

APPENDIX C.2: Dairy Sector Emissions Reduction Technology Assessment

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Technology Assessments**3-Nitrooxypropanol (3-NOP) – rumen methane inhibitor****Summary:**

3-NOP (Bovaer) is a synthetic compound that inhibits the final step of methanogenesis in the rumen by targeting the methyl-coenzyme M reductase enzyme (Duin et al. 2016). Met-analyses indicate it reduces enteric methane by roughly 23% (Almeida et al. 2021 found 23%; Krebeab et al 2023 found 30-33%, Macdonald et al. 2025 found 26%) but results are highly variable. Meta-analysis shows small DMI reductions (up to ~4.5%) and body weight production effects are generally neutral but not guaranteed and depend on diet and dosing (Almeida et al. 2021). 3-NOP must be provided frequently because it is rapidly degraded; therefore, practical use is strongest where cows receive daily supplementary feed (Garnett and Eckard 2024). In dairy systems the key constraint is delivery—most Australian dairy cows are pasture based, so supplementation is typically via concentrates at milking ('pulse feeding, twice daily'), which can reduce efficacy compared with continuous dosing.

Abatement Potential (Technical):

Assume range 23-39% of realised abatement drawing from:

- Up to 60% reductions have been reported in some controlled trials
Meta-analysis suggests 23% average reduction in methane yield, with 18–39% (95% CI) depending on dose and diet (Almeida et al. 2021).
- Kebreab et al (2023) found 3-NOP dose resulted in a significant reduction of 32.7%, 30.9%, and 32.6% for CH₄ production (g/d).
- MacDonald et al (2025) found that on average, 3-NOP supplementation reduced CH₄ yield by 26.4% in dairy cattle, at the recommended dose of 60mg 3-NOP/kg DMI.
- In grazing systems where there is twice daily pulse feeding effectiveness is reduced to approximately 5% less than control (Costigan et al. 2024)

Justification:

- Response is dose- and diet-dependent. A recent meta-analysis quantified heterogeneity and reported a functional relationship between methane yield response, dose (mg 3-NOP per kg DMI) and DMI, illustrating that higher intake and lower dose reduce efficacy (Almeida et al. 2021; Macdonald et al. 2025).
- Pulse feed studies show lesser effect when averaged over a 24 hour period (Costigan et al. 2024).

Abatement Potential – Economic/Feasible:

- Output: Estimated feasible abatement of 0.02–1.03 Mt CO₂-e/year under partial adoption in supplemented dairy systems.
 - Justification: Assume 1.4M head, of which close to 100% provide some level of supplementary feeding. Less than 2% of farms do not graze (<https://www.dairy.com.au/you-ask-we-answer/are-australian-dairy-cows->

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[completely-grass-fed](#)) . Assume low case emissions reduction 23% and high case 39%. Use NSW adoption range (Cowie et al 2025) of 3-73%

Breadth of Application

- Ranking: Medium
- Justification: Best suited to systems where cows can be dosed daily via concentrates (i.e. twice daily in the dairy), PMR or TMR. Applicability is limited in fully pasture-only systems unless new delivery solutions (e.g., sustained-release) are proven (Garnett and Eckard 2024).

Co-Benefit Potential

- Ranking: Medium
- Justification: Potential improvements in feed conversion efficiency (e.g. Hirstov et al. 2015, Lahart et al 2025) though not consistently or clearly demonstrated in Australian trials (Almeida et al. 2021, Garnett and Eckard 2024); inconsistent productivity gains due to altered rumen microbiota possible (Ahmad et al 2025).

Barriers and Knowledge Gaps

- Ranking: Medium
- Justification: Product access difficulties (limited production capacity), delivery mechanisms in grazing systems/slow-release options not yet resolved though research underway, lack of clarity on optimal dose due to variable response based on factors including diet, effects of pulse feeding on emissions reduction. Concerns on animal safety and accumulation in products appear unfounded but may require perception management. Need for emissions calculator integration.
- Following Denmark's 2025 requirement for conventional dairy farms to adopt methane-reducing feed strategies, including Bovaer® (3-NOP) or alternative dietary measures, some dairy farmers reported declines in feed intake, milk yield and animal health concerns (SEGES Innovation, 2025; <https://segesinnovation.com/about-us/news-and-media/seges-innovation-news/feedback-regarding-the-use-of-bovaer-in-danish-dairy-herds/>). However, the survey was based on farmer observations and did not establish that Bovaer caused the reported effects (SEGES Innovation, 2025; <https://segesinnovation.com/about-us/news-and-media/seges-innovation-news/dairy-farmers-experiences-with-the-use-of-bovaer/>). Subsequent investigations did not confirm a causal link between Bovaer and the reported health issues, and an Aarhus University analysis found no evidence of adverse effects on milk production or key animal health indicators (Aarhus University, 2026; <https://our-company.dsm-firmenich.com/en/our-company/news/latest-updates-about-bovaer/2026/aarhus-university-confirms-bovaer-works-safely-on-danish-dairy-farms.html>). During the investigation period, Danish authorities allowed exemptions where animal health concerns were suspected (<https://live.allaboutfeed.net/animal-feed/feed-additives/concerns-rise-over-bovaer-after-cow-health-issues-in-denmark>)

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Stacking Potential

- Ranking: High
- Justification: Can be combined with other practices (precision feeding, genetics, manure management). Additive effects have been demonstrated in studies combining 3-NOP with lipids and nitrate (Gruninger et al. 2022; Maigaard et al. 2024).

Technology Readiness Level (TRL)

- Ranking: 8-9
- Justification: Proven in multiple in vivo trials; Has been deployed into confined systems; mandated for widespread use in Denmark (though see discussion under barriers)

Commercial Readiness Level (CRL)

- Ranking: 6
- Justification: Commercial product (Bovaer) available internationally; no known commercial applications in Australia, Approved for use in USA, Brazil, Chile, EU among over 65 countries. Currently no ACCU methodology.

Enabling Potential

- Ranking: low
- Justification: Easily included in methane accounting and feed efficiency frameworks, but not real other enablement for other technologies.

Estimated Cost Range:

AUD \$0.3 to \$0.5 per head per day. This range reflects different inclusion rates and pellet formulations tested in feedlot trials at 60 and 80 mg/kg DMI (after Krebreab et al. 2023; EFSA 2021).

This variation depends on:

Dosage: 60 and 80 mg/kg DMI (after Krebreab et al. 2023; EFSA 2021)

Delivery method: Mixed in TMR (total mixed ration), pellets, or other feed systems

Formulation losses: Up to 12% during pelleting and 7.3% during storage, which may affect cost-effectiveness.

Estimated Benefits:

Estimate \$0.09 per animal per day.

Primary benefit is methane reduction. A simple carbon-value illustration: if a cow emits 0.352 kg CH₄/day (after Starsmore et al 2024 as conservative estimate, but noting range for Australia reported as high as 0.41-0.47 kg CH₄/day by Munidasa et al 2023 depending on diet), a 30% reduction equates to 0.09 kg CH₄/day (2.5 kg CO₂-e/day using GWP100=28), worth AU\$0.09/day at AU\$30/t CO₂-e before transaction costs.

Productivity benefits should be treated as uncertain.

Investment in R&D and Commercialisation

Range: >\$500M

Australian investment (RDC and CRCNZA): \$8,917,056

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- AWI: “Lower emissions supplements for grazing at scale” (Efficacy, safety and delivery testing of anti-methanogenic additives including 3-NOP (Bovaer), alongside other inhibitors.) Category: 1. R&D with 2. Commercialisation relevance.
- Meat & Livestock Australia: “Biopolymers to deliver bioactive compounds that reduce enteric methane” (Biodegradable biopolymer bolus to deliver controlled 3-NOP dosing in extensive and intensive systems; addresses grazing delivery constraint.) Category: 1. R&D with 2. Commercialisation relevance.
Meat & Livestock Australia: “Reducing emissions of backgrounded cattle – combining Bovaer®10 with supplementation to reduce methane and increase productivity” (Applied evaluation of Bovaer®10 with supplements in backgrounding systems; tests mitigation and productivity integration.) Category: 1. R&D with 2. Commercialisation relevance.
Meat & Livestock Australia: “Effect of Bovaer on performance, health, carcass characteristics and carbon footprint of Australian feedlot cattle.” (Large-scale commercial feedlot trial; measures production, health, carbon footprint and carbon-project feasibility.) Category: 1. R&D / Enabling.

International investment (itemised):

- DSM-Firmenich global R&D and commercial development: estimated >\$100M over multi-year global program.
- DSM manufacturing expansion (Scotland facility) to supply 4–5 million cattle/year (capital and scale-up investment part of DSM's >\$100M).
- Regulatory and market development costs in multiple countries (EU, US FDA clearance in 2024) are part of international investment pipelines.

Red seaweed (*Asparagopsis*) and extracts from seaweed as feed additive

Summary:

Asparagopsis, a red seaweed, reduces methane emissions in ruminants through its active compound bromoform. In the rumen, methane is produced by methanogenic archaea using hydrogen to reduce carbon dioxide. Bromoform inhibits the enzyme methyl-coenzyme M reductase (MCR), which is essential for this process. By blocking MCR, methane formation is suppressed, and hydrogen is redirected to more efficient fermentation pathways. Feeding can be with dried seaweed or bioactives extracted into a carrier, often oil, which is then added to feed. Not included in this section is synthetic bromoform.

In dairy systems the key constraint is delivery—most Australian dairy cows are pasture based, so supplementation is typically via concentrates at milking (‘pulse feeding’, twice daily), which can reduce efficacy compared with continuous dosing. Additional dairy-specific considerations include residues (bromoform and its breakdown products) and iodine transfer into milk when whole seaweed is used or when bioactives

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are extracted into oil, requiring careful dose management and regulatory oversight (Alvarez-Hess et al. 2023; Krizsan et al. 2023).

Annual Abatement Potential (Technical)

Estimate: Early meta-analysis (Almeida 2021; n=3) estimated 49% mean MY reduction (30–69% CI), but dairy results showed delivery and intake impacts at some doses; pasture ‘pulse feeding’ may reduce efficacy (Alvarez et al. 2023, 2024; Williams et al. 2024).

Justification: Emissions reduction can be very high under continuous dosing (often >60% and up to 90% in some controlled studies), but under pulse feeding in dairy is more plausibly 30–60% depending on dose, form (meal vs oil extract) and diet (Alvarez-Hess et al. 2023; Alvarez-Hess et al. 2024; , Krizsam et al 2023, Roque et al 2019). A broader meta-analysis across bromoform-containing ingredients indicates substantial average reductions in methane production/yield, but with material heterogeneity (Kebreab et al. 2025).

Abatement Potential – Economic/Feasible

Output: Estimated feasible abatement of 0.324-1.82 Mt CO₂-e/year under partial adoption in supplemented dairy systems.

Justification: Justification (assumptions): dairy herd size 1.4M head producing head producing 0.352 kg CH₄/cow/day (see 3NOP section for sources). 98% of dairy operations give supplementary feeding. Assume low case sustained emissions reduction 30% and high case of 69%. Assume adoption rates as for 3-NOP of 3-73%.

Breadth of Application

Ranking: Medium

Justification: Best suited to systems with controlled supplementation; pulse feeding at milking offers a pathway for pasture-based dairies but may reduce efficacy relative to continuous dosing.

Co-Benefit Potential

Ranking: Medium

Justification: Potential productivity gains and/or feed efficiency (Roque et al. 2019, Krizsan et al. 2023) though dry matter intake and milk fat yield may be reduced (Roque et al. 2019, Stefenoni et al. 2021, Krizsan et al 2023); concerns over bromoform residues and if dried seaweed used of iodine levels in milk and some studies report though below levels of concern for safety or regulatory concern (Alvarez-Hess, 2023, Krizsan 2023).

Barriers and Knowledge Gaps

Ranking: Moderate

Justification: Key barriers include scalable and consistent bromoform supply, product standardisation, long-term animal performance and hydrogen management under high inhibition, residue and iodine management in milk, and practical delivery systems for grazing periods. Currently a lack of complete environmental and animal health risks from long term (>180 day) use.

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Stacking Potential

Ranking: High

Justification: Can stack with herd efficiency and manure/pasture strategies; careful evaluation needed for combined effects on hydrogen balance.

Technology Readiness Level (TRL)

Ranking: 7

Justification: Demonstrated in multiple in vivo trials; broader commercial validation and delivery solutions for grazing systems are still developing.

Commercial Readiness Level (CRL)

Ranking: 5

Justification: Early commercialisation and pilot products exist; costs and supply constraints limit broad adoption. Lack of ACCU methodology constrains access to carbon payment.

Enabling Potential

Ranking: low

Justification: Primarily a methane inhibitor.

Estimated Cost Range:

AU\$0.40 to AU\$1.20 per head per day (pers. Comm. Alex Baker, CEO FutureFeed).

Lower end: minimal effective dose for methane reduction

Higher end: full dose for maximum efficacy (up to 90% methane reduction)

Some uncertainty on cost of goods till industry scales.

Estimated Benefits:

Estimate: \$0.12-0.33

Justification:

If a cow emits 0.352 kg CH₄/day, a 45% reduction equates to 0.09 kg CH₄/day (2.5 kg CO₂-e/day using GWP100=28), worth AU\$0.12/day at AU\$30/t CO₂-e before transaction costs. Productivity benefits should be treated as uncertain but can propose a 5% feed efficiency gain (5% less feed, same milk production and quality) assuming \$1500 per cow per year feed translates to \$75 per cow per year or \$0.21 per cow per day. We assume premium 'low methane' milk markets remain niche and uncertain.

Investment in R&D and Commercialisation

Range: \$100M–\$200M

- Australian investment:
 - RDC and CRC NZA **RDC investment: \$7,359,712. Investment directed at the following activities:**
 - “Mitigating methane with Asparagopsis (ssp.)” (quantifies intake–response relationships for grazing sheep; delivery form, frequency and pasture interactions). Category: 1. R&D with 2. Commercialisation relevance.
 - “Lower emissions supplements for grazing at scale” (efficacy, safety and delivery testing of Asparagopsis alongside other inhibitors in grazing systems). Category: 1. R&D with 2. Commercialisation relevance.

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- “Efficacy and safety of Asparagopsis extract in a canola oil carrier for feedlot cattle” (controlled animal trials using extract formulations; DMI, respiration chambers, residues and product quality). Category: 1. R&D / Enabling.
- “Biorefinery approaches to creating value from Asparagopsis” (processing pathways, flow diagrams, equipment requirements and multi-product valorisation options). Category: 1. R&D / Enabling.
- “Protoplast-based mariculture solutions for scalable Asparagopsis farming” (nursery and seedstock innovation to enable year-round, scalable production). Category: 1. R&D with 2. Commercialisation relevance.
- “Seaweed National Hatchery Network – Temperate Research Hub for Asparagopsis armata” (establishment of hatchery infrastructure, lifecycle closure, contamination control and industry knowledge sharing). Category: 2. Commercialisation / Enabling.
- “Regulatory framework for safety of Asparagopsis and derived bioproducts” (regulatory gap analysis and guidance to support feed and food approvals). Category: 1. R&D / Enabling.
- National commercialization investment:
 - FutureFeed capital raised \$21M
 - CH4 Global = \$42M in first two cap raises and then undisclosed in EcoPark (South Australia): commercial-scale Asparagopsis production facility — company reports capacity to serve ~45,000 cattle/day with plans to expand.
 - Provectus Algae (Bromata): Series A \$10.1M and a \$2.5M Australian government grant; total funding reported >\$33.5M.
 - Additional commercial investment in Australia by SeaStock and Fremantle Seaweed Company,
- International investment (sample):
 - CH4 Global: corporate capital to develop EcoPark and international expansion; partnerships with Mitsubishi and Symbrosia.
 - Blue Ocean Barns has raised approx. \$20M

Synthetic bromoform and various 2nd generation haloform anti-methanogenic feed supplements

Summary:

These supplements use synthetic haloforms (e.g. bromoform, tribromoacetic acid) or precursors that convert to active compounds in the rumen. They inhibit methyl-coenzyme M reductase, the key enzyme in methanogenesis by Archaea.

Some products use encapsulation or oil-based carriers to stabilize delivery and reduce volatility. For example, Rumin8 and Ruminant Biotech are developing stabilized bromoform formulations. Roam and Number8Bio are advancing toward commercial trials with synthetic analogues.

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These products are at various stages in TRL and CRL and may face different regulatory pathways. This is an active R&D and commercialisation area and some emerging technologies are briefly summarised.

Rumin8

Product: Synthetic bromoform-based feed additives in oil and powder forms.

Pipeline: Completed in vivo trials showing up to 94% (Gyeltshen et al 2025) but typically 70-90% methane reduction with no adverse effects on animal productivity under TMR diet. Improved or stable FCR, weight gain/milk neutral or slight increase.

Also tested water-soluble delivery for extensive grazing systems.

Regulatory Pathway: Classified as an Investigational Veterinary Product (IVP) by FDA in USA. Requires APVMA registration due to active constituents. Subject to residue risk assessments due to bromoform's toxicity.

Roam (purchased by Rumin8)

Product: Synthetic bromoform stabilized via non-GMO fungal fermentation. Up to 90% (lab), 50-60% field target. Expected FCR increase, yields stable

Pipeline: Developed slow-release formulations for pellets and ruminal devices.

Regulatory Pathway: Pilot trials AU, full AU commercial 2026 Likely requires APVMA registration as a feed additive with active constituents. May face scrutiny under biologicals regulation if fungal components are active.

Number8Bio

Product: BetterFeed™—a synthetic chemistry-based additive with non-bromoform inhibitors and prebiotics. Claim increase in average daily weight gain, increase in milk yield and quality.

Pipeline: Trials with UNE and QASP show up to 80-90% methane reduction in lab and early field trials. Pivoted from yeast fermentation to pure synthetic chemistry for cost-effectiveness.

Regulatory Pathway: Major AU trials in 2025, full AU commercial trial planned in 2026

May avoid APVMA registration if classified as a nutritional feed supplement without active constituents. Still subject to import and safety assessments under DAFF guidelines

Ruminant Biotech

Product: Slow-release rumen bolus delivering synthetic tribromomethane (TBM). Feed conversion efficiency improvement.

Pipeline: Funded by Australia's MERiL program with trials at University of Sydney. Targets 80% methane reduction over 6 months from a single bolus.

Regulatory Pathway: Major AU trials in 2025, full AU commercial trial planned in 2026 Requires APVMA registration as a veterinary medicine. Must demonstrate residue safety and long-term efficacy.

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Annual Abatement Potential (Technical)

Assume 49%

Justification: Clear evidence from range of sources that 60-90% or higher abatement possible but will be similar to those products when pulse fed. Assume same efficacy as Asparagopsis given low trialling.

Abatement Potential – Economic/Feasible

Estimated feasible abatement of 0.32-1.82 Mt CO₂-e/year under partial adoption in supplemented dairy systems.

Justification: dairy herd size 1.4M head producing 100kg CH₄/cow/year. 98% of dairy operations give supplementary feeding. Assume adoption rates as for 3-NOP of 3-73%.. Assume low case sustained emissions reduction 30% and high case of 69%.

Breadth of Application

Ranking: Medium

Justification: Delivery constraints will initially confine to close to barn situations

Co-Benefit Potential

Ranking: Medium

Justification: some emerging evidence of feed efficiency gains

Barriers and Knowledge Gaps

Ranking: high

Justification: emerging products

Stacking Potential

Ranking: High

Justification: can be combined with lipids and nitrates as well as breeding

Technology Readiness Level (TRL)

Ranking: 3-7

Justification: variable among products but generally prior research on haloforms additive in knowledge and embodiment

Commercial Readiness Level (CRL)

Ranking: 3

Justification: emerging products with early stage investments and many still to go to commercial trials

Enabling Potential

Ranking: low

Justification: do not really enable other technologies

Estimated Cost Range:

Variable and will depend on costs of carrier formulation. While synthetic bromoform is cheap will need a carrier to stabilise. Expectation is in 10-50c per animal per day when produced at scale (pers. comm. Alex Baker, CEO FutureFeed), and price point of 3NOP (around 20c per dose) may be indicative.

Estimated Benefits:

Estimate: \$0.12-0.33

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Justification:

If a cow emits 0.352 kg CH₄/day, a 45% reduction equates to 0.1 kg CH₄/day (2.7 kg CO₂-e/day using GWP100=28), worth AU\$0.13/day at AU\$30/t CO₂-e before transaction costs. Not well-established possible feed conversion gains similar to seaweed feeding may occur. Using those calculations: if 5% feed efficiency gains (5% less feed, same milk production and quality) assuming \$1500 per cow per year feed translates to \$75 per cow per year or \$0.21 per cow per day.

Investment in R&D and Commercialisation

- Aust government and RD: approx. \$4M
 - MERIL invested \$3.5M into Ruminant BioTech for development and trials of its slow release methane reducing bolus. Rumin8 participated in trials at UNE and UCDAvis.
 - Rumin8 were involved in a \$340,000 MERIL project with UMelb on lick blocks
 - Rumin8 were involved in a \$695000 trial with DPI,SA to deliver to sheep under MERIL
 - MERIL: Loam Bio (\$653,750) will deliver a cost-effective, scalable, adaptable and highly resilient low-emission feed supplement for grazing animals
 - “Lower emissions supplements for grazing at scale” (early-stage testing of synthetic and next-generation haloform inhibitors; efficacy, safety and delivery feasibility).
- National commercialisation:
 - In terms of commercialisation Rumin8 raised \$25M in Australia and US\$12M in the US, Number8Bio secured \$7M and Ruminant BioTech has \$12M private funding from New Zealand investors

Lipid/fat supplementation

Summary:

Lipid (fat) supplementation is a mature, well-studied dietary strategy that can reduce enteric methane by (i) lowering the amount of fermentable organic matter in the rumen, (ii) directly inhibiting methanogens and protozoa, and (iii) acting as an alternative hydrogen sink via biohydrogenation (especially for unsaturated fatty acids) (de Ondarza et al 2024).

Across ruminants, the effect size depends strongly on dose, fat type (medium chain fatty acids and polyunsaturated fatty acids are generally stronger), and how “rumen-available” the fat is (oils > processed/ground oilseeds > whole seeds; rumen-inert fats have minimal rumen effect) (de Ondarza et al 2024).

Lipids reduce fibre fermentation and hydrogen availability, yielding methane reductions on the order of approx. 3–5% per 1% added fat (Moate et al. 2011). Dairy diets already

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routinely include fat sources like forages, grains, and supplemental fats, but the specific levels and types of fats vary depending on the feeding system and regional availability of ingredients. Some diets may already be close to the optimal level for methane reduction, while others may have room for further fat supplementation. Diets with lipid intake of greater than 6-7% suppresses DMI and hence milk production setting a limit to potential reductions in emissions through lipid supplementation (Moate et al. 1999).

Annual Abatement Potential (Technical)

Estimate: 15%

Justification: Metanalysis suggests 12–20% (95% CI), mean 15% reduction in enteric CH₄ (Almeida et al. 2021, 95% CI 12-20%). This reduction is however against a base case of all diets being low in fat. Most highly producing dairy diets contain high levels of fat. Between 10-15% of Australian dairy systems are feed partial or total mixed ration. It is only in these diets that fat content is likely to exceed 3%.

Abatement Potential – Economic/Feasible

Estimate: 0.10-0.17MT CO₂-e per year

Justification: Assume minimum of 15% abatement applied over 15% of national herd (those in systems at which diets of 3% fats can be fed). Assume given 100% adoption (however much may not be additional to current feeding)

Breadth of Application

Ranking: medium

Justification: application in total and mixed ration with careful diet balancing. Limited applicability in forage-based diets.

Co-Benefit Potential

Ranking: low

Justification: risk of reduced intake and rumen irritation at high levels especially in high-fibre systems. Almeida et al. 2021 meta-analysis showed DMI reduced 1.24–6.17%, NDF digestibility reduced 6.3–13%, milk production decreased 1.17–13.7%, and no effect on growth rate detected in their dataset, and Ondarza et al. 2024 found a decrease in milk fat percentage (7.8% decrease) and milk yield (6%) were reduced with rumen fat supplementation.

Barriers and Knowledge Gaps

Ranking: moderate

Justification: productivity trade-offs at dose level; requires farms to be feeding total or partial mixed ration with capital costs associated with equipment purchase and changes to farming system.

Stacking Potential

Ranking: high

Justification: demonstrated additive effects when combined with nitrate and 3NOP (e.g. Gruninger et al 2022).

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Technology Readiness Level (TRL)

Ranking: 9

Justification: Widely used but often at lower levels than for maximal emissions reduction. Proven efficacy in controlled diets

Commercial Readiness Level (CRL)

Ranking: 6

Justification: Available and used. Adoption limited by cost and performance trade-offs in grazing systems.

Enabling Potential

Ranking: low

Justification: not a system enabler, only additive affects with 3NOP and nitrates.

Estimated Cost Range:

If palm fat used (e.g Megalac) cost per inclusion is around \$3/kg, vegetable oils are around \$2-\$3 per kg. If we assume 14kg DMI per day and 2kg of concentrate, then the cost per animal per day is AUD1.44 for a 3% inclusion.

Estimated Benefits:

It is observed that in addition to methane reduction addition of fats will increase milk yield. Rabiee et al. show an increase of 1.55kg/d milk yield. Megalac report a 2.3kg/d milk increase. If the average farmgate price for milk is around AUD\$0.65-\$0.75 then this is worth around \$1.00-\$1.60 per cow per day.

If a dairy cow produces 0.352 kg of methane per day then at a carbon price of \$30 per tonne and is reduced by 10% this is worth AU\$0.03 per cow per day

Investment in R&D and Commercialisation

- Australian R&D investment (itemised): \$1-5M range probably attributable historically
 - 2009-2012 MLA “Increasing productivity and reducing methane emissions by supplementing feed with dietary lipids”
 - “Lick-blocks for methane mitigation and production in grazing cattle” (use of vegetable oils and lipid-based modifiers in lick-block delivery systems; mitigation and productivity interactions).
- International investment (itemised):
 - Global industry investment in commercialisation would be >AUD\$1bn (excluding Cargill) with capitalisation into companies such as Megalac, Volmac, Energy Fees International, Cargill, Trouw Nutrition, ADM Animal Nutrition, Perdue Animal Nutrition, Moltech

Phytochemicals – Pasture species (e.g. tannin-rich legumes)

Summary:

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Certain pasture species naturally contain phytochemicals, including condensed tannins, hydrolysable tannins, saponins and other phenolic compounds, that can reduce enteric methane emissions and, in some cases, improve nitrogen use efficiency. Key examples include *Leucaena* and *Desmanthus* in northern Australian grazing systems, and *biserrula*, lucerne, plantain, chicory and *Lotus* spp. in temperate systems. These species provide a low-cost, pasture-integrated mitigation pathway with potential cobenefits for productivity, nitrogen cycling and animal health. However, methane responses are highly variable and system outcomes depend on pasture composition, animal intake, agronomic suitability, persistence and grazing management, rather than phytochemical presence alone (CardosoGutierrez et al. 2021; Badgery et al. 2023). Charmley (2025) also notes that most promising species with anti-methanogenic properties were forecast to improve the nutritive value of pasture, thus increasing reproductive efficiency and animal weight gain leading to changed herd/flock structure, earlier animal turnoff, and increased carrying capacity. Consequently, predicted reductions in methane production per unit of feed intake were often offset by increases in total methane emissions. In summary, the intensity of emissions per unit of animal product is likely to be reduced while total emissions per area may increase.

Annual Abatement Potential (Technical)

Estimated methane yield reductions of 0–30% depending on species and inclusion rate in the diet. Assume 11% as midpoint of Badgery et al range of 8–14%.

Justification: Meta-analyses and synthesis studies indicate a wide range of responses. Cardoso Gutierrez et al. (2021) reported reductions of 0–32% in enteric methane with tannin rich tropical plants, with a clear dose–response relationship. Badgery et al. (2023) showed that temperate legumes and herbs typically achieve 8–14% reductions in methane yield (g CH₄/DMI) on average, with higher reductions (occasionally >30%) reported for species such as *biserrula*, *Lotus* spp., chicory and plantain in specific trials. However, results vary substantially across species, seasons, animal classes and experimental methods Charmley (2025) noted the reduction reduction in methane yield (g/kg DM intake) from diets with the seven forages varied between 0 and 25%, but that increased animal productivity by 7% reduced overall methane emissions reduction by 3% and associated methane intensity (methane per unit of animal product) by 9%.

Abatement Potential – Economic/Feasible

Estimate: 0.03-0.12MT a year

Justification: Estimated feasible abatement of 8-14% CH₄ reduction in pasture-based systems (from Badgery analysis covering species where the dairy herd is situation). Requires agronomic adaptation and may not be suitable in all regions (assume 20% of regions) with between 36 and 80% adoption based on NSW herd management adoption assumption (Cowie et al 2025). No additional feeding infrastructure needed.

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Breadth of Application

Ranking: Medium

Justification: Phytochemical-rich pasture species are applicable across both northern and southern grazing systems, but adoption is uneven. Temperate species like plantain, chicory and biserrula show variable persistence and grazing tolerance. Badgery et al. (2023) note that limited persistence, seed availability and management complexity restrict broad uptake, particularly in mixed pastures. Limited persistence of tannin-rich species like plantain and biserrula in Australian pastures

Co-Benefit Potential

Ranking: medium

Justification: When included in pasture may improve forage quality in some cases through higher protein and energy content than pastures; may improve persistence of cover and extend the production window; with early sowing can provide protection against weeds. Tannins in diet may have positive impacts of fatty acid composition of milk; tannins may have rumen anti-parasitic effects.

Barriers and Knowledge Gaps

Ranking: Medium

Justification: Key barriers include variable establishment success, need for appropriate rhizobial inoculation, grazing management to maintain persistence, and seasonal variability in phytochemical concentration. Excessive intake of some species may increase risks of bloat, photosensitisation or reduced intake. Both Cardoso Gutierrez et al. (2021) and Badgery et al. (2023) highlight major knowledge gaps around the relationship between specific plant secondary compounds, methane suppression and animal performance under grazing. Standardised protocols for methane assessment and better in vivo validation are required.

Stacking Potential

Ranking: Medium

Justification: Phytochemical-rich pastures can be combined with other mitigation strategies, including genetic selection, improved herd efficiency, and some supplementary methane inhibitors. Their primary value is as a foundational, system level mitigation that can enhance or enable additional interventions.

Technology Readiness Level (TRL)

Ranking: 7

Justification: Proven in field trials. Requires further validation across diverse regions and farming systems.

Commercial Readiness Level (CRL)

Ranking: 5

Justification: Seed and agronomic knowledge exist for some species, but commercial uptake is limited by persistence, variable productivity and regional suitability. Broader

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adoption will require improved cultivars, clearer grazing guidelines and integration into existing pasture systems.

Enabling Potential

Ranking: Medium

Justification: Supports broader pasture improvement, nitrogen management and productivity strategies. May reduce fertiliser inputs and improve system resilience, indirectly enabling further emissions reductions.

Estimated Cost Range:

Au\$0.02-0.10 \$/animal/day (amortised cost of pasture establishment)

Estimated Benefits:

AU\$0.05–0.15

(from improved nitrogen efficiency, potential productivity gains, and reduced fertiliser costs)

Investment in R&D and Commercialisation

Range:

- Australian investment (itemised):
 - Eligible for concessional loans under NAB Agribusiness Emissions Reduction Incentive program
 - Production of sterile *Leucaena* (DPIRD, MLA, UQ)
 - QDAF/MLA/CSIRO invested in projects focussing on new management adoption strategies, mapping suitable areas, trialling psyllid tolerant cultivars, and trialling rumen inoculation with new bacterial mixes to degrade toxins.
- International investment (itemised):
 - Significant trialling and demonstration of *Leucaena* overseas going back more than 50 years.

Phytochemicals – extracts added to diet (e.g., essential oils)

Summary:

Phytochemical extracts such as essential oils, purified tannins, saponins and related plant secondary metabolites can be added to livestock diets to reduce enteric methane emissions by inhibiting methanogens and altering rumen fermentation pathways.

Reviews consistently show moderate reductions in methane yield, with high variability driven by compound type, dose, diet composition, and microbial adaptation (Patra & Saxena 2010; Almeida et al. 2021; Kholif & Olafadehan 2021). Garnett & Eckard (2024) report that polyphenolic compounds and tannins reduce methane yield by approximately 0.109 g CH₄ per kg DMI for every g/kg DMI added, consistent with the midrange responses in the Almeida et al. (2021) meta-analysis.

Commercial products such as Agolin Ruminant (essential oil blend) are among the most widely deployed phytogenic additives globally, particularly in dairy systems with controlled feeding.

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Annual Abatement Potential (Technical)

Abatement potential: Average methane reduction 10% (8–14%), with small but significant NDF digestibility reduction (~4–5%) (Almeida et al. 2021). Recent studies with pulse feeding (Adam et al. 2025) found no effect.

Justification:

In Almeida et al. (2021):

- Phytochemicals: mean MY reduction 10%, range 8–14%; DMI no effect, but NDF digestibility reduced 4.69% (95% CI 0.86–8.56).
- Tannins and saponins had the greatest effect.
- Tests with Agolin and Polygain (Adam et al 2025) showed no beneficial effect

Methane yield reductions of 8–14% depending on compound type, dose, and purity from Garnett and Eckard (2024). Highest and most consistent effects observed for tannins and saponins, followed by essential oils. This range is consistent with controlled in vivo trials of garlic–citrus EO blends (7–13% reduction; Ahmed et al. 2021) and broader phytogetic reviews (Kholif & Olafadehan 2021; Nastoh et al. 2024).

Abatement Potential – Economic/Feasible

National abatement potential 0.09-0.38 Mt CO₂-e yr⁻¹

Justification: High cost and inconsistent performance limit feasibility. More viable in confined systems with controlled feeding. To calculate potential we apply the same rationale as for 3NOP – and used in the 64% of dairy operations in Australia with some level of supplementary feeding and adopted between 3-73% of users as per 3NOP in Cowie et al. 2025.

Breadth of Application

Ranking: Medium

Justification: Applicable to dairy systems with controlled feeding (e.g., TMR or supplemented pasture). Less suited to extensive grazing without reliable delivery mechanisms.

Co-Benefit Potential

Ranking: medium

Justification: Risk of reduced dry matter intake or digestibility issues at high doses (Patra & Saxena 2010; Almeida et al. 2021).

Tannins in diet may have positive impacts of fatty acid composition of milk; may improve nitrogen use efficiency; tannins may have rumen anti-parasitic effects. Some positive results from essential oil (Agolin) on milk production. Maybe some benefit to animal health especially during periods of heat stress

Barriers and Knowledge Gaps

Ranking: High

Justification: Variable *in vivo* efficacy; Microbial adaptation with continuous feeding known to occur needs clarification; Limited longterm data on optimal dose

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and persistence ; Risk of intake depression or digestibility loss at high inclusion rates.
Strong variability in experimental results

Stacking Potential

Ranking: Medium

Justification: Phytochemicals are compatible with genetics, productivity gains, and some dietary strategies, but overlap mechanistically with other rumen modifiers limits full additivity.

Technology Readiness Level (TRL)

Ranking: 7-9

Justification: Numerous controlled trials demonstrate efficacy, though variably; several products (e.g. Agolin) are commercially available and widely used internationally (Ahmed et al. 2021; Nastoh et al. 2024)..

Commercial Readiness Level (CRL)

Ranking: 6

Justification: Commercial products exist, but uptake is limited by cost, variable returns, and modest carbon value. Adoption is strongest where supported by processors or integrated sustainability programs. Some products like Agolin supported by major dairy processors.

Enabling Potential

Ranking: Low

Justification: narrow range of application

Estimated Cost Range:

Agolin as example: dose in 1 gram per cow per day costs Au\$0.07-0.10

Estimated Benefit

Agolin as example: AU\$0.6–0.7 if reported improved milk solids (assume 1.48kg more milk per cow per day), feed efficiency (assume 4% gain) and monetised emissions reduction (assume 10% reduction) are realised

Investment in R&D and Commercialisation

Range:

- Australian investment (itemised): **\$1.95 M**
 - “Lower emissions supplements for grazing at scale” (evaluation of phytochemical extracts such as essential oils in grazing-relevant delivery contexts).
Category: 1. R&D with 2. Commercialisation relevance.
 - “Lick-blocks for methane mitigation and production in grazing cattle” (development of lick-block formulations using tannins, saponins and other phytochemicals; practical grazing delivery).
Category: 1. R&D with 2. Commercialisation relevance.

Nitrate supplementation in feed

Summary:

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Nitrate (NO_3^-) supplementation reduces enteric methane emissions by acting as an alternative hydrogen sink in the rumen, thereby competing with methanogenesis. It is particularly effective in grazing systems and feedlots, with moderate abatement potential and minimal impact on dry matter intake or fibre digestibility. However, risks of nitrite toxicity and regulatory concerns must be managed through careful dosing and adaptation strategies (In Australian pasture-based systems with already high protein forage, nitrate supplements are used cautiously due to poisoning risk). Technically effective and compatible with grazing (no DMI/NDF penalty on average), but uptake in pasture dairy may be constrained by nitrite toxicity risk, delivery control, and milk-market risk management (Garnett and Eckard 2024)

Annual Abatement Potential (Technical)

Meta-analysis shows methane yield reductions of 15.7% mean, 10.0–22.1% (95% CI) at 17.2–22.1 g/kg DM (Almeida et al. 2021), with some studies reporting up to 38% when combined with other additives.

Abatement Potential – Economic/Feasible

Estimate 0-0.05MT CO₂-e per year

Technically feasible in grazing systems and feedlots. Cost-effective due to dual role as a non-protein nitrogen source. Risks of nitrite toxicity require careful management, which may limit widespread adoption. Black et al. (2021) suggest 4% of the national herd might be accessed for nitrate feeding. Scaling this results in potential abatement of 0.05 MT per annum. Garnett and Eckard consider not relevant to dairy pasture systems due to risk.

Breadth of Application

Ranking: Medium

Justification: Applicable across dairy, beef, and sheep enterprises. Most effective in systems with controlled supplementation. Less suitable for extensive rangelands without infrastructure.

Co-Benefit Potential

Ranking: Medium

Justification: Supplies non-protein nitrogen to rumen microbes, potentially reducing need for other nitrogen sources (Villar et al 2020). No adverse effects on DMI or fibre digestibility. May improve nitrogen use efficiency.

Barriers and Knowledge Gaps

Ranking: Medium

Justification:

- Risk of nitrite toxicity (methaemoglobinaemia)
- Need for adaptation protocols
- Regulatory and consumer concerns
- Limited long-term field data

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Stacking Potential

Ranking: High

Justification: Nitrate shows additive or complementary effects when combined with other methane mitigation strategies such as lipids, essential oils, or 3NOP. Stacking can reduce the required nitrate dose, lowering toxicity risk while maintaining abatement (Almeida et al. 2021; Cottle & Eckard 2014).

Technology Readiness Level (TRL)

Ranking: 8-9

Justification: Proven in multiple in vivo trials. Included in Australia's Emissions Reduction Fund methodology. Ready for deployment with proper management.

Commercial Readiness Level (CRL)

Ranking: 6

Justification: Commercially viable in feedlot and dairy systems. Adoption limited by safety concerns and delivery logistics in extensive grazing systems and risk of animal death. Issues with high nitrate forages in Australia.

Enabling Potential

Ranking: Medium

Justification: Enables stacking with other feed-based mitigation options.

Estimated Cost Range:

AU\$0.10–0.30 \$/animal/day

Estimated Benefits:

AU\$0.05–0.15

(Savings from reduced protein supplementation; potential carbon credits)

Investment in R&D and Commercialisation

Range:

- Australian investment likely less <0.5M
MERIL: Mort and Co. Lot Feeders (\$387,667) will demonstrate the feasibility of a holistic technology solution for feeding nitrates to grazing cattle for methane reduction
- International investment (itemised):
 -

Garlic & citrus extract**Summary:**

Garlic and bitter orange (citrus) extracts are commercial phytogetic feed additives designed to reduce enteric methane emissions in ruminants. Mootral™, now in liquidation, was the most prominent commercial formulation and their product has been evaluated in multiple dairy studies. The proposed mode of action involves inhibition of rumen methanogens and modification of fermentation pathways, leading to reduced methane formation.

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Dairy systems are particularly suited to this class of additive because cows typically receive daily supplementary feed or mixed rations, allowing consistent delivery and intake. Evidence indicates moderate methane reductions are achievable in dairy cattle, although responses are variable, may require adaptation periods, and are influenced by diet composition, dose, and intake consistency. Cost remains a significant constraint on widespread adoption.

Annual Abatement Potential (Technical)

Estimate: 10-25%

Justification: In vivo dairy studies generally report methane reductions of approximately 10–25%, with higher reductions reported in some commercial farm trials.

- A commercial dairy study using laser methane detectors reported reductions of approximately 38% in Jersey cows and ~20% in Holstein-Friesian cows during periods of Mootral™ supplementation (Vrancken et al. 2019).
- Controlled research studies and longer-term trials indicate that average methane reductions across full feeding periods are typically lower, reflecting intake variability and adaptation effects (Roque et al. 2019; Honan et al. 2022).

Abatement Potential – Economic/Feasible

Estimate range 0.05 -0.396 MT per year

Justification:

- Eligible systems: Dairy farms providing regular supplementary feed (partial or total mixed rations, concentrates, or pellets).
- Eligible share of farms: Approximately 64% of dairy operations.
- Adoption among eligible farms: 14-30% as per essential oils into grazing from Cowie et al. 2025
- Sustained methane reduction (feasible): ~12–18%, discounted from technical maxima to reflect long-term averaging and intake variability.

Breadth of Application

Ranking: Moderate

Justification: Best suited to confined systems. Limited practicality in extensive grazing systems due to delivery challenges.

Co-Benefit Potential

Ranking: moderate

Justification:

Some studies report small increases in milk yield, typically around 3–5%, with larger responses occasionally observed under specific conditions (Belanche et al. 2020; Vrancken et al. 2019). Improvements in rumen fermentation patterns and some animal

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health indicators have also been reported, although results are inconsistent and context-dependent. Co-benefits should therefore be considered possible but not guaranteed.

Barriers and Knowledge Gaps

Ranking: moderate

Justification:

- Cost of commercial formulations remains high relative to methane value alone.
- Variability in methane response across herds, diets and time.
- Limited availability of long-term (>12 months), independent commercial dairy trials.
- Ongoing uncertainty regarding measurement methodologies (e.g. laser vs respiration-based systems) and implications for inventory reporting.
- Need for further evidence on milk composition, sensory attributes and consumer perception, although no consistent negative effects have been demonstrated (Vrancken et al. 2019; Honan et al. 2022).

Stacking Potential

Ranking: low

Justification: Garlic–citrus extracts can be combined with other dietary methane mitigation strategies (e.g. lipids or alternative hydrogen sinks). However, evidence for true synergistic effects is limited, and stacking increases cost and management complexity (Honan et al. 2022).

Technology Readiness Level (TRL)

Ranking: 8

Justification: Mode of action is reasonably well understood, efficacy has been demonstrated in multiple dairy trials, and commercial products are available and used in pilot and early commercial programs (Roque et al. 2019; Vrancken et al. 2019).

Commercial Readiness Level (CRL)

Ranking: 5

Justification:

Products are available in some markets, but adoption remains limited by cost, variable performance and commercial uncertainty. The receivership of a major supplier highlights ongoing scale-up and business risks.

Enabling Potential

Ranking: low

Justification: Garlic–citrus extracts function as a stand-alone methane mitigation option and do not enable or unlock other mitigation technologies or system transformations.

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Estimated Cost Range:

AU\$0.20-0.40 based on 20-25 grams per cow per day delivered as pellets ([Mootral](#) | [Enterix™](#))

Estimated Benefits:

AU\$0-0.10 (potential carbon credits) based on 10-25% methane production, maybe additional benefits in milk yield (increase of 3-18%) and animal health

Investment in R&D and Commercialisation:

Range:

- Australian investment (itemised):
 - No current RDC investment
 -

Ionophore antibiotic (Monensin)**Summary:**

Ionophores are antimicrobial compounds used in ruminant diets to improve feed efficiency and modify rumen fermentation, with methane reduction occurring as a secondary effect. Monensin, the most widely used ionophore, selectively inhibits gram-positive rumen bacteria and protozoa, reducing hydrogen production and shifting fermentation toward increased propionate formation, thereby indirectly limiting substrates available for methanogenesis (Marques and Cooke 2021; Appuhamy et al. 2013).

In dairy cattle, monensin has been shown to reduce methane emissions under certain dietary and management conditions, although responses are highly variable and generally modest. Meta-analytical evidence indicates that methane reductions are often short-lived, with diminishing effectiveness over time due to rumen microbial adaptation (Appuhamy et al. 2013; Cooke et al. 2024). Use of monensin is largely confined to confined or supplement-fed dairy systems and is restricted or prohibited in some jurisdictions due to regulatory and antimicrobial stewardship concerns (Marques and Cooke 2021).

Mechanistically, monensin does not directly suppress methanogens; rather, it alters rumen fermentation pathways. Studies have shown no consistent reduction in the abundance of methanogenic archaea, indicating that methane mitigation occurs primarily through changes in acetate:propionate ratios and reduced hydrogen availability (Schären et al. 2017; Appuhamy et al. 2013). Additional contributing mechanisms may include increased competition for hydrogen by alternative microbial pathways and reduced protozoal activity (Russell and Strobel 1989; Appuhamy et al. 2013).

Annual Abatement Potential (Technical)

Estimate 4% (reductions ranging from 0.5–7.4%)

Justification:

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Meta-analytical assessments indicate that monensin supplementation results in small average reductions in methane yield in dairy cattle, with substantial between-study variability:

A comprehensive meta-analysis reported methane yield (Y_m) reductions ranging from 0.5–7.4%, with a mean reduction of approximately 4%, across dairy and beef studies (Appuhamy et al. 2013).

Several dairy-specific studies have reported no significant effect of monensin on methane emissions, particularly under pasture-based systems or at lower inclusion rates (Grainger et al. 2010).

Overall, methane mitigation effects in dairy cows are less consistent and generally smaller than those observed in beef cattle, and are frequently not sustained over long supplementation periods, reflecting microbial adaptation (Appuhamy et al. 2013; Cooke et al. 2024).

Abatement Potential – Economic/Feasible

Estimate: 0.02–0.27 Mt CO₂-e per year (but see note below)

In dairy systems, monensin is already used primarily for performance and metabolic benefits, including improved feed efficiency and energy balance. Methane reduction remains a co-benefit, not a primary driver of adoption (Marques and Cooke 2021; Appuhamy et al. 2013).

In Australia, monensin is regulated as a Prescription Animal Remedy (S4). Its use requires veterinary oversight, and milk withholding periods apply to lactating dairy cows, which constrains management flexibility and limits uptake across the sector. Given that monensin is already widely used where permitted, any methane abatement achieved may not be additional, further reducing its effective contribution at scale. Accordingly, the economically feasible abatement potential in dairy systems is very low, with an indicative upper bound of 0.02–0.27 Mt CO₂-e per year, noting that much of this may already be realised under existing practice (Marques and Cooke 2021; Appuhamy et al. 2013) giving effectively an estimate of 0 Mt CO₂-e per year additional gain.

Breadth of Application

Ranking: low

Justification: Limited to confined or supplemented dairy systems; Milk withholding periods restrict use in lactating cows; Not applicable in grazing only or organic dairy systems.

Co-Benefit Potential

Ranking: High

Justification: Improves feed efficiency, protein availability, and rumen pH. Reduces risk of acidosis. Methane reduction is a secondary benefit.

Barriers and Knowledge gaps

Ranking: High

Justification:

- Microbial adaptation reduces long-term efficacy

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- Regulatory restrictions
- Public health concerns over antimicrobial resistance
- Lack of methane-specific formulations

Stacking Potential

Ranking: Moderate

Justification: Limited synergy with other additives due to overlapping microbial targets. Can be combined with additives such as 3-NOP or dietary lipids, but incremental methane benefits are generally modest (Cooke et al. 2024).

Technology Readiness Level (TRL)

Ranking: 6

Justification: Widely used and well-understood. Fully developed and deployed in commercial systems. Still significant questions however when applied to methane mitigation application (hence lower TRL).

Commercial Readiness Level (CRL)

Ranking: 7

Justification: Commercially available and adopted in conventional feedlot and dairy systems. Regulatory and market limitations restrict broader use.

Enabling Potential

Ranking: low

Justification: Methane reduction is incidental. Limited role in enabling broader mitigation strategies.

Estimated Cost Range:

Au\$0.05-0.15/animal/day depending on dose and product formulation

Estimated Benefits:

Au\$0.1-0.25/animal/day from improved feed efficiency

Investment in R&D and Commercialisation

Range:

- Australian investment (itemised):
 -
 -
- International investment (itemised):
 -

Probiotics & directed microbials

Summary:

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Live microbial feed supplements (probiotics or direct-fed microbials), including selected bacteria and yeasts such as *Lactobacillus*, *Propionibacterium*, *Bacillus*, and *Saccharomyces*, have been evaluated as a strategy to alter rumen fermentation and reduce enteric methane emissions in dairy cattle. Proposed mechanisms include diversion of hydrogen toward propionate production or reductive acetogenesis, suppression of protozoa, and indirect inhibition of methanogenic archaea (Jeyanathan et al. 2014; Doyle et al. 2019).

In dairy systems, however, in vivo evidence does not support a consistent methane mitigation effect. Controlled chamber and tracer studies generally report no significant reductions in methane emission, yield, or intensity, despite occasional numerical improvements in fermentation profiles or feed efficiency (Jeyanathan et al. 2019; Ncho et al. 2024, Williams et al 2023, Nair et al 2026). Responses vary widely depending on probiotic strain, dose, diet composition (particularly starch level), parity, and duration of supplementation.

A recent meta-analysis synthesising global cattle studies concluded that probiotics do not significantly reduce methane emissions in dairy cattle overall, although multi-strain bacterial formulations and longer supplementation periods showed more favourable responses in some subgroups (Ncho et al. 2024). Consequently, probiotics are currently best viewed as a performance and health intervention, with methane reduction remaining an uncertain and secondary outcome.

Annual Abatement Potential (Technical)

Estimate: 0%

Justification:

Meta-analytical and experimental evidence indicates low and unreliable methane abatement potential in dairy cattle:

- Across 49 in vivo comparisons, probiotic supplementation did not significantly affect methane emission, methane yield, or methane intensity in cattle, with dairy cows comprising most studies (Ncho et al. 2024).
- Dairy-specific trials using *Lactobacillus* and *Propionibacterium* strains frequently showed no effect on methane, even where in vitro screening suggested antimethanogenic potential (Jeyanathan et al. 2019).
- Subgroup analyses suggest that multi-strain bacterial probiotics, particularly those combining propionate-producing or acetogenic pathways, may reduce methane under certain dietary conditions, but these effects were not consistent across dairy studies (Ncho et al. 2024).
- Meta-regression indicates that longer dosing periods improve the likelihood of methane reduction, suggesting that microbial establishment time may be a limiting factor (Ncho et al. 2024).

Overall, the technical methane abatement potential in dairy cattle is low (<5% on average) and highly variable, with insufficient confidence for broad recommendation.

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Abatement Potential – Economic/Feasible

Insufficient evidence for presumed effect

Justification:

Probiotics are widely used in dairy systems for animal health, feed efficiency, rumen stability, and production outcomes, not for methane mitigation. Given the absence of consistent methane reductions, there is insufficient evidence to justify probiotics as a cost-effective methane abatement strategy in dairy systems at present (Ncho et al. 2024).

Because many dairy herds already use probiotics, any methane reduction achieved would likely be non-additional. As a result, the economically feasible methane abatement potential at scale is very low.

Breadth of Application

Ranking: moderate

Justification:

Probiotics can be readily applied in TMR-based and supplement-fed dairy systems. Effectiveness and delivery are more challenging in pasture-based systems, where intake consistency is variable (Ncho et al. 2024).

Co-Benefit Potential

Ranking: high

Justification:

Demonstrated benefits for rumen health, feed efficiency, immune function, and milk production stability.

Potential to reduce reliance on therapeutic antibiotics and improve overall herd resilience (Doyle et al. 2019; Ncho et al. 2024).

Barriers and Knowledge Gaps

Ranking: High

Justification:

- Inconsistent methane responses across strains and studies.
- Poor translation from promising in vitro results to in vivo dairy systems.
- Uncertainty around optimal strain combinations, dosing rates, delivery frequency, and supplementation duration.
- Limited long-term studies under commercial pasture-based dairy conditions (Jeyanathan et al. 2019; Ncho et al. 2024).

Stacking Potential

Ranking: Moderate if it did work

Justification: Would clearly combine with other methods in additive way

Technology Readiness Level (TRL)

Ranking: 5 for methane

Justification: need for further work on length of dosing, bacterial suite required and breed variability

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Commercial Readiness Level (CRL)

Ranking: 7

Justification: Commercial products marketed for general use but targeting other uses; Products are not designed or approved specifically for methane abatement (Doyle et al. 2019).

Enabling Potential

Ranking: low

Justification: does not enable or enhance other technologies

Estimated Cost Range:

\$0.10-\$0.50 per head per day (yeast at low end, multi-strain blends more likely to induced methane reduction effect at high end)

Estimated Benefits:

Some evidence of increased milk yield of 1-2 L/day per cow (Nalla et al 2022) with estimated value of \$1.05 assuming milk price of \$0.70/L

Feed efficiency gain 5-10% resulting in \$0.10-0.30/day (Bach 2024)

Health/vet savings with 20-30% reductions in disease - \$0.05-\$0.20/day in reduced treatment cost (Krishnan et al 2020)

Investment in R&D and Commercialisation

Range:

- Australian investment (some share of **\$0.98 M RDC and others**)
 - “Precision bovine microbiome modulation – Phase 1–3” (meta-omics-driven development of synbiotic solutions to redirect energy from methane toward productivity). Category: 1. R&D / Enabling.
- International investment (itemised):
 -

Anti-methanogen vaccine (in development)

Summary:

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Anti-methanogen vaccines aim to reduce enteric methane emissions in dairy cattle by stimulating the host immune system to generate antibodies against rumen methanogenic archaea, particularly dominant taxa such as *Methanobrevibacter* spp. (Baca-González et al. 2020; Khanum et al. 2022). Vaccine-induced antibodies produced in serum and secreted into saliva are intended to enter the rumen, bind to methanogen surface antigens, and inhibit growth or methanogenic activity (Wedlock et al. 2010; Subharat et al. 2015).

In dairy cattle, key mechanistic steps have been demonstrated, including antigen identification, induction of methanogen-specific antibodies, salivary transfer of immunoglobulins, and antibody stability in rumen fluid (Subharat et al. 2015; Baca-González et al. 2020). However, despite approximately two decades of research, no antimethanogen vaccine has demonstrated consistent and durable methane reduction in vivo in dairy cows, and no commercial product exists (Baca-González et al. 2020; Global Methane Hub 2024).

If successfully developed, a dairy methane vaccine could theoretically provide long-term emissions reduction without daily supplementation, offering particular appeal for pasture-based dairy systems where feed-delivered additives are difficult to implement (Baca-González et al. 2020; Global Methane Hub 2024).

Annual Abatement Potential (Technical)

In vitro and early in vivo studies suggest potential methane reductions of 10–20%.

Justification:

In vitro studies using antisera from vaccinated animals frequently show inhibition of methanogen growth and methane production, but these results have poor translation to in vivo dairy systems (Wedlock et al. 2010; Baca-González et al. 2020).

Dairy-specific vaccination trials have demonstrated robust antibody responses in serum and saliva, yet methane emissions have generally not been significantly or consistently reduced when measured in vivo (Subharat et al. 2015; Baca-González et al. 2020).

Reviews conclude that methanogen populations in the rumen appear resilient, with community shifts often compensating for targeted suppression, limiting sustained methane abatement (Baca-González et al. 2020; Khanum et al. 2022).

Overall, the technical abatement potential for dairy cattle remains unproven, and estimated reductions should be considered speculative until replicated at scale.

Abatement Potential – Economic/Feasible

0-0.34 Mt CO₂-e per year

Justification

No commercial product available. If successful, vaccines could be low-cost and easily administered and could be widely adopted, but feasibility remains speculative.

Assume that maximum adoption in 10 years is 30% of herd and all herd relevant for vaccination calculations (this is not to say longer term reach might well get close to 100%)

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Breadth of Application

Ranking: High

Justification:

In principle, a vaccine could be applied across all dairy production systems, including intensive TMR-fed and pasture-based herds (Baca-González et al. 2020).

Delivery could be integrated into existing dairy herd health and vaccination programs, if efficacy and regulatory approval were achieved (Global Methane Hub 2024).

Co-Benefit Potential

Ranking: unclear/low

Justification:

Dairy vaccination studies generally report no negative impacts on milk production or animal health, but positive productivity or feed-efficiency benefits have not been demonstrated (Subharat et al. 2015; Baca-González et al. 2020).

Effects of sustained methanogen suppression on rumen fermentation efficiency in dairy cows remain poorly understood (Baca-González et al. 2020).

Barriers and Knowledge Gaps

Ranking: High

Justification:

Lack of consistent in vivo methane reduction in dairy cattle despite successful antibody induction (Baca-González et al. 2020).

High diversity and functional redundancy of rumen methanogens, complicating broad-spectrum vaccine design (Khanum et al. 2022).

Limited transfer and persistence of antibodies in the rumen, reducing effective exposure of methanogens (Subharat et al. 2015; Baca-González et al. 2020).

Long development timelines (>10 years), extensive safety testing, and regulatory requirements for biologicals, including inclusion on the Australian Register of Therapeutic Goods (Global Methane Hub 2024).

Stacking Potential

Ranking: High

Justification:

Vaccines could theoretically be stacked with genetic selection, feed additives (e.g. 3-NOP), dietary lipids, and pasture strategies to achieve cumulative methane reductions in dairy systems (Baca-González et al. 2020; Global Methane Hub 2024). However, additive or synergistic effects have not yet been empirically demonstrated.

Technology Readiness Level (TRL)

Ranking: 3

Justification: Proof-of-concept demonstrated in vitro. No successful in vivo replication or commercial prototype.

Commercial Readiness Level (CRL)

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Ranking: 1

Justification: No commercial product available. Still in research phase.

Enabling Potential

Ranking: low

Justification: insufficient evidence to date to indicate if will enhance other technologies

Estimated Cost Range:

AU\$0.01–0.05 per cow per day, assuming lifelong or multi-year protection from an annual vaccine cost of AU\$5–20 per cow (Global Methane Hub 2024).

Industry projections suggest potential abatement costs < AU\$150 per tonne CO₂-e, contingent on successful development and deployment (Global Methane Hub 2024).

Estimated Benefits:

AU\$0.05–0.15 per cow per day, primarily from potential carbon credit revenue.

Productivity benefits in dairy cattle remain unproven and speculative (Baca-González et al. 2020; Global Methane Hub 2024).

Investment in R&D and Commercialisation

Range:

- Australian investment (itemised):
 - None through RDC current investments
 -
- International investment (itemised):
 -

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Early-life rumen programming**Summary:**

Early-life rumen programming involves applying methane-mitigating interventions during calf development to alter rumen microbial colonisation in a way that reduces methane emissions later in life. The underlying hypothesis is that the rumen microbiome is more plastic in early life, and that shaping microbial succession during this period could result in a persistently lower-methane adult phenotype (Yáñez-Ruiz et al. 2015; Kolathingal-Thodika et al. 2025).

In dairy systems, the strongest evidence comes from controlled early-life supplementation with the antimethanogenic compound 3-nitrooxypropanol (3-NOP). Meale et al. (2021) demonstrated that calves treated with 3-NOP shortly after weaning exhibited 9–17% lower enteric methane emissions up to one year later, despite treatment having ceased, indicating partial persistence of the intervention effect. More recent work indicates that while microbial community shifts can persist for several months post-treatment, methane suppression itself is less durable and may diminish as animals mature and post-weaning diet becomes the dominant driver of rumen function (Martinez-Fernandez et al. 2024; McSweeney et al. 2024).

Overall, early-life rumen programming shows promise as a short- to medium-term methane mitigation strategy, but available evidence does not yet support consistent, lifelong methane reductions in dairy cows (Meale et al. 2021; McSweeney et al. 2024).

Annual Abatement Potential (Technical)

Assessment: 0–15% methane reduction, persisting months rather than years, with durability highly sensitive to timing, intake consistency, and postweaning diet.

Justification:

Evidence to date shows mixed outcomes:

- Sustained methane reductions of approximately 9–17% were measured ~12 months after treatment cessation in dairy calves supplemented with 3-NOP post-weaning (Meale et al. 2021).
- Although changes in rumen bacterial community structure can persist for several months post-treatment, these changes do not consistently translate into altered rumen fermentation patterns or methane production after withdrawal (McSweeney et al. 2024).
- Under grazing conditions with beef, Martinez-Fernandez et al. (2024) reported 10–15% lower methane emissions for up to 20 weeks (around 5 months) post-treatment, extending to 28 weeks post-weaning in one calving group. This represents the clearest demonstration to date of posttreatment methane suppression in beef systems.
- The same study showed that rumen microbial signatures characteristic of low methane phenotypes persisted longer than methane reductions, with microbial resemblance to the preweaning state accounting for ~60–65% of the yearling microbiome.

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- Other studies show shorter persistence or no sustained methane effect despite detectable microbial changes, indicating high inter-animal and cohort variability (McSweeney et al. 2024; Huuki et al. 2022).
- Evidence from sheep and goats suggests similar month-scale persistence, but not lifelong abatement (Abecia et al. 2013; Abecia et al. 2014).
- Collectively, these studies indicate that microbial shifts are more persistent than methane abatement, and methane emissions often revert toward baseline as diet and management override early-life effects (Yáñez-Ruiz et al. 2015; McSweeney et al. 2024).

Abatement Potential – Economic/Feasible

Estimate: assume lower of 0 Mt CO₂-e/yr and upper of 0.05 Mt CO₂-e/yr

Justification:

Implementation costs are relatively low because interventions are limited to the calf-rearing phase and could be integrated into existing dairy feeding systems (Meale et al. 2021). However, feasibility remains constrained by:

- Uncertainty around durability of methane reductions (Martinez-Fernandez et al. 2024; McSweeney et al. 2024),
- Absence of commercial early-life delivery protocols, and
- Lack of approved abatement methodologies.

For abatement accounting, conservative assumptions are appropriate:

- Maximum methane reduction: 9% (Meale et al. 2021),
- Duration: 1 year of a 5-year productive lifespan,
- Adoption ceiling: lower adoption of 3 and upper of 73%, analogous to feed-additive uptake (since will require feed additives).

Breadth of Application

Ranking: Moderate

Justification:

Most applicable to intensive dairy systems with controlled calf-rearing and individual feeding. Application is less practical in systems without early-life intake control or structured calf nutrition programs (Meale et al. 2021; Kolathingal-Thodika et al. 2025).

Co-Benefit Potential

Ranking: Moderate

Justification:

No negative impacts on growth or health have been reported in dairy calves treated early with 3-NOP (Meale et al. 2021). Potential co-benefits include improved rumen development consistency and reduced emissions intensity per unit of milk, though evidence for consistent productivity or reproductive gains is limited (McSweeney et al. 2024).

Barriers and Knowledge Gaps

Ranking: High

Justification:

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Limited in-vivo evidence for long-term or lifetime methane suppression (Meale et al. 2021; McSweeney et al. 2024),
 Uncertainty around optimal timing, dose, and duration (Martinez-Fernandez et al. 2024),
 Strong microbiome resilience post-weaning, with diet dominating long-term outcomes (Yáñez-Ruiz et al. 2015),
 Absence of commercial products or protocols, and
 Insufficient understanding of maternal or combined parent–calf programming strategies (Kolathingal-Thodika et al. 2025).

Stacking Potential

Ranking: high

Justification:

Early-life programming could be combined with genetic selection or adult feed-based methane mitigation. There is a plausible biological basis for priming the rumen to respond more effectively to later interventions, although direct evidence of additive or synergistic effects is currently lacking (McSweeney et al. 2024).

Technology Readiness Level (TRL)

Ranking: 5

Justification: Demonstrated in controlled trials but with variable results and uncertain duration.

Commercial Readiness Level (CRL)

Ranking: 2

Justification: Not yet commercially available. Research is ongoing to develop practical delivery systems and protocols.

Enabling Potential

Ranking: low

Justification:

Current evidence does not demonstrate that early-life rumen programming reliably amplifies the effectiveness of other methane mitigation strategies across the animal's lifetime (McSweeney et al. 2024).

Estimated Cost Range:

Cost will depend on additive (see those categories) though cost will only be for duration of feeding.

Estimated Benefits:

Nil beyond carbon credit (\$0.05 per animal per day)

Investment in R&D and Commercialisation

Range:

- Australian investment (itemised):
 -
 -
- International investment (itemised):
 -

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Selective breeding for low methane**Summary:**

Selective breeding for lower methane-emitting dairy cattle is a permanent, cumulative, and low-cost mitigation strategy that can be integrated into existing national breeding programs (de Haas et al. 2021; Richardson et al. 2022). Methane-related traits such as residual methane production, methane yield ($\text{CH}_4/\text{kg DMI}$), and methane intensity ($\text{CH}_4/\text{kg milk}$) are moderately heritable ($h^2 \approx 0.12\text{--}0.35$), indicating scope for genetic improvement (Lassen and Løvendahl 2016; Richardson et al. 2021; Worku 2024).

To date, reductions in dairy greenhouse gas (GHG) emissions achieved through genetic selection have occurred primarily via increased productivity, improved efficiency, and reduced cow numbers, leading to substantial declines in emissions intensity but smaller changes in absolute emissions (Capper et al. 2007; Bell et al. 2012; Pryce and Bell 2017; Bell 2024). Modelling shows that if methane traits are not explicitly included in breeding goals, total methane emissions per cow may increase over time due to higher intake associated with greater production, even as emissions intensity declines (de Haas et al. 2021; González-Recio et al. 2020).

Most modelling studies indicate that explicit inclusion of methane traits in breeding objectives has negligible impacts on milk production and farm profitability, with at worst small reductions in the rate of genetic gain for fat and protein yields (González-Recio et al. 2020; de Haas et al. 2021; Richardson et al. 2022). This is largely because genetic correlations between methane traits and key economic traits are modest, allowing methane to be reduced without major trade-offs (Bell 2024; Worku 2024).

Annual Abatement Potential (Technical)

Estimated potential: low per year, moderate cumulatively

Justification:

- Long-term modelling suggests annual reductions of $\sim 0.2\text{--}1.0\%$ $\text{CO}_2\text{-e}$ per year, accumulating over decades (Capper et al. 2007; Bell et al. 2012; de Haas et al. 2021; Richardson et al. 2022).
- Over a 30-year breeding horizon, emissions intensity reductions of $\sim 20\text{--}25\%$ are plausible under realistic selection scenarios (Bell et al. 2012; González-Recio et al. 2020; Richardson et al. 2022).
- Australian and European modelling indicates that absolute methane reductions of $\sim 5\text{--}10\%$ per cow by 2050 are achievable without reducing herd size, provided methane traits or methane-weighted indices are adopted (de Haas et al. 2021; Richardson et al. 2022).

Importantly, selection focused only on productivity is likely to continue reducing emissions intensity but not necessarily absolute emissions, reinforcing the need to explicitly weight methane in breeding objectives (de Haas et al. 2021; González-Recio et al. 2020).

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Abatement Potential – Economic/Feasible

Estimate: 0.11-0.45 Mt CO₂-e yr⁻¹ by 2050, if gains are reductions if reduced cow numbers of cows and constant output

Justification:

- Very low implementation cost, as selection is embedded within existing breeding programs and AI systems (Bell 2024; Richardson et al. 2022).
- No additional on-farm infrastructure or management change is required.
- Benefits accrue automatically and permanently as improved genetics disseminate through the population.

For abatement accounting, assuming:

- Assume adoption same as for herd management from NSW abatement studies of minimum 36% and upper of 80% for grazing animals over 10 years, and
- 8% (range 5-10%, noting that in theory upper limit remains unknown) absolute emissions reduction per cow under methane-weighted selection,

Breadth of Application

Ranking: High

Justification:

Selective breeding for lower methane emissions is applicable across all dairy production systems, including intensive housed, mixed, and pasture-based operations. In dairy systems, genetic improvements spread rapidly at the population level because breeding relies heavily on artificial insemination, allowing a small number of genetically elite sires to produce very large numbers of offspring across many herds (de Haas et al. 2021; Richardson et al. 2022).

Co-Benefit Potential

Ranking: low

Justification:

While selection indices are finite and increasing the number of traits can marginally reduce selection intensity for individual goals, most studies show little to no adverse impact on productivity or profitability when methane traits are included (González-Recio et al. 2020; de Haas et al. 2021). Co-benefits primarily arise indirectly through improved feed efficiency, longevity, and survival (Bell et al. 2012; Pryce and Bell 2017).

Barriers and Knowledge Gaps

Ranking: Medium

Justification:

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Limited large-scale phenotyping for methane traits remains the main constraint (de Haas et al. 2021; Worku 2024).

Need for validated proxies (e.g. milk MIR spectra, sniffers, residual methane EBVs) that are affordable at scale (González-Recio et al. 2020; Richardson et al. 2022).

Uncertainty around optimal trait definition (methane production vs yield vs intensity) and weighting (de Haas et al. 2021).

Stacking Potential

Ranking: High

Justification:

Genetic selection is fully compatible with feed additives, dietary strategies, pasture improvement, and herd management interventions, and provides a permanent baseline reduction upon which short-term strategies can stack (Bell 2024; Richardson et al. 2022).

Technology Readiness Level (TRL)

Ranking: 8

Justification:

Methane traits are identified, heritable, and increasingly available via genomic prediction. Multiple national programs are actively testing or implementing methane-weighted indices (de Haas et al. 2021; Richardson et al. 2022).

Commercial Readiness Level (CRL)

Ranking: 5

Justification:

Sustainability-oriented indices exist (e.g. Australia, Netherlands, NZ), but full routine integration of high-accuracy methane traits is still emerging and dependent on expanded reference populations (de Haas et al. 2021; Richardson et al. 2022).

Enabling Potential

Ranking: low

Justification:

Genetic selection does not directly enable other mitigation practices but reduces baseline emissions permanently, improving the long-term effectiveness of stacked strategies (Bell 2024).

Estimated Cost Range:

AU\$0.01–0.05 (costs embedded in breeding programs), may be slight negative economic value cost in reducing selection intensity for other production values.

Estimated Benefits:

Gains will be through other breeding values, slight value if methane reductions were to be monetised.

Investment in R&D and Commercialisation

Range:

- Australian investment **\$30.97 M via RDC and CRCNZA**

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- “LESTR – Low Emission Saliva Test” (development of proxy phenotyping tools to identify high- and low-methane animals and support breeding index integration).
Category: 1. R&D / Enabling.
- “Genetic evaluation of production efficiency and profitability” (integration of feed intake, energy use and productivity into breeding objectives; cumulative, low-friction mitigation).
Category: 1. R&D / Enabling.
-
- International investment (itemised):
-

Optimized N fertilizer-use on pasture**Summary:**

Reducing the application of synthetic nitrogen fertilizer on pastures to only the level needed for near-maximum pasture growth. Less excess N means lower nitrous oxide emissions from soils and less nitrate leaching, without big sacrifice in pasture production. Variable rate applications can be used to avoid spreading fertiliser on urine patches.

Annual Abatement Potential (Technical)

Christie et al (2020) found that N fertiliser losses could be reduced by 34-74% by lowering N fertiliser rates to that required to achieve 90% of potential maximum pasture production. Smith et al (2018) similarly found minimal production changes and 2-75% lower N losses with 20-50% N fertiliser reduction. Application of variable N application to avoid application to urine patches can reduce requirement for N fertiliser input by 10-50% (and by analogy reduce N losses by at least the same fraction, especially give losses will be higher on high concentration N patches).

Abatement Potential – Economic/Feasible

Potential abatement: 0.03-0.245 Mt CO₂e/yr

Assume N fertiliser loss rate reduction has low of 34 and high of 74%. Assume that N fertiliser contributes 4% of dairy emissions after Christie et al (2020) resulting in 0.35MT CO₂e/yr. This is low compared to estimates from University of Melbourne of around 0.6-0.8Mt CO₂e/yr. Assume adoption rates of low of 25% and high of 94% from NSW nitrogen fertiliser management scenarios (Cowie et al. 2025)

Breadth of Application

Ranking: high

Justification: dairy pastures in Australia receive on average 214 kg/N/yr and with higher rates approach 500 Kg>N/yr where stocking is heavier (after Garnett and Eckard 2024).

Co-Benefit Potential

Ranking: 3

Justification: Clear environmental co-benefits and potential reduced cost of fertiliser

Barriers and Knowledge Gaps

Ranking: low

Justification: guidelines, modelling and recommendations exist

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Stacking Potential

Ranking: high

Justification: works well with enteric methane technologies

Technology Readiness Level (TRL)

Ranking: 9

Justification: well established

Commercial Readiness Level (CRL)

Ranking: 7

Justification: well established however practice uptake can be influenced by risk of decreased production.

Enabling Potential

Ranking: low

Justification: stand alone

Estimated Cost Range:

Estimate based on apply fertiliser at 90% of rate required for maximum dry matter. This is modelled ([Quantifying-the-whole-farm-system-impact-of-nitrogen.pdf](#)) as a 5-10% reduction in annual pasture dry matter yield with minimal milk production impact if supplementary feed provided, if not there may be a loss of around 100 litres or around \$70 if milk price \$0.7/litre). If fertiliser added at 200kg/ha then assuming fertiliser at \$1.8 per kg N (typical urea) then the saving is around \$36/ha.

Estimated Benefits:

See above

Investment in R&D and Commercialisation

Range:

- Australian investment (dairy relevant cross-sector from RDC partners):
 - “More Profit from Nitrogen – NUE indicators for cotton, sugar, dairy and horticulture” (development of nitrogen use efficiency indicators; benchmarking and MRV foundations). Category: 1. R&D / Enabling.
 - “More Profit from Nitrogen – evaluation and economic case studies” (economic assessment of NUE practices across industries including dairy). Category: 2. Commercialisation / Enabling.
 - “Enhanced efficiency nitrogen fertilisers in the grains industry” (multi-site field trials, ¹⁵N tracing, modelling and economics for CRF, NIs and UIs; dairy tagged as secondary beneficiary). Category: 1. R&D / Enabling.
 -
- International investment (itemised):
 -

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Urine patch inhibitors (spray)**Summary:**

Applying a nitrification inhibitor across pasture (or in specific high-urine zones) after grazing. These inhibitors slow the conversion of ammonium to nitrate, reducing N₂O losses from urine patches. By treating urine patches with inhibitors like DCD, experiments have recorded anywhere from ~0% up to 80% (typical 50-60%) reduction in urine-derived N₂O emissions, though Australian studies have shown lesser effects in the range up to 40% (see Garnett and Eckard 2024). Practical challenges include the cost and effort of spraying large areas after each grazing, and environmental regulation of chemicals like DCD. After DCD residues were detected in milk in New Zealand use was suspended and in Australia DCD is restricted to research setting or under specific permits.

Annual Abatement Potential (Technical)

See above for potential 30-40% reduction.

Abatement Potential – Economic/Feasible

Range 0-0.12MT CO₂-e/yr

If we urine and dung contribute around 4% of dairy emissions direct from pasture (after Christie et al 2020) and the reduction potential is 30% then the upper potential abatement is 0.24Mt. Given regulatory constraints zero setting the lower estimate of adoption and we use the 91% as the 10 year upper adoption for nitrification inhibitors from Cowie et al. (2025).

Breadth of Application

Ranking: low

Justification: constrained by regulatory and market constraints.

Co-Benefit Potential

Ranking: low

Justification: no positive effects recorded

Barriers and Knowledge Gaps

Ranking: high

Justification: need clarity on residue risk and efficacy differences with soil type and climate.

Stacking Potential

Ranking: high

Justification: can be combined with a range of other pasture and enteric methane emissions strategies

Technology Readiness Level (TRL)

Ranking: 7

Justification: commercial products used and tested and scale

Commercial Readiness Level (CRL)

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Ranking: 5

Justification: produced commercially but constrained by regulation (needs a US codex listing) and markets

Enabling Potential

Ranking: low

Justification: stand alone approach, can be combined with but does not enhance variable N application

Estimated Cost Range:

Application costs of DCD and Nitrapyrin is in the order of \$50-100/ha/year

Estimated Benefits:

No effects on production

Investment in R&D and Commercialisation

Range:

- Australian investment (itemised):
 -
 -
- International investment (itemised):

On-off grazing (stand-off pads)

Summary:

Temporarily removing cattle from pasture (to a concrete pad or barn) during periods when soil conditions would cause high N₂O emissions. For example, in wet winter months or overnight, cows can be kept on a stand-off pad so that urine and dung are collected rather than deposited on wet soil.

Annual Abatement Potential (Technical)

Shown to reduce winter and early spring N₂O emissions by and leaching by 40-65% (; de Klein et al 2006; Luo et al 2013)

Abatement Potential – Economic/Feasible

0-0.029 Mt CO₂e/yr.

Effective only on farms with poorly drain soils and for wet parts of year (<150days per year), (Reisinger et al 2018). Assume 10% of farm emissions from manure management, technology applicable to 10% of farms, for half year.

Breadth of Application

Ranking: low

Justification: only farms with poorly drained soils

Co-Benefit Potential

Ranking: low

Justification: No real extended benefits

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Barriers and Knowledge Gaps

Ranking: moderate

Justification: Identification of where and extent of benefit, would need more detailed modelling

Stacking Potential

Ranking: high

Justification: Combines with animal based and pasture based abatement activities

Technology Readiness Level (TRL)

Ranking: 9

Justification: Tested and established

Commercial Readiness Level (CRL)

Ranking: 5

Justification: In principle no scaling impediments, but uptake may be impacted by cost

Enabling Potential

Ranking: moderate

Justification: stand alone technology, but can enhance manure and urine collection for relevant treatments

Estimated Cost Range:

Significant infrastructure cost. Costs in New Zealand for setting up wintering pads in 2016 was estimated at \$322 per cow with an annualised cost of \$72 per cow (Chrystal et al 2016).

Estimated Benefits:

There will be benefits in pasture protection, and potential improved grazing efficiency. There may be improved animal health from risks associated with wet conditions (lameness, mastitis)

Investment in R&D and Commercialisation

Range:

- Australian investment (itemised):
 -
 -
- International investment (itemised):
 -

Covered anaerobic lagoons and anaerobic digesters (biogas capture)

Summary:

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Covered anaerobic lagoons and anaerobic digesters involve placing an impermeable cover over dairy manure effluent ponds to capture biogas, predominantly methane (CH_4), generated during anaerobic decomposition of manure. Captured methane can be flared or used to generate renewable electricity and heat. In Australia, this technology is most applicable to intensive dairy systems with liquid effluent management, where a large proportion of manure is collected and directed to anaerobic ponds (Pratt et al. 2014; McCabe et al. 2014).

Annual Abatement Potential (Technical)

Up to 86%

Justification:

Across livestock systems, manure capture varies substantially:

- 10–20% in pasture-based systems,
- >70% and up to >90% in intensive total mixed ration systems, including housed dairy operations (Grell et al. 2024).

Even where manure capture is high, not all methane generated is abated. Empirical studies indicate that 10–20% of methane may be lost due to fugitive emissions through covers, pipework, or incomplete combustion in flares or engines (Flesch et al. 2011; Rotz et al. 2025).

Where anaerobic digesters operate continuously and $\geq 90\%$ of manure is treated, studies indicate that greenhouse gas emissions from manure management can be reduced by up to 86% compared with uncovered anaerobic lagoons (Pratt et al. 2014). This abatement corresponds almost entirely to reductions in methane emissions, which dominate emissions from anaerobic manure storage (Pratt et al. 2014).

GHG emissions, corresponding to almost all methane from manure storage

Abatement Potential – Economic/Feasible

0.2–0.3 Mt $\text{CO}_2\text{-e yr}^{-1}$

Justification:

Australian greenhouse gas inventories estimate methane emissions from dairy anaerobic effluent ponds at approximately 0.4 Mt $\text{CO}_2\text{-e yr}^{-1}$ (Pratt et al. 2014). This represents the maximum addressable emission source for covered lagoons and anaerobic digesters in the dairy sector.

Applying an upper-bound technical reduction of 86%, the theoretical maximum abatement from dairy manure management is approximately:

- 0.34 Mt $\text{CO}_2\text{-e yr}^{-1}$

However, this upper bound assumes:

- near-complete manure capture,
- continuous digester operation,
- minimal downtime, and
- low fugitive losses.

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Accounting for realistic system performance (70–85% effective methane capture) and adoption constraints, plausible national abatement from this technology in the Australian dairy sector is lower, likely in the order of 0.2–0.3 Mt CO₂-e yr⁻¹.

Breadth of Application

Ranking: low

Justification:

Application is limited to larger dairy farms (>1000 cows) due to:

- minimum manure volume requirements,
- high capital and operating costs,
- specialist technical and operational expertise,
- complexity of environmental approvals and zoning restrictions, and
- limited feed-in tariffs or other incentives for biogas electricity in Australia

Co-Benefit Potential

Ranking: moderate

Justification:

Where adopted, systems can:

- generate renewable electricity and heat,
- reduce odour and local air quality impacts,
- produce digestate suitable for land application as fertiliser,

although these co-benefits are typically insufficient on their own to justify investment (McCabe et al. 2014; Baylis et al. 2015).

Barriers and Knowledge Gaps

Ranking: low

Justification:

The technology is well established and commercially mature (Pratt et al. 2014).

Remaining issues relate mainly to:

- adequacy of greenhouse gas accounting frameworks,
- quantification of fugitive methane emissions, and
- economic performance under Australian energy and carbon market conditions

Stacking Potential

Ranking: high

Justification:

Manure methane abatement is additive with:

- animal productivity improvements,
- enteric methane mitigation,
- pasture and feed management strategies,

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and does not interfere with animal-level mitigation options. Consideration may need to be given to feed additives that influence methanogens which may interfere with pond digestion processes.

Technology Readiness Level (TRL)

Ranking: 9

Justification:

Commercially available and deployed in Australia and internationally

Commercial Readiness Level (CRL)

Ranking: 5

Justification:

Adopted at limited scale in Australia; constrained by capital costs, uncertain revenue streams, and policy settings (Baylis et al. 2015)

Enabling Potential

Ranking: low

Justification:

Biogas can support on-farm electricity generation, heating, and stationary equipment, but broader system transformation remains limited under current Australian conditions

Estimated Cost Range:

The typical cost of an anaerobic digester for a dairy farm in Australia ranges from AUD \$1.6M to over \$7 million, depending on the scale, technology, and integration level from [Market Analysis of Opportunities in Australia for Anaerobic Digestion Deployment](#)

Estimated Benefits:

Using a 180 hectare dairy farm as an example (after [Dairy Farm Small-Scale Anaerobic Digester - Hart Bioenergy Biogas Australia](#)). May reduce electricity costs – a small-scale system may generate 10KW and produce more than 215000kWh of electricity per year (\$10-30000 per year). Eligible for ACCUs and or renewable energy certificates where digester meets requirements of the Clean Energy Regulator (\$5-20000 per year). Digestate from the system can be sold as fertiliser (\$5-15,000 per year)

Investment in R&D and Commercialisation

Range:

- Australian investment (itemised):
 -
 -
- International investment (itemised):
 -

Effluent solid separation (flocculation)

Summary:

Treating liquid dairy manure (effluent) to remove organic solids, which reduces methane formation in storage ponds. For example, using mechanical separation plus chemical

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flocculants (like lime and polyferric sulfate) can take out ~85–99% of volatile solids from effluent, nearly eliminating subsequent methane emissions from the liquid fraction. The separated solids can be dried/composted and used as fertilizer. Research has shown that significant amounts of greenhouse gases (GHGs) are emitted during the storage and field application of slurry.

Annual Abatement Potential (Technical)

Compared to the conventional solid liquid separation methods through use of mechanical separation, the employment of the enhanced solid liquid separation (flocculant + mechanical separator) reduced GHG emissions during the storage and soil application phases by 53.64% and 31.63% however NH₃ emissions increased by 71% during the soil application phase (Gao and Wang 2025).

Abatement Potential – Economic/Feasible

0-0.013MT CO₂-e/yr

Assume 30-50% reduction compared to mechanical separation. Dairy Australia suggest 3% of dairy emissions from N₂O through manure spreading. If dairy emissions are 8.8MT/year. Maximum abatement potential 0.08-0.13Mt/yr. Extent of adoption may be lower due to costs and environmental and regulatory concerns about chemical residues. Assume adoption range 0-10%

Breadth of Application

Ranking: moderate

Justification: relevant to most enterprises but most relevant where some level of animal containment

Co-Benefit Potential

Ranking: moderate

Justification: Can create organic fertiliser for spreading

Barriers and Knowledge Gaps

Ranking: high

Justification: Some issues with coagulants altering manure nitrogen mineralisation and increasing nitrous oxide emissions, large scale field trials required (Ellison and Horwath 2021). Costs of flocculants (e.g. tannic acid, polyacrylamide) can be expensive and requires additional operational task of dosing. Requires specialist equipment and often retrofitting of existing set ups. Some flocculants may require regulatory approval for land application of subsequent slurry. Effectiveness of flocculants depends of slurry characteristics which can change seasonally requiring frequent adjustments in dosing. May not be compatible with anerobic and composting systems.

Stacking Potential

Ranking: high

Justification: works with animal and pasture management

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Technology Readiness Level (TRL)

Ranking: 7

Justification:

- Flocculant-based separation has been successfully demonstrated on-farm in Australia and internationally.
- Research trials (e.g., using tannic acid or polyacrylamide) have shown consistent performance in reducing total solids and improving separation efficiency.
- Systems have been integrated with existing effluent infrastructure on pilot farm

Commercial Readiness Level (CRL)

Ranking: 2

Justification:

- While technically proven, flocculant use is not yet widespread in the Australian dairy sector.
- Adoption is limited to a few demonstration sites or research-linked farms.
- Barriers include cost, regulatory uncertainty, and lack of farmer familiarity.

Enabling Potential

Ranking: low

Justification: stand alone

Estimated Cost Range:

Flocculants are in the order of \$3-10/kg and dose rates are in the order of 1-10g/l slurry. In addition to fixed costs for pumps and mixers (\$10-30,000) therefor for a small farm generating 5000m³ slurry per year cost \$3-\$10,000.

Estimated Benefits:

May generate ACCU return under the Animal Effluent Management Method. For the small farm described above this may be in the order of 500-100 t CO₂-e per year which at a carbon price of \$30/t would be worth \$1,500-3,000/year

Investment in R&D and Commercialisation

Range:

- Australian investment (itemised):
 -
 -
- International investment (itemised):
 -

Manure slurry acidification

Summary:

Dosing stored manure or effluent with acids (e.g. sulfuric acid) to lower p and reduce emissions.

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Annual Abatement Potential (Technical)

Acidification of dairy slurry has been shown to cut methane emissions during storage by anywhere from 17% up to over 90%, depending on acid amount and method (Fangueiro et al 2015, Sokolov et al 2019, Kavanagh et al 2019) .

Abatement Potential – Economic/Feasible

0.045-0.238Mt CO₂-e/yr

Given cost effectiveness assume 100% adoption in target population

Breadth of Application

Ranking: high

Justification: emerging compact systems extends technology to all farm sizes

Co-Benefit Potential

Ranking: low

Justification: stand alone

Barriers and Knowledge Gaps

Ranking: medium

Justification: More research is needed to describe the manure buffering capacity and emission reductions and ultimately find the best approaches for treating farm-scale liquid dairy manure tanks (Sokolov et al 2019)

Stacking Potential

Ranking: high

Justification: can be combined with other manure, animal and pasture management.

Technology Readiness Level (TRL)

Ranking: 9

Justification: systems widely deployed.

Commercial Readiness Level (CRL)

Ranking: 5

Justification: manure slurry acidification systems market size reached USD 1.24 billion in 2024 ([Manure Slurry Acidification Systems Market Research Report 2033](#))

Enabling Potential

Ranking: low

Justification: only manure management

Estimated Cost Range:

Assuming sulfuric acid applied at 2-5L per m³ of slurry, cost is \$0.5-\$2 per m³ of slurry which for a 200 cow farm produce around 10000m³ slurry per year results in \$7500-15,000 per year, and requires system site of storage tanks, dosing pumps and mixers and safety equipment totalling in the range \$10-\$30000 per farm.

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Estimated Benefits:

May generate ACCU return under the Animal Effluent Management Method. For the small farm described above this may be in the order of 500-100 t CO₂-e per year which at a carbon price of \$30/t would be worth \$1,500-3,000/year

Investment in R&D and Commercialisation

Range:

- Australian investment (itemised):
 -
 -
- International investment (itemised):
 -

Biochar feed supplementation**Summary:**

Biochar (charcoal) has been proposed as a dietary additive to reduce enteric methane by adsorbing hydrogen and altering rumen fermentation. Across dairy-relevant studies, results are highly variable and context dependent. Recent controlled feeding cattle studies using engineered or “fit for purpose” biochars have reported modest methane reductions (9–13%) under housed or pen conditions, without adverse effects on intake or rumen fermentation (MartínezFernández et al. 2024³²). However, these effects were not reproduced under grazing conditions, where no reductions in methane or improvements in productivity were detected (MartínezFernández et al. 2024). In dairy relevant trials, no consistent methane abatement has been observed. Recent reviews and syntheses conclude that biochar cannot be expected to deliver ≥10% methane mitigation in practical dairy systems, particularly where supplementation is pulsed (e.g. at milking) rather than delivered continuously in a total mixed ration (Dittmann et al. 2024; NZAGRC/GRA 2021).

Annual Abatement Potential (Technical)

Nil

Justification:

No reproducible methane reductions demonstrated in dairy cows under grazing or partial-ration supplementation conditions; modest effects observed only in controlled feeding systems have not scaled to dairy production environments.

Abatement Potential – Economic/Feasible

Nil

Justification: Any observed antimethanogenic effects are limited to specific biochars under controlled feeding conditions and do not generalise to pasture-based dairy systems dominant in Australia.

Breadth of Application

Ranking: low

Justification: ineffective

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Co-Benefit Potential

Ranking: low

Justification:

Dairy trials show no consistent improvements in feed efficiency, milk yield, or milk composition; no reliable animal performance co-benefits identified.

Barriers and Knowledge Gaps

Ranking: high

Justification:

- Strong dependence on biochar properties (feedstock, pyrolysis temperature, surface chemistry, nitrate content).
- Inconsistent responses between *in vitro*, housed, and grazing systems.
- Lack of efficacy under pulsed supplementation typical of dairy systems.
- No validated delivery strategy for pasture-based dairies.

Stacking Potential

Ranking: low

Justification:

No demonstrated additive or synergistic effect with other methane mitigation strategies in dairy cattle.

Technology Readiness Level (TRL)

Ranking: 7-8

Justification:

Multiple laboratory and animal trials completed; technology is technically mature but performance is not fit-for-purpose in dairy systems.

Commercial Readiness Level (CRL)

Ranking: 2

Justification:

No commercial adoption in dairy due to weak and inconsistent efficacy, particularly under grazing.

Enabling Potential

Ranking: low

Justification: no effect

Estimated Cost Range:

Most trials feed biochar at 0.5–1% of dry matter intake (DMI).

Assuming:

- 20 kg DMI/cow/day
- 36–73 kg biochar/cow/year
- Feed-grade biochar at \$1–2/kg

Estimated cost: \$36–146 per cow per year, with no reliable methane abatement or productivity return demonstrated.

Estimated Benefits:

Nil benefits

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Investment in R&D and Commercialisation

Range:

- Australian investment (itemised):
 -
 -
- International investment (itemised):
 -

Low-emission farm machinery

Summary:

Using alternatives to diesel tractors and vehicles on the farm to cut fuel emissions. Electric and hybrid tractors are in early development; once issues of battery runtime and power are resolved, they could eliminate on-farm diesel use. Similarly, farm equipment running on biogas (from a covered lagoon digester) or hydrogen fuel cells are being explored. Though these technologies are not yet common on dairy farms, they represent future options to reduce CO₂ emissions from farm operations (transport, tillage, feed mixing, etc.). Scope 2 emissions for milking and refrigeration equipment not considered here.

Annual Abatement Potential (Technical)

Use of electric vehicles powered by renewable energy could virtually eliminate machinery emissions. If powered with biofuels emissions reductions will be between 10 and 70% depending on biofuel production process. Studies show that existing generation of biogas and methane tractors produce NO_x emissions during engine warm up (Kuranc et al 2025)

Abatement Potential – Economic/Feasible

0.01-0.103 MT CO₂-e/yr

Diesel represents 2% of on-farm emissions for dairy – with the potential to reduce this by 10- 70% - giving a potential abatement of between 0.02 and 0.12Mt/year. Tractor longevity will slow rate of adoption. Use NSW (Cowie et al 2025) adoption range of 4-84%.

Breadth of Application

Ranking: high

Justification: with supply, price and support could be adopted in all systems.

Co-Benefit Potential

Ranking: low

Justification: substitution technology.

Barriers and Knowledge Gaps

Ranking: moderate

Justification: Hybrid, battery electric and fuel cell electric tractors in development but may be confronted with horsepower challenges. Methane (and biomethane) and other biofuels tractors available. Some work need on LCA emissions reductions during use.

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Stacking Potential

Ranking: high

Justification: additive to other farm technologies

Technology Readiness Level (TRL)

Ranking: 9

Justification: examples available commercially

Commercial Readiness Level (CRL)

Ranking: 3

Justification: multiple products available but not supply chains for fuel or service sector available in regional locations.

Enabling Potential

Ranking: low

Justification: substitution technology

Estimated Cost Range:

Electric tractors 20-30% dearer than diesel (diesel \$80-\$150,000 compared with \$100-\$200,000 for electric) and biofuel tractors are perhaps 10% more expensive than diesel.

Estimated Benefits:

Electrics cost lower than diesel costs, particularly if on farm solar generation. Biofuel generally more costly than diesel (1.5 -2x) however this may be reduced with on farm biomethane production which is around \$10-27/GJ compared with \$30-35/GJ for diesel (cost derived from [Analysis – How global energy prices are affecting the price of Australian farm inputs - DAFF](#) and <https://www.energynetworks.com.au/assets/uploads/Blunomy-%E2%80%93-2025-%E2%80%93-Biomethane-Opportunities-to-Decarbonise-Australian-Industry.pdf>).

Maintenance costs may be lower for electric vehicles. Generation of on farm biomethane requires high initial capital outlay.

Calculations based on following assumptions (100-cow herd, 10-year tractor life, 2,000 L diesel/year equivalent energy use):

Electric Tractor vs Diesel

- Extra capital cost:
 $\$138,000 - \$115,000 = \$23,000 \rightarrow \text{annualized} = \$2,300/\text{year}$
 $\rightarrow \$0.063 \text{ per cow per day}$
- Fuel saving (on-farm solar):
 Diesel \$2,470/year vs electric \$1,158/year $\rightarrow \$1,312 \text{ saved/year}$
 $\rightarrow \$0.036 \text{ per cow per day}$
- Net effect:
 $\$2,300 - \$1,312 = \$988 \text{ extra/year}$
 $\rightarrow \$0.027 \text{ extra cost per cow per day}$

Biofuel Tractor vs Diesel

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- Extra capital cost:
 $\$126,500 - \$115,000 = \$11,500 \rightarrow \text{annualized} = \$1,150/\text{year}$
 $\rightarrow \$0.032 \text{ per cow per day}$

Fuel scenarios:

- On-farm biomethane:
 $\$1,544/\text{year}$ vs diesel $\$2,470/\text{year} \rightarrow \926 saved/year
 $\rightarrow \$0.025 \text{ per cow per day}$
 Net: $\$224 \text{ extra/year} \rightarrow \$0.006 \text{ extra cost per cow per day}$
- Off-farm biofuel (1.75× diesel):
 $\$4,323/\text{year}$ vs diesel $\$2,470/\text{year} \rightarrow \$1,853 \text{ extra/year}$
 $\rightarrow \$0.051 \text{ per cow per day}$
 Net: $\$3,003 \text{ extra/year} \rightarrow \$0.083 \text{ extra cost per cow per day}$

Summary Table (per cow per day)

Tractor Type	Capital Cost	Fuel Benefit	Net Effect
Electric (solar)	\$0.063	\$0.036	+\$0.027
Biofuel (biomethane)	\$0.032	\$0.025	+\$0.006
Biofuel (off-farm)	\$0.032	-\$0.051	+\$0.083

Key Assumptions:

- Herd size = 100 cows (cost scales inversely with herd size).
- Tractor life = 10 years.
- Diesel energy cost = \$32/GJ; electric = \$15/GJ; biomethane = \$20/GJ.
- Maintenance savings for electric not included (could reduce net cost).
- On-farm solar and biomethane require separate capital outlays (not included).

Investment in R&D and Commercialisation

Range:

- Australian investment (itemised):
 -
 -
- International investment (itemised):
 -

Grape marc

Summary:

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Grape marc (also referred to as grape pomace) consists of the skins, seeds, stalks, and stems remaining after grapes are pressed for wine. It contains condensed tannins, high crude fat, and lignin, which can reduce enteric methane (CH_4) production in ruminants. Across Australian and international studies, methane reductions from grape marc are primarily associated with reduced fermentable organic matter intake and altered rumen fermentation, rather than a targeted anti-methanogenic effect, and are frequently accompanied by reductions in metabolisable energy intake when grape marc replaces higher-quality feeds (Moate et al. 2014; Caetano et al. 2019; Black et al. 2021).

Annual Abatement Potential (Technical)

Grape marc typically achieves 10–20% reductions in absolute methane emissions, but little or no reduction in methane intensity (per unit of production) when energy intake is accounted for (Moate et al. 2014; Caetano et al. 2019).

Justification:

The technical effectiveness of grape marc for methane reduction is highly context dependent and closely linked to the metabolisable energy (ME) content of the diet component it replaces.

Across controlled feeding trials:

- In late lactation dairy cows, replacing alfalfa hay with either dried or ensiled grape marc reduced daily methane emissions by 17–20% and methane yield ($\text{g CH}_4 \text{ kg}^{-1} \text{ DMI}$) by a similar magnitude. However, this was accompanied by reduced milk yield and body weight gain, particularly for ensiled grape marc, due to lower ME intake rather than improved fermentation efficiency (Moate et al. 2014).
- In early lactation pasture based dairy systems, partial replacement of perennial ryegrass with grape marc reduced methane emissions by 15%, but resulted in 10% lower milk production, reflecting energy dilution from the high lignin and low ME content of grape marc (Moate et al. 2020).
- In beef cattle, inclusion of 30% ensiled crimped grape marc reduced daily methane output by 14%, but this reduction was fully explained by lower ME intake, with no reduction when methane was expressed per unit of ME intake or weight gain. Growth performance declined due to reduced digestibility and energy availability (Caetano et al. 2019).
- In sheep, replacement of 20% of a standard forage grain ration with grape marc maintained liveweight gain while increasing intake and shifting nitrogen excretion from urine to faeces. Methane outcomes were not directly measured, but the absence of productivity loss at moderate inclusion levels indicates limited scope for large methane reductions without energy tradeoffs (Wu et al. 2022).

Abatement Potential – Economic/Feasible

Minimal given restrictions and trade-offs

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Justification:

While absolute methane reductions are technically achievable, they are largely driven by reduced fermentable energy intake, which frequently leads to reduced milk yield or growth rate. As a result, economically feasible abatement is limited under commercial Australian conditions unless grape marc replaces feeds of similarly low ME value (Moate et al. 2014; Moate et al. 2020).

Breadth of Application

Ranking: low

Justification:

Confined to situations where partial ration fed, costs of transport suggest need proximity to vineyards, metabolic energy trade-off confines to low pasture quality areas, and may be best confined to areas where feed supply low (after Black and Davidson 2021).

Co-Benefit Potential

Ranking: low

Justification:

While grape marc enables utilisation of a viticulture by-product and can modify milk fatty acid profiles, it commonly reduces milk yield or growth performance at inclusion levels required for methane abatement (Moate et al. 2014; Caetano et al. 2019).

Barriers and Knowledge Gaps

Ranking: low

Justification:

The nutritional characteristics, methane response, and productivity trade-offs of grape marc are well characterised across ruminant species. Remaining uncertainty relates mainly to optimising low inclusion rates that avoid energy penalties rather than to methane mitigation mechanisms per se (Moate et al. 2014; Wu et al. 2022).

Stacking Potential

Ranking: moderate

Justification:

Grape marc could be combined with other feed additives, herd management, or pasture strategies; however, stacking potential is constrained by intake limits and energy dilution effects that cap inclusion rates (Moate et al. 2020).

Technology Readiness Level (TRL)

Ranking: 6

Justification: trialled extensively

Commercial Readiness Level (CRL)

Ranking: 3

Justification:

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Not widely adopted as a standardised feed ingredient. Use depends on local availability, processing capacity, and *ad-hoc* arrangements between wineries and livestock producers (Moate et al. 2020).

Enabling Potential

Ranking: low

Justification: no enabling effect

Estimated Cost Range:

Grape marc is often free or low-cost at source (though demand from the feedlot industry may restrict supply to others), but processing, storage, and transport typically cost AUD \$50–100 t⁻¹. At daily intakes of 2–5 kg head⁻¹ day⁻¹, this equates to approximately: AUD \$0.10–0.30 per head per day (Moate et al. 2020).

Estimated Benefits:

Assume: nil

Justification:

Grape marc typically substitutes 10–20% of the diet. Where a total mixed ration costs \$300–500 t⁻¹, gross feed cost savings at 10% substitution are approximately of \$0.30–0.50 per head per day, but these savings are often offset or exceeded by reduced milk yield or growth rate when grape marc replaces higher-energy feeds (Moate et al. 2014; Caetano et al. 2019 pp. 168–170).

Investment in R&D and Commercialisation

Range:

- Australian investment (itemised):
 -
 -
- International investment (itemised):
 -

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