RESPONSIBLE CLIMATE ACTION IN DAIRY AND BEEF

Evaluating Enteric Methane Solutions for Supply Chain Adoption

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EXECUTIVE SUMMARY

Reducing methane emissions from human activities is widely recognized as one of the most effective opportunities to slow the rate of near-term climate warming (Ocko et al., 2021). Because agriculture is one of the largest sources of anthropogenic methane emissions globally, increasing attention has focused on strategies to reduce enteric methane produced by dairy and beef cattle. A rapidly expanding pipeline of enteric methane solutions is creating new opportunities to reduce emissions from dairy and beef production. These solutions include feed additives and ingredients, emerging biological and technological interventions, and complementary management approaches. However, these strategies can vary considerably in reduction efficacy, strength of supporting evidence, productivity implications, and trade-offs and risks linked to the health and safety of the animals, consumers and the environment. As innovation accelerates, companies and value chain actors are increasingly challenged to distinguish solutions that are ready for commercial deployment from those that require additional validation.

Environmental Defense Fund (EDF) presents this report to support responsible climate action by highlighting key considerations for evaluating enteric methane solutions before supply chain implementation. This report is a practical resource for dairy and beef value chain actors who are considering the adoption of enteric methane reducing solutions in their supply chains to reduce their carbon footprint. These value chain actors may include producers, processors and cooperatives, packers and manufacturers, and retailers and food service companies. The report lays out factors related to methane efficacy, animal performance, safety considerations and regulatory oversight. It also shares critical questions that can help decision-makers assess the readiness, risks, and opportunities associated with different enteric methane solutions. The report is largely grounded in U.S. production and regulatory systems, but the considerations it outlines will also be useful to companies operating globally as they evaluate the same highlighted strategies.

Key takeaways

- **Credible climate action depends on scientific rigor.**
  Not all enteric methane solutions are backed by the same level of scientific validation, safety data or regulatory oversight. Evaluation is essential to ensure methane reductions are credible, durable, and deployable at scale.

- **Methane reduction alone is not enough.**
  Enteric methane solutions should be evaluated not only on methane-reduction potential, but also on impacts to animal productivity, animal health, food safety, environmental outcomes and practical deployment within dairy and beef production systems.

- **Dairy and beef value chain actors can help close the gap between innovation and implementation.**
  Dairy and beef value chain actors can accelerate the development and adoption of enteric methane solutions by supporting research, regulatory data generation, pilot testing and producer engagement, while also reinforcing science-based standards.

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BACKGROUND

Methane is a potent greenhouse gas with more than 80 times the warming power of carbon dioxide over the first 20 years after it reaches the atmosphere. Within agriculture, livestock contribute a substantial share of methane emissions, primarily through enteric fermentation and, to a lesser extent, manure management. Heightened urgency for climate action in food and agriculture has driven the development of novel enteric methane reducing solutions for dairy and beef cattle, including feed additives such as 3-nitrooxypropanol (3-NOP) and red seaweed. Climate urgency has also increased interest in characterizing the methane-reduction potential of existing feed ingredients, including tannin-containing forages, lipids, and probiotics. Beyond diet and feed additives, additional emerging interventions include anti-methanogenic vaccines, wearable methane-oxidizing muzzle masks, and low-methane genetic selection. While new enteric methane mitigation technologies continue to emerge, foundational management practices remain critical to improving both productivity and environmental performance. High-quality diets, optimized nutrient balance and ration formulation, strong animal health programs and effective reproductive management provide the foundation for efficient and sustainable dairy and beef production and should be considered alongside any methane mitigation strategy.

As the number and diversity of enteric methane reducing solutions increases, stakeholders across the dairy and beef value chain — including producers, cooperatives, processors, packers, retailers, and food service companies — have become increasingly engaged in evaluating their potential role in broader sustainability strategies. These dairy and beef value chain actors are seeking credible solutions that can contribute to climate goals while maintaining animal performance and food safety as well as supporting producer adoption. The growing focus on enteric methane is exemplified by initiatives such as EDF's Dairy Methane Action Alliance, a global coalition of dairy companies committed to publicly disclosing methane emissions and advancing reduction strategies across their supply chains.

As stakeholders evaluate a growing range of methane mitigation options, understanding how to critically assess the evidence supporting methane reduction claims is essential for informed decision-making. Not all claims should be interpreted equally, as the credibility and relevance of reported reductions depend on factors such as study design, study duration, methane measurement methodology, and applicability to commercial production systems. At the same time, enteric methane solutions should not be evaluated solely on their ability to reduce methane emissions. Decisions regarding adoption should also consider impacts on animal productivity, health and welfare, food safety, and broader environmental outcomes. Furthermore, stakeholders should assess not only the magnitude and durability of methane reductions achieved, but also their effects on animal performance, safety for animals and consumers, and feasibility under commercial conditions.

Moving enteric methane solutions from discovery to commercial readiness can be complex. As innovation accelerates, companies and value chain actors need clear guidance to distinguish near-term, deployable solutions from those that remain earlier in development. Regulatory pathways play an important role in shaping both the strength of evidence supporting product claims and the confidence stakeholders can place in their adoption. However, the regulatory landscape for enteric methane solutions in the United States (and globally) continues to evolve, and pathways for product authorization are not always clear.

Against this backdrop, EDF presents this report to highlight key factors that companies and value chain actors should consider when evaluating enteric methane solutions. The report focuses on assessing the readiness of enteric solutions for implementation by posing critical questions related to strength of evidence of methane reduction, animal performance and safety implications for animals, consumers and the environment. These questions can then inform decision-making prior to adoption within dairy and beef supply chains. Within this context, the report also highlights opportunities to support both solution providers and producers throughout the innovation-to-implementation pipeline.

CONSIDERATIONS FOR ENTERIC METHANE SOLUTIONS

Dissecting an Enteric Methane Claim

Table 1 highlights common ways research findings can be misinterpreted or over-generalized, and outlines what to look for when critically reviewing published methane reduction claims. While every study adds value to the evidence base, maintaining a grounded and context-driven perspective is critical when interpreting results.

- *In vitro* studies are conducted outside of a living animal in a laboratory setting. For enteric methane research, this often means using rumen simulation systems or labbased models.
- *In vivo* studies are conducted in living animals. These studies measure methane emissions, animal health, and performance under real biological conditions.

TABLE 1

Research Interpretation Checkpoints and Insights for Methane Mitigation Claims

Translation to Real-World Animal Performance

CHECKPOINT: Are claims based on live-animal (in vivo) evidence at the proposed level of intervention/dosage?

INSIGHT: Findings generated from modeled systems or laboratory environments can inform early research but do not always translate to whole-animal outcomes under commercial conditions.

Look for findings validated in live-animal (in vivo) studies conducted at the proposed intervention level or dosage, rather than relying solely on modeled or in vitro data.

Credibility of Methane Measurement

CHECKPOINT: Are methane reduction claims substantiated by robust measurement methods?

INSIGHT: Methane emissions are highly variable throughout the day, and methane concentration alone does not indicate how much methane an animal emits.

Look for studies that measure methane ***flux*** *(actual methane emissions released over time) rather than concentration alone, and that use sampling protocols capturing daily variation rather than limited spot measurements. Independent scientific review of the methodology can provide additional confidence in reported reductions.*

Relevance of Study Duration to Commercial Use

CHECKPOINT: Do study timelines reflect how the product would actually be used in beef or dairy systems?

INSIGHT: Short-term trials may not capture biological adaptation or sustained responses over a full production cycle.

Considerations Beyond Methane

Safety implications across consumers, the environment, animals and handlers require direct evaluation of enteric solutions rather than reliance on literature-based assumptions or non-peer-reviewed research. There should be significant scientific evidence demonstrating that in addition to being safe for the animal, inclusion at the specified dose:

- does not compromise the safety of animal-derived food products for consumers
- poses no risk to individuals handling the product (ie. manufacturers, farmers)
- does not introduce unintended environmental consequences

Animal safety should be demonstrated both at the intended use level and at elevated inclusion rates (e.g., up to double the proposed dose). Assessments should encompass tolerance, health status, production performance, and relevant clinical measures to establish appropriate safety margins.

Consumer safety requires careful assessment of animal-derived food products for residual compounds associated with enteric solutions that could pose acute or long-term health risks. Appropriate toxicological evaluations, including genotoxicity and mutagenicity testing where warranted, are important to ensure food safety.

Handler safety is a key consideration that extends beyond animals and consumers to include farm workers, feed manufacturers, transporters, and others involved in storing, mixing, applying, or handling enteric solutions. Potential risks may arise through inhalation, dermal contact, or accidental ingestion during routine operations.

Environmental safety may be compromised by residues from enteric solutions entering agricultural and environmental systems through animal excreta and other pathways. These residues may affect nutrient cycling, fertilizer value, soil health, water quality, crop safety, and the food chain, while also raising broader environmental and human health concerns.

Table 2 outlines a checklist for evaluating the completeness, safety, and substantiation of enteric solutions. Key questions persist regarding effective dosage levels, consistency of methane reduction responses, practical on-farm delivery methods, and impacts on animal performance and productivity. With this information provided, companies and value chain actors can more effectively assess readiness, identify gaps and determine where targeted support could responsibly advance innovation.

TABLE 2

Beyond the Claim: Due Diligence Checklist for Enteric Solutions

How will it be used?	1. The target species or class, inclusion levels or doses, and duration of use should be clearly specified. 2. The intended use and corresponding label claims should be explicitly defined. 3. Inclusion rate characterization across representative diets and management systems should be described.
Are the findings based on primary data collection?	This clarifies whether conclusions are supported by original measurements or rely solely on existing literature.
Is it safe for cattle?	Safety studies should be conducted in cattle both at the intended use level and at elevated inclusion levels (e.g., up to double the proposed dose), incorporating assessments of tolerance, health, performance and relevant clinical parameters to establish appropriate safety margins.
Is the duration of study sufficient to evaluate sustained effectiveness?	Studies in target animals should demonstrate outcomes over biologically and commercially relevant timeframes (e.g., ≥90 days or representative production phases).
Are animal productivity outcomes adequately captured and reported?	Animal productivity parameters, including feed intake, weight change and milk production (when applicable) should be collected and reported alongside methane measurements.
Does the use of this product pose any safety risks to handlers, farm workers or consumers of resulting dairy and beef products?	Human food safety assessment should include an in-depth look at any mutagenic and carcinogenic potential of the residues/metabolites as well as any contaminants. Assessment should also consider if it is safe for front end users (i.e., producers) to be handling it.
What's the environmental impact beyond enteric methane?	Assessment should consider the full environmental footprint of the solution, including impacts associated with manufacturing, use, and the fate of excreted residues or metabolites. Potential effects on soil health, water quality, nutrient cycling, manure management and ecosystem health should be evaluated, along with any unintended increases in other emissions, particularly nitrogen-related emissions such as ammonia or nitrous oxide.
Is there any impact on the taste profile of the end dairy or beef product?	While impacts to taste profile do not hold regulatory weight, they are still relevant to supplychain acceptance and market viability.

Regulatory Landscape for Enteric Solutions

There is no global consensus on how enteric solutions should be classified, assessed for safety, or authorized for use. This situation results in substantial variation across and within jurisdictions. As the regulatory landscape continues to evolve, it is important for solution providers, companies and other value chain stakeholders to understand the pathways that may apply to enteric methane solutions, and the corresponding evidence expectations. Regulatory oversight plays an important role in evaluating safety, product quality and intended use, while helping to safeguard animal health, environmental integrity and consumer safety.

A central principle of regulatory oversight is that products are evaluated according to their intended use. For enteric methane solutions, the intended use is the reduction of enteric methane emissions, and this intended purpose defines the context in which a product is assessed and the claims that can be supported by available evidence. This distinction is important because regulatory approval is tied to the conditions under which safety and efficacy have been demonstrated. Use beyond the approved purpose may not be supported by evidence and could introduce unassessed risks or uncertainties for animals, consumers, the environment or the broader value chain. Currently, the Food and Drug Administration (FDA) reviews enteric methane solutions under existing animal feed or animal drug authorities on a case-by-case basis, as no dedicated regulatory category exists for these products. Authorization generally requires evidence of effectiveness for enteric methane reduction under intended-use conditions, animal safety, product quality, and food safety.

At the same time, some feed additives and ingredients have previously obtained Association of American Feed Control Officials (AAFCO) recognition or Generally Recognized as Safe (GRAS) status for purposes such as improving growth performance or milk production. However, neither AAFCO ingredient definitions nor the GRAS framework were designed to evaluate efficacy claims related to enteric methane reduction. Ideally, solution providers would pursue FDA regulatory pathways that have frameworks to ensure responsible climate action with thorough assessment of the safety implications. In practice, however, solution providers often face significant financial barriers and lack the resources required to conduct the studies necessary to generate the robust data required for regulatory review. As a result, they may seek regulatory pathways that require different types or amounts of supporting evidence while continuing to build research portfolios related to methane reduction.

FDA regulatory pathways do include mechanisms that permit investigational use prior to full approval. As enteric methane solutions advance through development and require larger-scale studies under commercial conditions, solution providers may seek an Investigational Food Use Authorization (IFUA) from FDA. An IFUA allows the limited use of an investigational product in animals entering the food supply for the purpose of generating data to support regulatory review. IFUAs are not a substitute for commercial approval; rather, they provide a mechanism for conducting research under regulatory oversight while managing food safety considerations. Depending on the product, this may include requirements related to product accountability, residue monitoring, withdrawal periods and the handling or disposal of animal-derived products. When used appropriately, IFUAs can help bridge the gap between controlled research and commercial authorization while maintaining protections for animals, consumers and the food supply.

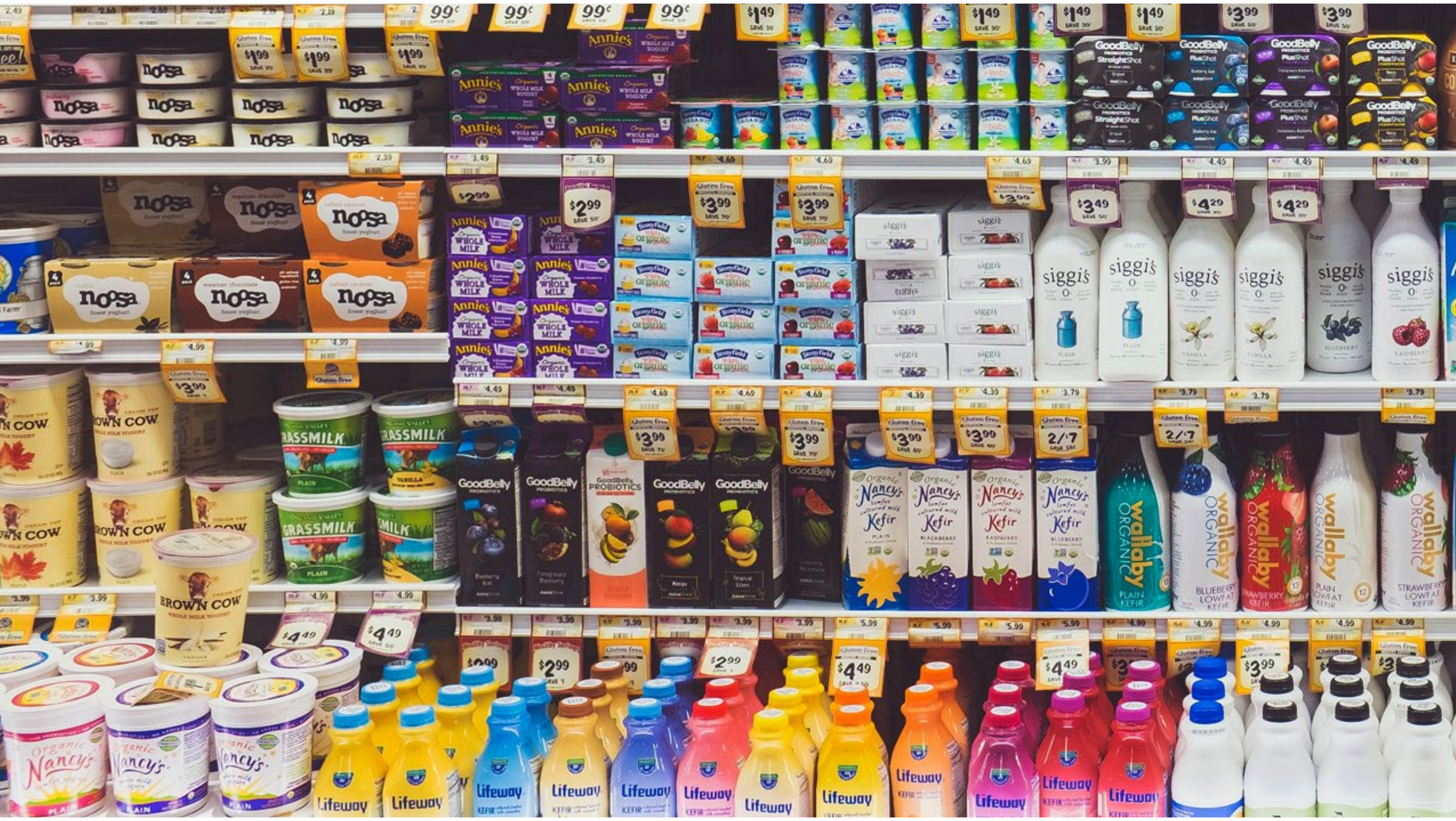
Regulation of Enteric Methane Mitigating Feed Additives

The governance bodies that regulate feed additives are the U.S. Food and Drug Administration (FDA) and Center for Veterinary Medicine (CVM).

The proposed Innovative Feed Enhancement and Economic Development (Innovative FEED) Act of 2025 (H.R. 2203) would establish a new pathway for regulating these products as zootechnical animal food substances, defined as feed additives intended to reduce foodborne pathogens, decrease byproducts such as enteric methane or affect the gut microbiome. The legislation would also streamline the approval process for these products by allowing them to be reviewed through the existing Food Additive Petition pathway rather than the New Animal Drug Application process.

Regulation of Enteric Methane Mitigating Vaccinations

Approval for vaccines has historically been managed by the U.S. Department of Agriculture when intended to prevent, treat or control disease. However, vaccines developed for other purposes may fall under FDA jurisdiction, and the appropriate regulatory pathway for enteric methane vaccines remains an evolving area.



ENTERIC SOLUTIONS MATRIX

TABLE 3

Comparative Assessment of Enteric Methane Reduction Technologies

This matrix is limited to available public data on each enteric solution

	SCIENCE				SAFETY	REGULATORY
ENTERIC METHANE REDUCING SOLUTION	Evidentiary strength as a CH_4 reduction tool	Demonstrated absolute CH_4 reduction	Dairy production impacts	Beef production impacts	Of concern under intended use	Approved to feed for enteric methane reduction (intended use)
Feed Additive and Ingredients						
3-Nitrooxypropanol (3-NOP)	★★★	Medium	• May increase milk fat and true protein but reduces feed intake and milk yield, with mostly neutral effects on feed efficiency. • Intake and yield reductions are less pronounced in higher fiber-to-concentrate diets but become more severe at higher doses.	• May increase feed efficiency driven by reductions in feed intake but additional improvements in growth or carcass output are inconsistent.	✓	Reduction claim allowed for dairy cows (EU/UK/CA); Acknowledged in US under FDA discretion
Biochar	★	No effect	• May increase fiber and protein digestibility in cattle consuming low-quality forage.	• May reduce feed intake, average daily gain and carcass weights in finishing steers.	Not fully evaluated	✗
Bromoform (Asparagopsis and synthetic)	★★★	High	• May reduce feed intake, milk yield, and milk components.	• May reduce feed intake without rendering a reduction in production.	Consumer, Animal, Environment	✗
Direct-fed Microbials (DFM)	★	No effect/Low	• May increase efficiency, milk yield, and milk components.	• May increase feed intake and digestibility that inconsistently translate to increases in performance variables.	Not fully evaluated	✗
Essential oils	★★	No effect/Low	• May increase efficiency, milk yield, and milk components.	• Limited evidence of impacts. • May increase feed intake and average daily gain.	Not fully evaluated	✗
Ionophores	★★	Low	• May reduce feed intake while improving the efficiency of energy use resulting in increased milk yield and components, and increased efficiency.	• May reduce feed intake while mproving energy utilization, leading to improvements in efficiency and, in many cases, average daily gain.	Consumer, Animal, Environment	✗
Lipids	★★	Low	• May improve milk fat quality by increasing unsaturated fatty acids but high inclusion rates and/or certain lipid sources can lower milk fat yield by impairing rumen fibre digestion	• May increase performance while in some cases modifying the fatty acid profile of meat.	✓	✗
Nitrates	★★	Low/Medium	• May increase efficiency but also may decrease milk protein production.	• No impacts.	Animal, Environment	✗
Tannins	★★	Low	• May increase or decrease dry matter intake, milk yield, or milk composition.	• May reduce fiber digestibility, although current evidence does not indicate consistent negative effects growth performance.	Animal	✗
Husbandry						
Diet optimization	★★★	Low/Medium	• Increases digestibility (through improved forage quality and an appropriate forage-to-concentrate ratio) and balancing amino acid requirements while reducing crude protein, leads to improvements in productivity and animal health, and reduces environmental impacts.		✓	Not a claim bearing product
Early life programming	★★	Low	• Early stage research.	• Early stage research.	Consumer, Animal, Environment	✗ Management practice that will vary by claim bearing product
Genetic selection: Methane Phenotypes	★★	Low	• Early stage research.	• Early stage research.	Not fully evaluated	Not a claim bearing product but exporting of genetics (ie semen, embryos) requires signficant regulatory complaince
Vaccinations						
Vaccination: Salivary antibodies	★★	Low	• Early stage research.	• Early stage research.	Not fully evaluated	✗
Wearable Technology						
Methane oxidizing mask	★	Low/Medium	• No impacts.	• No impacts.	✓	NA

Evidentiary Strength

- ★★★ High confidence (consistent & repeatable)
- ★★ Moderate confidence (emerging or mixed)
- ★ Low confidence (limited or early evidence)

CH_4 Reduction (Daily)

- High (>50%)
- Medium (20-50%)
- Low (5-20%)
- No effect (<5%)
- No Data

Safety Icon Key

- Consumer
- Animal
- Environment
- ✓ No significant concern after evaluation

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Glossary of terms for Enteric Solutions Matrix

Evidentiary Strength: The evidentiary strength is based on the availability of peer-reviewed evidence of being an effective methane reduction solution.

★ **Low confidence (exploratory):** Methane reductions demonstrated only in vitro or not at all, with no in vivo validation to date; dosage is preliminary, poorly defined, or not yet applicable.

★★ **Moderate confidence (emerging evidence):** Clear methane reductions observed in vitro, with limited, inconsistent, or shortterm in vivo evidence; dosage is illdefined to moderately defined (when applicable).

★★★ **High confidence (established efficacy):** Consistent and reproducible in vivo methane reductions observed at clearly defined and repeatable dosages (when applicable), under practical feeding or production conditions.

Demonstrated Absolute CH_4 Reduction: Demonstrated CH_4 reduction denotes the typical percent (%) reduction in enteric methane production (g/day) observed under controlled feeding conditions in dairy and beef cattle compared to a control group in published, peer-reviewed literature: low (<20%), medium (20–45%), or high (>50%).

Dairy and Beef Production Impacts: Changes in performance and production variables including dry matter intake, feed conversion efficiency, average daily gain, and milk yield compared to a control group in published, peer-reviewed literature.

Safety: Safety considerations for enteric solutions are a critical piece of responsible deployment. Within the provided enteric matrix, , , and are symbols to represent consumers, animals and the environment, respectively.

These symbols are included in the Safety column when potential risks have been identified or hypothesized and require further investigation.

A designation of indicates that, based on the currently available scientific evidence, no significant concerns have been identified for consumers, animals or the environment. A designation of **Not Fully Evaluated** indicates that no major concerns have been raised to date, but the solution has not yet undergone a comprehensive safety assessment under its intended conditions of use. As a result, additional research may be needed to fully characterize potential risks and to establish confidence in its safe deployment.

Reducing enteric methane emissions is only one dimension of evaluating an enteric methane solution. While methane represents an energetic loss to the animal, inhibiting methanogenesis does not function as a simple "off switch" that automatically redirects energy toward milk production, growth, or feed efficiency. The biological response depends on the complex interactions among rumen fermentation, nutrient utilization and host metabolism.

Regulatory status: A check '' denotes that the solution is federally recognized as an methane-inhibiting product, and not as a standard ingredient.

FEED ADDITIVES AND INGREDIENTS AS ENTERIC SOLUTIONS

3-Nitrooxypropanol (3NOP)

The synthetic compound 3-nitrooxypropanol (3NOP; marketed as Bovaer® through Elanco Animal Health) directly inhibits methanogenesis, the microbial production of methane in the rumen. Meta-analyses of 17 beef cattle studies and 14 dairy cattle studies have demonstrated average reductions in absolute enteric methane emissions of 36% in beef cattle and 32% in dairy cattle (Kebreab et al., 2023, de Oliveira et al., 2026). To achieve these reductions, Bovaer® must be uniformly incorporated into a formulated ration and consumed consistently throughout the day, making it particularly well suited for confined animal feeding operations rather than more extensive grazing systems (Melgar et al., 2020; Hristov et al., 2015).

Bovaer® is currently the only feed additive in the United States approved by the FDA for the mitigation of enteric methane emissions. However, despite demonstrated methane reductions in both beef and dairy cattle, its approval is limited to lactating dairy cattle. Regulatory approval requires efficacy and safety data to be generated within the target animal class, and only under limited circumstances can data be extrapolated across production groups; consequently, Bovaer® is not currently an approved enteric solution for U.S. beef cattle.

Biochar

Biochar is a carbon-rich material with a characteristic porous structure. The structure is produced through pyrolysis, a process in which organic feedstocks, such as crop residues and food-processing byproducts, are exposed to high temperatures under limited or no oxygen conditions (Manikandan et al., 2023). Traditionally used as a soil amendment because of its stability and theoretical ability to influence biological dynamics, biochar has also been investigated as a feed additive in ruminant diets. Its use as a digestive and metabolic aid is based on proposed mechanisms including the adsorption of toxins, the modulation of rumen microbial communities and the improvement of nutrient absorption that may enhance animal health and feed utilization (Kazemi, 2025).

The proposed ability of biochar to alter rumen microbial communities has also led to interest in its potential to influence methanogenesis and reduce enteric methane emissions. However, evidence supporting consistent and biologically meaningful methane mitigation remains limited. Across both beef (Winders et al., 2019; Sperber et al., 2022) and dairy cattle (Dittman et al., 2024; Terler et al., 2023), reported reductions in enteric methane emissions have generally been inconsistent or negligible. The largest *in vivo* reductions reported to date, approximately 9–13%, were observed in beef steers fed in confinement; however, the same biochar source failed to reduce methane emissions when evaluated in grazing heifers (Martinez-Fernandez et al., 2024). Interpretation of these contrasting findings is complicated by differences in treatment delivery, the use of different methane measurement techniques between experiments and a lack of reported dietary chemical composition data.

Bromoform

Bromoform is a halogenated compound that occurs naturally at high concentrations in some red seaweeds. It has emerged as one of the most extensively investigated enteric methane mitigation compounds. Research has focused on both seaweed-based products, primarily *Asparagopsis armata* and *Asparagopsis taxiformis*, and purified or synthetic bromoform formulations. Across these delivery methods, bromoform has consistently demonstrated substantial methane-reducing efficacy, with reported reductions ranging from 25 to 65% in dairy cattle (Roque et al., 2019; Krizsan et al., 2023) and up to 95% in beef cattle supplemented with *Asparagopsis* species (Cowley et al., 2024), and near-complete suppression of methane production in growing beef cattle receiving synthetic bromoform (Kelly et al., 2025). However, evidence suggests that the methane mitigating effects of *Asparagopsis* may not be attributable solely to bromoform, as whole-seaweed biomass has been shown to produce greater methane reductions than equivalent doses of purified bromoform within study. This indicates that additional unidentified bioactive compounds may contribute to its anti-methanogenic activity (Ahmed and Nishida, 2024). Conversely, the use of whole-seaweed products introduces challenges in standardization, as bromoform concentrations can vary substantially with seaweed genetics, cultivation conditions and processing, making it difficult to consistently deliver a targeted dose.

Despite this substantial mitigation potential, concerns remain regarding the transfer of bromoform residues and associated compounds into animal-derived food products. These concerns are particularly relevant given that bromoform has been classified by the U.S. Environmental Protection Agency (EPA) as a Group B2 probable human carcinogen although the International Agency for Research on Cancer (IARC) considers the available evidence insufficient to classify its carcinogenicity in humans (US EPA; IARC, 2026). Consequently, understanding the fate of bromoform, its metabolites and related halogen compounds within animals and the environment is critical for evaluating the long-term safety, regulatory acceptance and sustainability of bromoform-based methane mitigation technologies.

Direct-Fed Microbials

Direct-fed microbials, also known as probiotics, are live bacteria or yeasts supplemented in animal diets. Common bacterial species include *Lactobacillus*, *Propionibacterium*, *Bifidobacterium*, *Enterococcus*, *Streptococcus*, *Bacillus*, *Megasphaera elsdenii*, and *Prevotella bryantii*, and common yeast species including *Saccharomyces cerevisiae* and *Aspergillus oryzae* (Seo et al., 2010; Kholif et al., 2024). Evidence supporting methane reductions from direct-fed microbials in dairy and beef cattle remains limited. Although improvements in performance and productivity have been observed in some studies, results are inconsistent and often highly variable due to differences in probiotic strains, inclusion rates and underlying diet characteristics (Kholif et al., 2024).

Essential Oils

Essential oils are commonly used in cattle production to support animal productivity and performance. Evidence for production-related benefits is most established in dairy cattle, where supplementation has, in some cases, been associated with improvements in milk yield and milk components (Belanche et al., 2020; Daning et al., 2021). In beef systems, essential oils are increasingly being explored as alternatives to in-feed antibiotics, particularly in finishing diets (Estrada-Angulo et al., 2022). Some dairy studies have also reported modest reductions in enteric methane emissions (typically <10%) from specific essential oil formulations (Belanche et al., 2020). However, a more recent meta-analysis found no statistically significant overall reduction in enteric methane emissions associated with essential oil supplementation in dairy cattle (Dalmonte et al., 2026). Given the wide diversity of compounds, sources and formulations encompassed by the term "essential oils," their mechanisms of action as methane mitigation agents remain incompletely understood. Consequently, the production conditions under which methane reductions may occur are not yet well characterized, and neither are the optimal inclusion rates needed to achieve consistent and reliable responses. Table 4 lists common essential oils and their sources.

TABLE 4

Common Sources of Essential oils

Chile Peppers	Capsaicin
Cinnamon	Cinnamaldehyde and eugenol
Citrus	Citral
Cloves	Eugenol
Coriander	Coriander seed oil
Garlic	Allicin and other sulfur containing compounds (garlic oil)
Lemongrass	Geranyl acetate, limonene, and geraniol
Oregano	Carvacrol
Thyme	Carvacrol and thymol

Ionophores

Ionophores are antibiotic-derivative compounds that are commonly implemented on many nonorganic U.S. feedlots and dairies. Common ionophores used in cattle production include monensin, lasalocid, and laidlomycin propionate, which are available through multiple commercial feed products in various markets (Callaway et al., 2003). While specific inclusion levels of ionophores are approved by the FDA for production purposes, their use for enteric methane mitigation is not specifically approved under a dedicated methane reduction claim. In a global context, ionophores are considered restricted ingredients in some regions, which may limit or preclude their continuous use as enteric methane mitigation tools.

While ionophores can reduce methane intensity through improvements in feed efficiency, evidence for reductions in absolute methane emissions is stronger in beef cattle than in dairy cattle. A recent meta-analysis reported that monensin supplementation reduced methane production in dairy cattle by only 5% and noted a lack of long-term studies evaluating persistence of the response (Marumo et al., 2023). In feedlot cattle, monensin supplementation can reduce enteric methane emissions by approximately 15% (Cooke et al., 2024). The greatest reductions were observed when monensin was included at 32–44 mg/kg of dietary dry matter, a range that is at or slightly above the levels typically used to improve feed efficiency (approximately 32–33 mg/kg of dietary dry matter).

Lipids

Dietary lipids are a highly diverse and layered feed category. They include:

- short and mediumchain saturated fatty acids (e.g., lauric acid, C12:0)
- longchain mono and polyunsaturated fatty acids (e.g., oleic acid, C18:1; linolenic acid, C18:3)
- free oils (e.g., soybean or linseed oil)
- whole oilseeds
- extruded products
- rumenprotected fats

Because these forms differ in carbon chain length, degree of unsaturation, and ruminal availability, their effects on methane emissions, fiber digestion, and animal performance are highly variable and not straightforward (Brask et al., 2013).

Reduction of enteric methane emissions by lipids occurs through multiple mechanisms. These include coating fiber particles, which limits microbial fermentation, and serving as alternative hydrogen sinks. Lipids also shift ruminal fermentation toward pathways associated with lower overall methane production by exerting toxic effects on rumen microbes (Beauchemin et al., 2007). Research has yielded inconsistent responses in methane reduction, and when effective, reductions have been relatively low (<10%). Excessive dietary lipids can impair digestion and reduce animal performance, including diminished milk fat percentage in dairy cattle.

Nitrates

Nitrates divert hydrogen away from methanogenesis in the rumen, instead capturing it as ammonia. This approach has been shown to reduce enteric methane emissions by up to approximately 20% in dairy cattle and around 10% in beef cattle (Feng et al., 2020; Dicks et al., 2026).

A key safety consideration is the accumulation of nitrite, an intermediate in nitrate reduction, which can impair oxygen transport by increasing methemoglobin in the blood. However, across the reviewed studies, observed methemoglobin levels remained well below the clinical risk threshold, reaching at most about 50% of levels associated with toxicity. Delivery method (slow-release) can also be adapted to further reduce the risk (Dicks et al., 2026).

Tannins

Tannins are a subclass of polyphenols. Reductions in methane emissions from tannins are often moderate, below 15–20% (Souza et al., 2025). Many studies of tannins have reported no reductions in methane emissions, which could be due to chemical composition, animal diet, dose, or method of delivery. It has been documented that excessively high levels of tannins can have undesirable impacts on animal performance and health by reducing feed intake and ruminal digestibility (Makkar, 2003).

A key challenge to the broader implementation of tannins as enteric solutions is the difficulty of accurately characterizing tannin content and activity in practical feeding situations. While many forage and feed ingredients naturally contain tannins, differences in tannin chemistry, source, and analytical approaches can complicate efforts to predict efficacy, determine optimal inclusion rates, and achieve consistent methane mitigation outcomes across production systems (Souza et al., 2025).

EMERGING AND EARLY-STAGE METHANE-MITIGATION APPROACHES

While enteric methane mitigation strategies based on feed additives represent the most widely studied and near-term interventions, they are not the only approaches under exploration. A growing array of complementary solutions aims to reduce enteric methane emissions through alternative biological, genetic, and technological pathways. Like feed-based interventions, these emerging approaches vary in maturity, scalability, and evidentiary support, and many remain at an earlier stage of development. The following section briefly highlights these strategies to provide broader context on the evolving enteric methane mitigation landscape, rather than to assess their readiness for near-term deployment.

Early Life Programming

The rumen's microbial community that strongly influences digestion and methane production begins establishing immediately after birth as the calf encounters its environment and feeds (Jami et al., 2013). Early life programming is the concept that early and temporary introduction to rumen-modifying and methane-inhibiting feed additives or ingredients could manipulate the development of the rumen microbiota in the longer term without continuous supplementation. Early life feeding strategies have long been used to support rumen development and improve performance, but are now being investigated as an enteric methane reducing practice as well (Xiao et al., 2020).

Low-Methane Genetics

There are already a number of phenotypes (observable traits that you can see, measure, or record) identified as being relevant to the production and management of beef and dairy cattle, including health and reproduction traits. The rumen microbiome, which is responsible for methane production, also shows evidence of heritability, meaning that aspects of its composition and function are partly influenced by the animal's genetics rather than environment alone (Li et al., 2019). If microbiome profiles can be identified in cattle that remain equally productive while producing lower absolute methane emissions, then small but permanent reductions could be achieved across future generations (Pickering et al., 2015).

However, further research is needed to define and validate lowmethane genetic traits that are stable across diets, environments, and production systems while not negatively impacting production. From an industry perspective, the use of measurable biological proxies such as milk fatty acid profiles to identify low-methane phenotypes would enable scalable monitoring of enteric methane emissions and support informed breeding and management decisions (Youngmark and Kraft, 2025).

Vaccines

Vaccinations that can curb methane emissions are being actively developed, but are not yet at the stage of FDA approval and commercial deployment. These vaccines reduce methane emissions by synthesizing methanogen-targeting antibodies in the saliva of ruminants. To date, peerreviewed evidence demonstrating consistent and scalable methane reduction in ruminants has not yet been made publicly available, and these technologies remain largely in the research and preregulatory phase. To date, Improvac (Zoetis), a vaccine that reduces boar taint (unpleasant odor from pork production), is the only livestock vaccine that has undergone this pathway and obtained approval.

Wearables

Unique in many ways, and advantageous given that they do not alter the physiology of the animal, methane-oxidizing masks that convert methane to carbon dioxide are in the early research stages of development. A potential challenge, however, is that it may take some time for the animal to get used to wearing and keeping on a muzzle-like mask. To potentially broaden the appeal of wearables, it would be advantageous if wearables also served as a method of data collection and possible MMRV tool.

WHAT DAIRY AND BEEF COMPANIES CAN DO NOW

Engage in the Innovation-to-Implementation Pipeline

Companies can play an important role in advancing development and adoption of enteric solutions. They can do this by engaging across the innovation-to-implementation pipeline (Figure 1) in ways that strengthen evidence, reinforce regulatory integrity, and support producers. Importantly, the nature of this engagement should evolve as solutions mature. Early-stage activities may focus on supporting research, evidence generation, and stakeholder education, while later-stage activities may emphasize regulatory readiness, commercial validation, and implementation support. By aligning engagement with a solution's stage of development, companies can help accelerate innovation while maintaining scientific rigor and producer trust. Table 5 contains details about engaging with solutions at various stages in the pipeline.

FIGURE 1
The Innovation-to-Implementation Pipeline

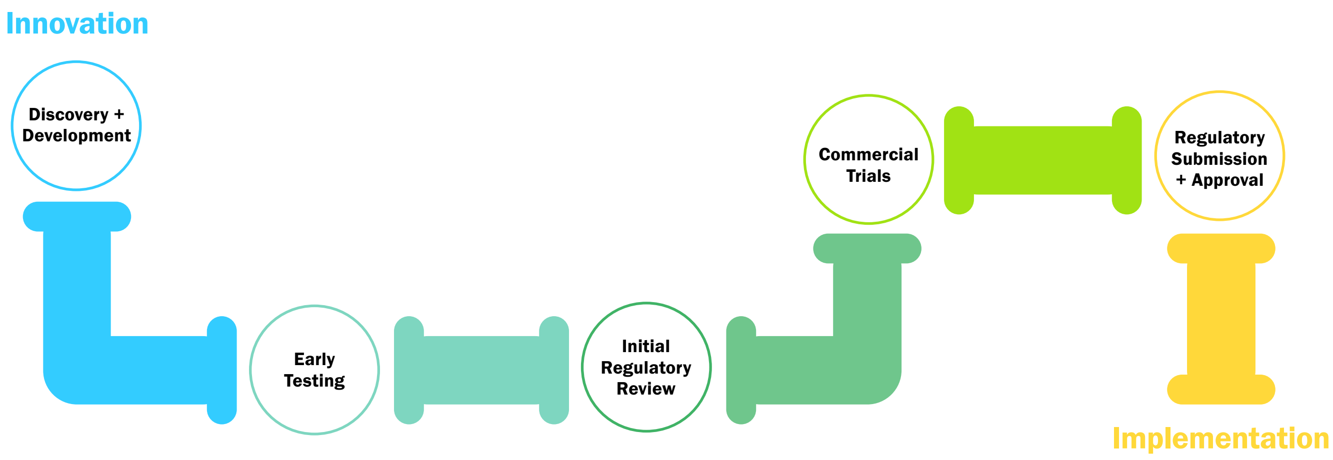

TABLE 5

How Companies Can Support Solution Providers and Producers Across the Innovation-to-Implementation Pipeline

<table>
<tr><th></th><th colspan="2">SUPPORT TO:</th></tr>
<tr><th>Pipeline Stage</th><th>Solution Providers</th><th>Producers</th></tr>
<tr><td>Discovery and Development</td><td>• Set early expectations around evidence quality.

• Support policies and programs that expand funding for early-stage research.</td><td>• Continue supporting foundational management practices, including animal health programs, precision feeding technologies, and ration-balancing initiatives.

• Build awareness of the importance of enteric methane reduction and its role in achieving climate goals across the dairy and beef value chain.

• Support producer education through extension specialists, technical advisors, and producer networks.</td></tr>
<tr><td rowspan="2">Early Testing</td><td>• Invest in in vitro and controlled research-based testing, such as rumen simulation systems or other laboratory studies, alongside appropriately controlled in vivo studies.

• Facilitate relationships with trusted regulatory, academic, or technical experts who can advise on study design, measurement approaches, and compliance considerations aligned with regulatory expectations.</td><td>• Ensure producers have access to accurate information about ongoing research efforts both inside and outside their supply chain:

✓ Provide regular updates on what projects are being funded and what has been learned so far.

✓ Host webinars where researchers explain what they’re studying and why.

✓ Fund producer attendance at events that bring together researchers, technology developers, and industry stakeholders.</td></tr>
<tr><td colspan="2">• Facilitate a feedback loop by contextualizing early research of enteric solutions for producers and communicating aggregated producer feedback to solution providers.

✓ Gather producer feedback on solutions through interviews, surveys, focus groups, or pilot project presentations.

✓ Share insights back with solution providers so they can refine their products, messaging, research priorities, or implementation strategies.</td></tr>
</table>

SUPPORT TO:

Pipeline Stage	Solution Providers	Producers
Regulatory: Testing, Review, and Approval	• Support regulation-related policy efforts that that aim to improve the clarity and efficiency of approval pathways for enteric methane solutions, while preserving rigorous, sciencebased standards for evaluating safety and effectiveness. ✓ **Policy engagement is directed at improving regulatory processes and transparency, not at influencing individual product evaluations or approval outcomes.**	• Support participation in authorized research programs that generate evidence required for regulatory review. • Ensure any on-farm participation that takes place before regulatory approval occurs under an FDA Investigational FoodUse Authorization (IFUA). Ensure clear communication on the purpose of the study, approved use conditions, data requirements, and the distinction between research use and commercial adoption. ✓ **Within this context, reduce financial, operational, and administrative burden by compensating producers for time, labor, disruption, and data collection, and by providing logistical support.**
Commercial Trials	• Facilitate introductions to trusted dairy or beef producers willing to participate in solution trials.	• Provide funding to participating dairy or beef producers for time, operational disruptions, and data collection associated with early trials. • Share early implementation experiences and lessons learned.
Implementation	• Support deployment and integration of technologies in real-world farm settings. • Share continued learnings and feedback.	• Invest to share solution cost and risk, rather than placing the full burden on producers. • Share continued learnings among both users and nonusers of the solution within the producer network.
	• Help coordinate deployment across multiple producers within regions to improve logistics and enable more efficient training for solution deployment and monitoring.	

For readers interested in other ways of supporting the advancement of enteric methane mitigation that are beyond the scope of this report, the Spark Roadmap for Enteric Methane Mitigation is a complementary resource. In addition to assessing the innovation landscape, the roadmap explores topics not covered in depth here, including economic feasibility, market demand, public perception, investment priorities, and the diversity of livestock production systems globally. It is intended to help funders and other stakeholders identify high-impact opportunities, address key gaps, and coordinate actions that can accelerate progress toward scalable methane mitigation.

CONCLUSION

Enteric methane mitigation is becoming an increasingly important component of climate strategies across dairy and beef supply chains. Achieving meaningful reductions, requires solutions that are supported by robust evidence and can be implemented safely and effectively under commercial conditions. This report supports that process by highlighting key considerations related to evidence quality, safety, and regulatory oversight.

Companies can play a valuable role in accelerating responsible progress by supporting research, evidence generation, producer engagement, regulatory clarity, and responsible commercialization. Through these actions, value chain actors can help solution providers address critical questions related to the efficacy, safety, practicality, and scalability of enteric methane solutions. Early engagement and strategic investment can help de-risk innovation while ensuring that promising technologies are evaluated rigorously before widespread adoption.

Ultimately, responsible methane mitigation is not simply about identifying solutions that work — it is about ensuring that solutions are effective, safe, practical, and supported by evidence strong enough to justify adoption at scale. By maintaining a commitment to scientific rigor and responsible implementation, the dairy and beef industries can advance methane reduction efforts while supporting animal health, food safety, producer trust, and long-term sustainability.

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