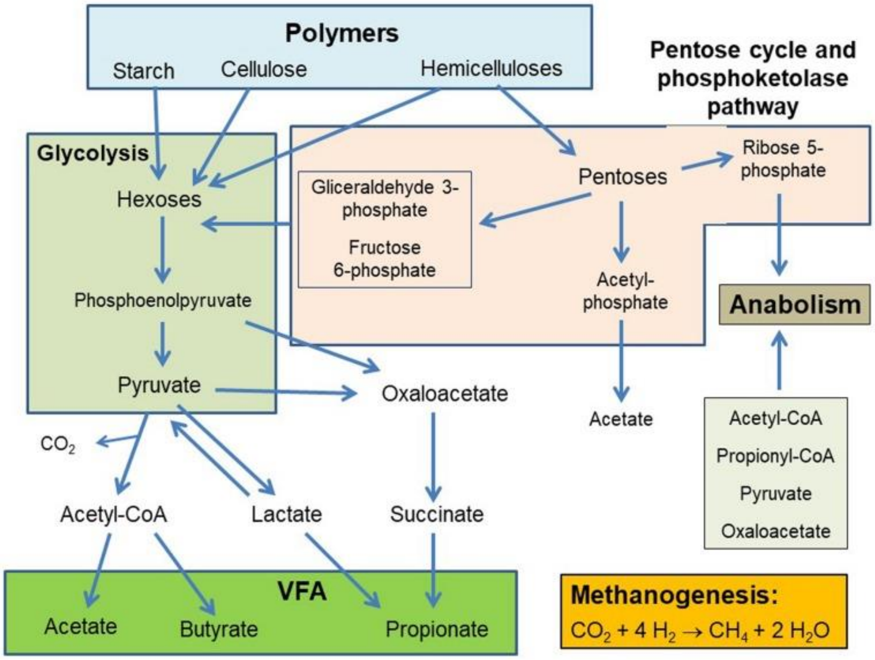
[1] F N Tubiello et al., "Agriculture, Forestry and Other Land Use Emissions by Sources and Removals by Sinks," no. 2 (2014).

[2] OAR US EPA, "Inventory of U.S. Greenhouse Gas Emissions and Sinks," Reports and Assessments, February 8, 2017, https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

[3] Byeng R. Min et al., "Dietary Mitigation of Enteric Methane Emissions from Ruminants: A Review of Plant Tannin Mitigation Options," Animal Nutrition 6, no. 3 (September 1, 2020): 231–46, https://doi.org/10.1016/j.aninu.2020.05.002.

[4] Min et al.

level of concentrate in the diet will lead to lower acetate production and increased propionate production.[5] Propionate acts as a hydrogen sink and reduces the H_2 availability for methane production. Additionally, other feed additives can be utilized to re-route these biochemical pathways, which will be explored in more detail below. The diagram below illustrates the different biochemical pathways within the rumen that lead to methanogenesis.



[6]

Methods of Measuring Enteric Methane

Accurate measurement of methane production in cattle and ruminant animals is crucial for assessing emission levels, evaluating mitigation strategies, and analyzing cattle genetics. Some of the methods used are outlined below:

1. Micrometeorological Estimates[7]

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[5] Valiollah Palangi and Maximilian Lackner, "Management of Enteric Methane Emissions in Ruminants Using Feed Additives: A Review," Animals : An Open Access Journal from MDPI 12, no. 24 (December 7, 2022): 3452, https://doi.org/10.3390/ani12243452.

[6] Emilio M. Ungerfeld, "Metabolic Hydrogen Flows in Rumen Fermentation: Principles and Possibilities of Interventions," Frontiers in Microbiology 11 (April 15, 2020): 589, https://doi.org/10.3389/fmicb.2020.00589.

[7] N. W. Tomkins et al., "Comparison of Open-Circuit Respiration Chambers with a Micrometeorological Method for Determining Methane Emissions from Beef Cattle Grazing a Tropical Pasture," Animal Feed Science and Technology, Special Issue: Greenhouse Gases in Animal Agriculture - Finding a Balance between Food and Emissions, 166–167 (June 23, 2011): 240–47, https://doi.org/10.1016/j.anifeedsci.2011.04.014.

Method: Open path lasers, combined with micrometeorological dispersion methods, are employed to capture CH_4 emissions from herds of animals. This approach facilitates whole-farm CH_4 measurements across multiple pastures. Methane concentration measurements are taken using tunable infrared diode lasers mounted on scanning units.

Challenges:

- Highly dependent on environmental factors such as wind turbulence, atmospheric stability, and source location.
- Requires continuous equipment monitoring, which can be resource-intensive.
- Installation and maintenance of equipment can be expensive.

2. Respiration Chambers[8]

Method: Respiration chambers are used to measure CH_4 at an individual animal level and provide precise measurements. Animals are housed within chambers, and environmental conditions are controlled. Gas concentrations, including CH_4 and CO_2, are measured using gas analyzers.

Challenges:

- Chambers are technically complex and require precise calibration and maintenance.
- Setting up and maintaining chambers is very expensive.
- The number of chambers and infrastructure limitations restrict the number of animals that can be measured simultaneously.
- Animals' movement and behavior are limited inside the chamber, potentially affecting feed intake and representing their natural behavior.

3. GreenFeed Machine[9]

Method: The Greenfeed^{TM} device measures short-term CH_4 emissions from individual cattle over 24 hours by attracting animals to the head chamber unit with pelleted concentrate. It utilizes an automated feeding system with CH_4 analyzers to measure CH_4 and CO_2 mass fluxes from individual cattle's breath and eructation gas.

Challenges:

- Measures CH_4 only when the animal's head is in the feeder, missing other emission events.

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[8] M. Zaman et al., "Methane Production in Ruminant Animals," in Measuring Emission of Agricultural Greenhouse Gases and Developing Mitigation Options Using Nuclear and Related Techniques: Applications of Nuclear Techniques for GHGs, ed. Mohammad Zaman, Lee Heng, and Christoph Müller (Cham: Springer International Publishing, 2021), 177–211, https://doi.org/10.1007/978-3-030-55396-8_6.

[9] Patrick R. Zimmerman and Robert Scott Zimmerman, Method and system for monitoring and reducing ruminant methane production, United States US8307785B2, filed April 14, 2011, and issued November 13, 2012, https://patents.google.com/patent/US8307785B2/en.

- The use of concentrate pellets to attract cattle may affect their digestibility, dry matter intake (DMI), and natural volatile fatty acid (VFA) profiles leading to unrepresentable results.

4. SF_6 Bolus Tracer[10]

Method: The SF_6 technique involves measuring CH_4 emissions by introducing a predetermined release ratio of SF_6 into the rumen through a permeation tube. Air around the animal's muzzle and mouth is continuously sampled and analyzed to estimate CH_4 production, allowing cattle to graze and move naturally along the pasture.

Challenges:

- Significant variation in CH_4 measurements is observed both within and among animals, making it less precise.
- The SF_6 method is more prone to equipment failures.
- Requires more manual labor compared to other methods.

5. Proxy Measurements[11]

Method: Enteric methane production (EMP) can be estimated indirectly from factors such as feed intake and diet quality. Various algorithms attempt to quantify EMP based on diet, milk composition, and feces, but estimates can vary significantly.

Challenges:

- Estimates can vary by 35% or more for a particular diet, reducing accuracy.
- Proxy measurements may not provide precise CH_4 production values.
- Not indicative of actual enteric methane production.

6. In Vitro Incubations[12]

Method: In vitro incubations involve the fermentation of rumen inoculum with a feed substrate in gastight culture bottles. Gas production is measured over time and used to estimate kinetic parameters of total gas production.

Challenges:

- Not ideal for predicting methane production in vivo.

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[10] Victoria Asselstine et al., "The Potential for Mitigation of Methane Emissions in Ruminants through the Application of Metagenomics, Metabolomics, and Other -OMICS Technologies," Journal of Animal Science 99, no. 10 (October 1, 2021): skab193, https://doi.org/10.1093/jas/skab193.

[11] Asselstine et al.

[12] Zaman et al., "Methane Production in Ruminant Animals."

- More suitable for measuring the effects of additives on fermentation factors than directly quantifying methane production.

Ultimately, there are a variety of methods, each with its own set of limitations on the accuracy of methane measurements. These need to be taken into consideration when reviewing data on feed additives or other methods of reducing enteric methane production.

Methane Reduction Technologies

Feed Additives to Reduce Methane Emissions

In addition to controlling the feed of cattle to reduce methanogenesis in the rumen, feed additives are a promising tool for reducing methane emissions. Two categories of feed additives have shown potential: methane inhibitors and rumen fermentation modifiers.

Methane Inhibitors block methane formation by targeting the methanogens that convert H_2 and CO_2 into CH_4 in the animal's rumen. They usually work by interfering with the metabolic pathways of methanogens, inhibiting key enzymes involved in the production of CH_4, or disrupting the metabolic process itself. Well-known examples of methane inhibitors include 3-nitrooxypropanol (3NOP) and bromoform found naturally in the red seaweed Asparagopsis taxiformis.

Rumen fermentation modifiers are additives that reduce methane production by altering how the animal's stomach processes its feed. One common method is for these additives to shift the activity of the microbial community and favor the growth of certain microbes while inhibiting others, such as methanogens. They can also alter the fermentation pathway to produce less methane by reducing the need for anaerobic digestion through the hydrogenotrophic pathway or increase the production of VFAs. These additives can also enhance animal productivity and health by increasing dietary protein availability. Some examples include ionophores, tannins, and essential oils.

Select Examples of Feed Additives

Feed Additive	**Method**	**Results**
Red Seaweed (*A. taxiformis*)	A. taxiformis contains bromoform, a known methane inhibitor.	Reduction in methane yield (methane production/kg of DMI) of ● up to 55% in dairy cattle[14]

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[14] H. A. Stefenoni et al., "Effects of the Macroalga Asparagopsis Taxiformis and Oregano Leaves on Methane Emission, Rumen Fermentation, and Lactational Performance of Dairy Cows," Journal of Dairy Science 104, no. 4 (April 1, 2021): 4157–73, https://doi.org/10.3168/jds.2020-19686.

	Bromoform is a halogenated alkane and blocks metalloenzymes key to the Wolfe cycle. The Wolfe cycle is the reduction of CO_2 into CH_4 by the methanogenic archaea. Bromoform can compete with coenzyme M methyltransferase for substrates and hinder the release of methane.[13]	- up to 98% in beef cattle[15] No effect on digestibility of forage[16]
3-Nitrooxypropanol (3NOP)	3NOP inhibits methyl-coenzyme M reductase (MCR), responsible for methane formation in methanogens.[17]	Decrease methane yield by - up to 36% in dairy cattle[18][19] - Up to 50% in beef cattle[20][21]
Tannins	Secondary metabolites of plants that can help protect the plant from herbivory and can bind and denature proteins. The binding of proteins leads to reduced breakdown by microbes, so more protein is broken down in the abomasum	Some tannins have shown the potential to reduce enteric methane emissions - by 13 - 16 % in dairy cattle[23] Too many tannins can lead to indigestibility by cattle leading to reduced DMI and lower performance

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[13] Christopher R. K. Glasson et al., “Benefits and Risks of Including the Bromoform Containing Seaweed Asparagopsis in Feed for the Reduction of Methane Production from Ruminants,” Algal Research 64 (May 1, 2022): 102673, https://doi.org/10.1016/j.algal.2022.102673.

[15] Robert D. Kinley et al., “Mitigating the Carbon Footprint and Improving Productivity of Ruminant Livestock Agriculture Using a Red Seaweed,” Journal of Cleaner Production 259 (June 20, 2020): 120836, https://doi.org/10.1016/j.jclepro.2020.120836.

[16] Lorenna Machado et al., “Identification of Bioactives from the Red Seaweed Asparagopsis Taxiformis That Promote Antimethanogenic Activity in Vitro,” Journal of Applied Phycology 28, no. 5 (October 1, 2016): 3117–26, https://doi.org/10.1007/s10811-016-0830-7.

[17] Dipti W. Pitta et al., “The Effect of 3-Nitrooxypropanol, a Potent Methane Inhibitor, on Ruminal Microbial Gene Expression Profiles in Dairy Cows,” Microbiome 10, no. 1 (September 13, 2022): 146, https://doi.org/10.1186/s40168-022-01341-9.

[18] A. Melgar et al., “Dose-Response Effect of 3-Nitrooxypropanol on Enteric Methane Emissions in Dairy Cows,” Journal of Dairy Science 103, no. 7 (July 1, 2020): 6145–56, https://doi.org/10.3168/jds.2019-17840.

[19] Alexander N. Hristov et al., “An Inhibitor Persistently Decreased Enteric Methane Emission from Dairy Cows with No Negative Effect on Milk Production,” Proceedings of the National Academy of Sciences 112, no. 34 (August 25, 2015): 10663–68, https://doi.org/10.1073/pnas.1504124112.

[20] D. Vyas et al., “Optimal Dose of 3-Nitrooxypropanol for Decreasing Enteric Methane Emissions from Beef Cattle Fed High-Forage and High-Grain Diets,” Animal Production Science 58, no. 6 (May 26, 2016): 1049–55, https://doi.org/10.1071/AN15705.

[21] A. Romero-Perez et al., “Sustained Reduction in Methane Production from Long-Term Addition of 3-Nitrooxypropanol to a Beef Cattle Diet1,” Journal of Animal Science 93, no. 4 (April 1, 2015): 1780–91, https://doi.org/10.2527/jas.2014-8726.

[23] S L Woodward, G C Waghorn, and P G Laboyrie, “Condensed Tannins in Birdsfoot Trefoil (Lotus Corniculatus) Reduce Methane Emissions from Dairy Cows,” Proceedings of the New Zealand Society of Animal Production 64 (2004).

	(acidic compartment of the stomach)[22]	
Nitrates	Nitrates have higher affinity for H_2 than methanogens and can bind to H_2 before methanogens ferment to produce CH_4	Nitrate supplementation has been found to reduce methane emissions by ● up to 16% in dairy[24] ● Up to 12% in beef cattle[25] Nitrate,can be converted to nitrite which is toxic to ruminants if the level is too high or exposure is too long, thus requiring close monitoring of nitrate in the diet.
Essential Oil Complex (eg. garlic, citrus, coriander, etc.)	Essential oils extracted from secondary plant metabolites that are known to have antioxidant and immunological properties. Essential oils can inhibit the growth of methanogenic archaea and stimulate other rumen microbes that contribute to rumen fermentation.	One example is Agolin, a commercially available essential oil complex. At 1g/day of Agolin, methane intensity was reduced ● 11% reduction in methane intensity[26] ● Other trials found 6% and up to 20% reductions in methane intensity and increases in milk yield[27] ● This likely requires a 4-week adaptation period for Agolin to be effective[28]
Probiotics & Prebiotics	Probiotics are beneficial active microorganisms that influence activities of the ruminal microorganisms and inhibit CH_4 production. Prebiotics are substances that are not easily digested and can stimulate the growth of certain ruminal microorganisms to	● Lactic acid bacteria is a commonly used feed additive that has been shown to reduce CH_4 emissions per unit volatile fatty acid ● Acetic acid bacteria has been show to reduce the number of methanogens in the rumen

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[22] Min et al., “Dietary Mitigation of Enteric Methane Emissions from Ruminants.”

[24] S. M. van Zijderveld et al., “Persistency of Methane Mitigation by Dietary Nitrate Supplementation in Dairy Cows,” Journal of Dairy Science 94, no. 8 (August 1, 2011): 4028–38, https://doi.org/10.3168/jds.2011-4236.

[25] C. Lee et al., “Effects of Encapsulated Nitrate on Growth Performance, Nitrate Toxicity, and Enteric Methane Emissions in Beef Steers: Backgrounding Phase1,2,” Journal of Animal Science 95, no. 8 (August 1, 2017): 3700–3711, https://doi.org/10.2527/jas.2017.1460.

[26] Angelica V. Carrazco et al., “The Impact of Essential Oil Feed Supplementation on Enteric Gas Emissions and Production Parameters from Dairy Cattle,” Sustainability 12, no. 24 (January 2020): 10347, https://doi.org/10.3390/su122410347.

[27] Kenton J. Hart et al., “An Essential Oil Blend Decreases Methane Emissions and Increases Milk Yield in Dairy Cows,” Open Journal of Animal Sciences 9, no. 3 (May 8, 2019): 259–67, https://doi.org/10.4236/ojas.2019.93022.

[28] Alejandro Belanche et al., “A Meta-Analysis Describing the Effects of the Essential Oils Blend Agolin Ruminant on Performance, Rumen Fermentation and Methane Emissions in Dairy Cows,” Animals 10, no. 4 (April 2020): 620, https://doi.org/10.3390/ani10040620.

	compete with methanogens for H_2	
Melatonin	Melatonin lowers VFA production, thereby reducing the raw material for CH_4 synthesis. It also inhibits protozoa populations to hinder the symbiotic relationship between methanogens and protozoa in the rumen.	One study spanning 24 days providing 15 mg/day of melatonin illustrated: ● Cows treated reduced methane from their respiration by approx. 50%[29]
Ozone (O_3) treatment	Ozone is highly oxidative and volatile and can reduce enteric methanogenesis through interactions with archaea, bacteria, feed, and oxygen.[30]	In vitro study of rumen fluid and microbiota found that O_3 treatment: ● Decreased CH_4 production by up to 20% ● Decreased total gas content by 15%[31]

Numerous companies in this sector are researching feed additives and supplements aimed at mitigating methane emissions. One of the most established feed additives is Bovaer, produced by DSM, which gained market approval in early 2022 and has been adopted on farms in over 40 countries including through the EU. Bovaer's primary active component is 3-NOP, and large-scale farm trials have shown methane reductions of 30-50%. Another noteworthy example is Mootral, a Swiss startup that has developed a proprietary feed additive featuring an essential oil complex to diminish methane emissions. Similar to other essential oil inputs, it selectively targets archaea populations, thereby reducing methane-producing archaea. When administered to steers at a rate of 15g/day and measured using a GreenFeed machine, Mootral lowered methane emissions by 23% during the 12th week of supplementation, although the overall methane yield (g/kg DMI) remained unchanged. [32][33] Other startups are also exploring seaweed-based feed supplements, claiming potential methane reductions ranging from 70% to 90%. Two such companies are CH4 Global, based in Australia, and Volta Greentech, headquartered in Sweden.

These examples illustrate the diverse array of novel approaches for reducing enteric methane emissions through feed additives. Nevertheless, several challenges accompany this strategy. Firstly, it is crucial to validate the effectiveness of these feed additives in reducing methane output, which can be accomplished

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[29] Yao Fu et al., "Effects of Melatonin on Rumen Microorganisms and Methane Production in Dairy Cow: Results from in Vitro and in Vivo Studies," Microbiome 11, no. 1 (August 29, 2023): 196, https://doi.org/10.1186/s40168-023-01620-z.

[30] Lucy Zhao et al., "Ozone Decreased Enteric Methane Production by 20% in an in Vitro Rumen Fermentation System," Frontiers in Microbiology 11 (2020), https://www.frontiersin.org/articles/10.3389/fmicb.2020.571537.

[31] Zhao et al.

[32] Johanna Brede et al., "Long-Term Mootral Application Impacts Methane Production and the Microbial Community in the Rumen Simulation Technique System," Frontiers in Microbiology 12 (October 8, 2021): 691502, https://doi.org/10.3389/fmicb.2021.691502.

[33] Breanna M. Roque et al., "Effect of Mootral-a Garlic- and Citrus-Extract-Based Feed Additive-on Enteric Methane Emissions in Feedlot Cattle," Translational Animal Science 3, no. 4 (July 2019): 1383–88, https://doi.org/10.1093/tas/txz133.

through extensive pilot testing or more precise methane emission measurement technologies. There are very clear differences in the effectiveness of different approaches. Additionally, since these are feed additives, gathering data on their impact on factors such as Feed Conversion Ratio (FCR), milk yield, milk quality, beef quality, and potential implications for animal and human health is essential. Several companies have attempted to move through this quickly, and are therefore likely to struggle with customer uptake as these are crucial parameters that cannot be sacrificed on.

Assuming the scientific aspects are confirmed, the next hurdle is the commercial challenge—determining who will bear the cost of this technology. One prominent example of an effective commercial incentive is using a plus/minus mechanism on milk payments to incentivize methane reductions at the farmer level. Arla is the first dairy company to employ this strategy. Nonetheless, pricing remains a fundamental concern, as the adoption of this technology must be financially neutral or advantageous for farmers.

Genetic Approaches

Another method often explored to reduce methane emissions is through cattle genetics, aiming to identify breeds with lower emissions. This approach may necessitate improvements in enteric methane measurements to more accurately select cows with lower methane emissions. For example, there is a strong focus on milk solids in NZ with Jersey and Jersey cross cows featuring prominently. These smaller animals have a higher milk solid content and lower methane output than Holsteins and many European varieties. These are, therefore, more attractive on a methane per kg of milk solids metric.

The application of new omics technology, such as metagenomics and metabolomics, enables the identification and evaluation of the underlying functional biology of relevant traits.[34] Additionally, a deeper understanding of the relationship between host phenotypes and microbial diversity and density in the rumen can help pinpoint the genetic processes controlling methane production.

While there is potential in this area, it is a costly and time-intensive process due to the extended reproductive cycle of cattle required to create a new breed. In some cases, the genetic breeding process, without genetic modification, can span several years, if not decades. Moreover, it is essential to consider trade-offs with desirable production traits in genetic breeding.

For some ruminant animals, breeding for reduced CH_4 emissions has proven effective, as demonstrated in a 10-year study in New Zealand in sheep. Low CH_4 sheep exhibited benefits such as increased wool growth, smaller rumens with distinct microbiomes, leaner body composition, and a different fatty acid profile in muscle tissue, contributing to greater economic sustainability than high CH_4 sheep.[35]

Furthermore, a study by Difford et al. found that individual variation in CH_4 production was influenced by the host (cow) genotype and the host's rumen microbiome composition. Specific bacteria and archaea taxa were

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[34] Asselstine et al., "The Potential for Mitigation of Methane Emissions in Ruminants through the Application of Metagenomics, Metabolomics, and Other -OMICS Technologies."

[35] Suzanne Rowe et al., "Selection for Divergent Methane Yield in New Zealand Sheep - A Ten Year Perspective," 2019.

influenced to some extent by the host's genotype, and certain taxa were associated with CH_4 emissions. The cumulative effect of all bacteria and archaea on CH_4 production was 13%, while host genetics (heritability) accounted for 21%, and these factors appeared to be largely independent.[36] Based on these findings, it is likely that modulating CH_4 emissions is more effectively achieved by manipulating the rumen microbiome rather than solely relying on cow genetics.

Nonetheless, there are companies focused on reducing enteric methane through precision breeding. Vytelle is an Australian company that has proprietary IVF and analytics data that can help producers make more efficient and sustainable breeds. Another example is Semex, a genetics company that has sold low-methane cattle semen to farms in the US, UK, Slovakia, and Canada. It claims it can reduce methane emissions by 1.5% annually with its genetic breed.

Other approaches

In addition to strategies around feed supplements and genetics, there are companies developing entirely different approaches to reduce methane emissions. One example is Zelp, a company that produces methane-absorbing wearable devices for cows to convert CH_4 to CO_2. While an interesting approach that eliminates many of the challenges associated with feed additives, there are concerns around logistics, because similar to other cattle wearables, cows are likely to damage or remove the masks. Moreover, this approach has a large initial cash and maintenance costs that are unlikely to be absorbed by farmers or producers at this stage.

There are also a range of farm management practices that can be used to lower methane emissions on cattle farms, such as employing better grazing and grassland management strategies or using methane digesters, which can decompose organic waste into biogas. However, these strategies are focused on the methane from cattle manure, which only accounts for 10% of the methane emissions.

Conclusion

Arguably the largest threat to the beef and dairy industries is their current GHG footprint. Whilst initially driven by consumer sentiment, governments are in the process of enacting ever-stricter environmental regulations and requirements that can have a significant impact on farm profitability and viability. Within this, methane output is the primary target. Farms and processors are increasingly looking for solutions to tackle this issue, with this stimulating increasing R&D into potential solutions. DSM with its Bovaer product is a real first mover in this space, but many more will follow. It is very likely that a range of potential inputs, technologies and methodologies will be required to tackle this challenge, creating an exciting period of innovation for the industry.

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[36] Gareth Frank Difford et al., "Host Genetics and the Rumen Microbiome Jointly Associate with Methane Emissions in Dairy Cows," PLoS Genetics 14, no. 10 (October 2018): e1007580, https://doi.org/10.1371/journal.pgen.1007580.