

## Appendix C.1: Red Meat and Sheep Sector

### Technology Assessment

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#### Technology Assessments

##### 3-Nitrooxypropanol (3-NOP) – rumen methane inhibitor

###### Summary:

3-NOP 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 methane yield with a mean response of close to 25% in

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beef cattle but with widely varying response based on dose of 3-NOP fed to animals and diet composition (Macdonald et al 2025). It is administered as a feed additive and has been trialled extensively in dairy cattle. It is noted as having a greater suppressing effect in high-forage than high-grain diets (Kim et al. 2019) though delivering it consistently to grazing animals is a challenge.

**Annual Abatement Potential (Technical):**

- Output: Up to 88% reduction in enteric methane emissions per animal, but meta-analysis shows 18–39% (95% CI), mean 23% reduction in methane yield.
- Justification: Trials in Australian dairy systems show reductions ranging from 18–39% (95% CI), mean 23% (MY) with beef studies spanning 1.5–59% in the Almeida dataset depending on diet and dosage (Almeida et al. 2021, Garnett and Eckard 2024, Macdonald et al 2025). The latter suggest the following formulae to describe response: Reduction in CH<sub>4</sub> yield ( %) =  $-25.9 - 0.17(3\text{NOP} - 125) - 8.76(\text{DMI} - 8)$ , where 3-NOP is the dose (mg 3-NOP kg<sup>-1</sup>DMI) and DMI is dry matter intake (kg head<sup>-1</sup>day<sup>-1</sup>)
- Waters et al (2020) in their analysis suggest technical abatement likely as 29% with a minimum of 18 and a maximum of 39%

**Abatement Potential – Economic/Feasible:**

- Output: Estimated feasible abatement of 0.06-0.34 Mt CO<sub>2</sub>-e/yr
- Justification: Assume only accessible to feedlot cattle with Australia capacity at 1.7M head and that there is 100% occupancy. Assume total enteric annual enteric methane from these animals is 1.18Mt CO<sub>2</sub>-e/yr. Assume access low adoption of 3% and high of 73% after Cowie et al 2025. Assume 23% reduction as per meta-analysis (Almedia et al 2021)
- Waters et al (2020) suggest likely adoption at 2% of beef grazed herd (range 0-30%), 60% of feedlot beef (range 30-70%) and 0% of sheep herd (range 0-10%).

**Breadth of Application**

- Ranking: Medium
- Justification: Currently confined feeding systems; limited applicability in pasture-based systems without daily feed control and further development of slow-release formulations, most effective in high forage than high grain diets

**Co-Benefit Potential**

- Ranking: Medium
- Justification: Potential improvements in feed conversion efficiency (e.g. Hristov et al. 2015, Lahart et al 2025). Meta-analysis shows small DMI reductions (up to 4.5%) though productivity outcomes depend on whether weight gain is maintained
- (Almeida et al. 2021, Garnett and Eckard 2024) highlight inconsistent productivity gains due to altered rumen microbiota possible (Ahmad et al 2025).

**Barriers and Knowledge Gaps**

- Ranking: Medium

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- 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.

## Stacking Potential

- Ranking: High
- Justification: Can be combined with precision feeding, genetic selection, manure management strategies and pasture management for synergistic effects. Demonstrated additive effects when combined with oils ( e.g. Gruninger et al 2022) and nitrates (Maigaard et al. 2024).

## Technology Readiness Level (TRL)

- Ranking: 8-9
- Justification: Proven in multiple in vivo trials; Has been deployed into confined systems.

## Commercial Readiness Level (CRL)

- Ranking: 6
- Justification: Commercial product (Bovaer) available internationally; no known commercial applications in Australia and any potential future usage of Bovaer would be subject to assessment by FSANZ for its safety for inclusion in animal feed as part of ensuring food safety in dairy and meat products, lack of ACCU methodology. Approved for use in USA, Brazil, Chile, EU among over 65 countries.

## Enabling Potential

- Ranking: low
- Justification: Easily included in methane accounting and feed efficiency frameworks, but no other enabling aspects.

## Estimated Cost Range:

AUD \$0.15 to \$0.6 per head per day. This range reflects different inclusion rates and pellet formulations tested in feedlot trials.

[https://www.agmanager.info/sites/default/files/pdf/FeedlotProducerAdoption-3-NOP\\_08-19-24.pdf](https://www.agmanager.info/sites/default/files/pdf/FeedlotProducerAdoption-3-NOP_08-19-24.pdf) ; FarmerDB. Bovaer: The Ruminants' Feed Additive to Reduce Methane Emissions (2025). Available at: <https://farmerdb.com/bovaer-the-ruminants-feed-additive-to-reduce-methane-emissions/>

## Estimated Benefits:

There is no strong, consistent evidence yet that Bovaer® increases productivity. Most studies show neutral effects on production, with the primary benefit being methane reduction. At \$30 t carbon price estimate return (without costs of accrediting etc) is around \$0.02 per animal per day if 25% of methane mitigated.

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## Investment in R&amp;D and Commercialisation

RDC and CRCNZEA investment: \$8,917,056

- Efficacy and delivery research for grazing and mixed systems: bundled programs testing 3 NOP alongside other inhibitors and delivery regimes “Lower emissions supplements for grazing at scale”
- Delivery technology development for extensive systems: biodegradable biopolymer bolus concepts to deliver controlled release 3 NOP in grazing animals “Biopolymers to deliver bioactive compounds that reduce enteric methane”
- Applied trials in commercial production contexts: evaluation of Bovaer®/3 NOP with supplementation in backgrounding systems “Reducing emissions of backgrounded cattle - combining Bovaer® with supplementation to reduce methane and increase productivity”
- MRV / carbon-footprint validation in commercial settings: large scale feedlot trials measuring performance, health and carbon footprint “Effect of Bovaer on performance, health, carcase characteristics and carbon footprint of Australian feedlot cattle.”
- Translation/IP activities: early work supporting bolus/compound IP and translation “Methane Reduction Bolus”
- CRC NZEA projects that creating a supporting environment including Project 4010 Strengthening the enabling environment for adoption and scaling of low emissions on-farm solutions and Project 4030 Demonstrating an Insetting Business Model in the Beef Value Chain

## Other Australian investment:

- MERiL (CSIRO-led) Stage 1: \$800,000 for 3-NOP trials in tropical and northern cattle (Mort & Co, Australian Agricultural Company, Northern Australia Pastoral Company partnership).
- Australian commercial trials and partnerships (Mort & Co, Coles) estimated investment: \$5M–\$10M.
- Mort and Co. Lot Feeders (\$367,186) in partnership with CSIRO, MultiCube, AACO and DSM Nutritional Products Australia, will demonstrate delivery of the methane-reducing feed additive 3-NOP in the form of a fodder cube for grazing animals.

## 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.

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**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. This can reduce methane emissions by up to 98% in trials and give feed efficiency or productivity gains. *Asparagopsis* is being explored as a feed supplement for cattle and sheep, with ongoing research into its safety, dosage, and scalability for commercial use. 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.

**Annual Abatement Potential (Technical)**

Emissions reduction have been recorded to be as high as 99% in controlled feed total mixed ration conditions but likely technical abatement lower with 60% plausible in feedlot situations. Early meta-analysis (Almeida 2021; n=3) found mean 49% (30–69% CI); subsequent trials/meta-analyses report higher reductions under feedlot delivery and standardised bromoform dosing.

Justification: Beef cattle fed high grain diets have achieved a high level of CH<sub>4</sub> mitigation if over 98% using respiration chambers as the measurement tool, and at inclusion levels between 25 - 35 mg bromoform (CHBr<sub>3</sub>)/kg total dry matter intake (DMI) for both *Asparagopsis* dried seaweed meal (Kinley et al 2020) and *Asparagopsis* steeped in edible oil (Cowley et al 2024). Roque et al. (2021) reported significant CH<sub>4</sub> mitigation of up to 70% (at 35 mg CHBr<sub>3</sub> /kg DMI) and 80% (at 70 mg CHBr<sub>3</sub> /kg DMI) in feedlot steers using GreenFeed Emissions Monitor (GEM) units, with Asp-Meal that persisted the duration of a 147-day feeding period. Kebreab et al. 2025 in a meta-analysis of the effects of *Asparagopsis* on methane production and yield found a -58% difference in methane production (g/d), -55% reduction in methane yield (g/kg DMI) and -50% reduction in CH<sub>4</sub> intensity (g/kg product). There are a variety of factors that influence the mitigation potential of *Asparagopsis* as either a meal or oil, which may include dietary composition, animal breed and genetics, or a combination of these factors. Waters et al. 2020 suggest 50% emissions reduction as the technical abatement potential (range 30-69%).

**Abatement Potential – Economic/Feasible**

Output: Estimated feasible abatement of 0.01-0.59 Mt CO<sub>2</sub>-e/yr

Justification:

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- Assume only accessible to feedlot cattle with Australia capacity at 1.7M head and that there is 100% occupancy. Total enteric methane from these animals is 1.18 MT CO<sub>2</sub>-e yr,. Assume adoption at 3-73% after Cowie et al 2025. Assume 30-69% reduction as per meta-analysis (Kebreab et al. 2025)
- Waters et al (2020) suggest likely adoption at 5% of beef grazed herd (range 0-10%), 60% of feedlot beef (range 0-70%) and 5% of sheep herd (range 0-10%).

**Breadth of Application**

Ranking: Medium

Justification: Best suited to confined feeding systems; limited applicability in pasture-based systems without daily feed control, can resort to pulse feeding methods with reduced efficacy.

**Co-Benefit Potential**

Ranking: Medium

Justification: Variable results on production gains from no effects (Cowley et al 2024) to average of 7.4% increase in feed use efficiency in 300 steer trial (Kinley et al 2024).

**Barriers and Knowledge Gaps**

Ranking: Moderate

Justification: Seaweed cultivation and scale while occurring is slow, product uniformity for dose response requires improved cultivation or post-processing.

Aspects externalities and bromoform risk are covered in Jia et al (2022).

Storage and handling require attention to avoid worker health risk. Requires stabilisation to avoid loss of bioactive though remains stable when steeped in oil (Tian et al. 2023)

**Stacking Potential**

Ranking: High

Justification: Can be combined with precision feeding, genetic selection, manure management strategies and pasture management for synergistic effects.

**Technology Readiness Level (TRL)**

Ranking: 7

Justification: Proven in multiple in vivo trials; scaling underway. Further validation needed for grazing systems.

**Commercial Readiness Level (CRL)**

Ranking: 5

Justification: Early commercialisation; pilot farms, niche or specialist products in market, cost of goods challenges for broadscale uptake, lack of ACCU methodology

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## Enabling Potential

Ranking: low

Justification: With product standardisation could be readily included in methane accounting and feed efficiency frameworks

## Estimated Cost Range:

AU\$0.40 to AU\$1.20 per head per day.

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:

Evidence of 7% feed efficiency gains Kinley et al. 2024 estimated at \$0.35/head/day and \$0.23/kg weight gain. Not found in all trials. If 58% of methane abated then around \$0.05 per head per day in carbon price (ex of any transaction costs).

## Investment in R&amp;D and Commercialisation

- RDC and CRCNZE \$7,359,712 (MERiL funding not included)

Dose–response and grazing delivery evidence: quantifying intake–mitigation relationships and delivery effects “Mitigating methane with Asparagopsis (ssp.)”

- Multi additive efficacy/safety and delivery work: programs testing Asparagopsis alongside other additives “Lower emissions supplements for grazing at scale”
- Product formulation and safety/residue studies: extract in oil carrier trials with residue and product quality assessment – ASSA Individual assessment 2023-177 “Efficacy and safety of Asparagopsis extract in a canola oil carrier for feedlot cattle”
- Value chain and scale-up pathway work: biorefinery “blueprint” projects mapping products and markets “Biorefinery approaches to creating value from Asparagopsis”.
- Regulation/standards/legitimacy: regulatory framework and guidance for food/feed products “Formulate a comprehensive framework to inform relevant regulatory bodies on safety regulations and legislation pertaining to food, feed, and other forms of bioproducts of Asparagopsis spp. and other seaweeds of key interest to the Australian seaweed”.
- Nursery/production scale-up R&D: seedstock/nursery innovation and process optimisation “Protoplast-Based Mariculture Solutions for scalable Asparagopsis farming” and “Evaluate and optimise cost and energy effective solutions for lighting, carbon delivery and mixing in intensive commercial scale tetrasporophyte production of Asparagopsis”
- Other Australian investment (itemised):
  - 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.
  - Investment and raises by SeaStock and Fremantle Seaweed Company
- International investment (itemised):

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- 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 2<sup>nd</sup> 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.

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. Improved or stable FCR, weight gain 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

*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. It is not possible at this stage to confidently identify the bioactive

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though a recently published patent family aimed at methane reduction describes a new class of methanogen inhibitors, including pyrometallic diimide derivatives (WO2025/178501)

*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 bromoform. 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.

#### Annual Abatement Potential (Technical)

Clear evidence from range of sources that 60-90% or higher abatement possible

Justification: evidence from trials, comparable performance from observations with 3NOP and Asparagopsis extracts (chemically the same); scalable if production expands. diet and dose dependent

#### Abatement Potential – Economic/Feasible

Output: Estimated feasible abatement of 0.01-0.54 MT CO<sub>2</sub>e/yr

Justification: Calculations as per Asparagopsis failing further evidence

#### Breadth of Application

Ranking: Medium

Justification: probably initially confined to close to barn situations until invention and commercialisation of safe and reliable carriers for extensive grazing systems

#### Co-Benefit Potential

Ranking: Medium

Justification: some emerging evidence of feed efficiency gains (as per Asparagopsis trials)

#### Barriers and Knowledge Gaps

Ranking: high

Justification: emerging products

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## 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, and price point of 3NOP (around 20c per dose) may be indicative.

## Estimated Benefits:

If 60% of methane abated then around \$0.05 per head per day in carbon price (ex of any transaction costs). Feed conversion efficiencies likely to be on par with Asparagopsis (\$0.35 per head per day) but as yet unclear.

## Investment in R&amp;D and Commercialisation

- RDC and CRCNZE: 3,856,970  
Bundled inhibitor efficacy, safety and delivery research: projects assessing bromoform/haloform options as part of multi additive portfolios “Lower emissions supplements for grazing at scale.”
- Alternative delivery concepts for extensive systems: delivery via water as an enabling route for large systems “Exploring methane inhibitors supplemented through water to increase beef industry sustainability
- Translation/IP support: IP and early translation work around long acting delivery (bolus) approaches that include haloform inhibitor classes “Methane Reduction Bolus”

Other Australian Investments:

- 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

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- Rumin8 were involved in a \$695000 trial with DPI,SA on delivery 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
- 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 Oндarza 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 Oндarza et al 2024). In beef cattle on high-forage diets, adding around 3% lipid can reduce CH<sub>4</sub> meaningfully, but some fat sources reduce fibre digestibility and/or intake depending on form and fatty acid profile (Beauchemin et al. 2007). In sheep, meta-analysis shows fat supplementation reduces methane across multiple expressions (g/d, g/kg DMI, % GEI) with little/no average effect on DMI, but higher fat levels can depress DM and NDF digestibility (Patra 2014). Diets with lipid intake of greater than 6-7% suppresses DMI setting a limit to potential reductions in emissions through lipid supplementation (Moate et al. 1999).

In Australia, the practical opportunity is constrained because most beef and sheep are grazing and do not receive consistent, controlled rations; therefore, lipid supplementation is most applicable where animals already receive regular supplements (feedlots, backgrounding, confinement/partial mixed rations, drought feeding, some intensive lamb systems). Some diets (dairy but possibly feedlots) may already be close to the optimal level for methane reduction, while others may have room for further fat supplementation

### Annual Abatement Potential (Technical)

Estimate: 12–20% (95% CI), mean 15% reduction in MY is typical at trialled doses (Almeida et al 2021), but adoption is constrained in grazing due to DMI and fibre digestibility penalties.

### Justification:

Beauchemin et al (2007) showed in a meta-analysis of supplementation for growing cattle that adding lipid sources to reach around 3% added fat (total dietary fat ~5.9% dry matter) when the fat was tallow or sunflower oil reduced methane by close to 14%

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compared with the control and when the fat was from whole sunflower seed by up to 33%. Among sheep studies dietary fat decreased methane production linearly (g/d; g/kg DMI; % GEI), while dry matter intake was not significantly affected, but dry matter and non detergent fibre digestibility declined with increasing fat, implying an upper practical limit if fibre digestion is important (Patra 2024).

In another meta-analysis Almeida et al. 2021, suggested that the 95% CI for emissions reduction compared to controls was 12–20% (95% CI), mean 15%

Taken together these reviews and studies suggest a practical limit of 12–120% reduction in enteric CH<sub>4</sub> for moderate additions of rumen-available fat (e.g., +1–3% units of fat in the diet), consistent with the approximate 3.8% per 1% lipid addition relationship and common feeding levels used in trials with a potential of up to 20–30% in some controlled experiments and specific fat sources/forms (e.g., whole sunflower seeds in high-forage cattle), but often accompanied by digestibility or intake effects that may not be acceptable commercially across systems.

A key consideration is that if methane falls mainly because intake or digestibility falls, animal performance can decline, and the net climate benefit per kg product may be smaller or uncertain unless productivity is maintained.

#### Abatement Potential – Economic/Feasible

Estimate: 0.07 to 0.24 Mt CO<sub>2</sub>-e/yr is a plausible range, dominated by beef feedlot/supplement segments, assuming modest uptake and no major new incentives. The lower end assumes limited adoption, short feeding window, conservative dose. The upper end assumes strong uptake in feedlots, meaningful backgrounding use and some intensive lamb finishing.

Justification:

Assumed practically feasible for feedlot beef and a subset of intensively supplemented/backgrounded cattle and a smaller subset of intensive lamb finishing or confined sheep feeding. Assume average CH<sub>4</sub> reduction while on ration of 15%. This assumes no leakage of emissions gains due to emissions generated during transport and assumes full lifecycle feeding of lipids. Assume 50% adoption at low end and over the long term 100% achievable if carbon credits linked.

#### Breadth of Application

Ranking: medium (beef) low (sheep)

Justification: Lipid supplementation is straightforward in controlled feeding (feedlots, partial mixed rations, confinement), but much harder in extensive grazing where dose control and daily intake are variable. The Australian cattle herd is large and heterogeneous; sheep are even more dominated by grazing. The grazing population (millions of head), are not “reachable” by a ration-based strategy

#### Co-Benefit Potential

Ranking: medium

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Justification: Potential productivity benefit can occur when added fat increases dietary energy density, supporting gain or performance. However, there are risks in that some fat sources/forms reduce fibre digestibility and/or intake, which can reduce performance in forage-based systems. Dairy-focused meta-regression highlights performance trade-offs (e.g., reductions in milk fat % and yield associated with rumen-available fats), from which we can infer into beef and sheep systems that co-benefits are not guaranteed and depend on fat type, dose and basal diet. Co-benefits are most likely where added energy is limiting and rations are balanced (feedlots, finishing rations, drought supplements), and least likely where fibre digestion drives performance (high-forage grazing without careful ration design).

### Barriers and Knowledge Gaps

Ranking: moderate

Justification:

Delivery/consistency in grazing systems: Achieving consistent daily dosing is difficult without infrastructure (supplement systems, controlled intake). This is a central practical barrier for Australia's grazing-dominant cattle and sheep industries.

Performance trade-offs at higher inclusion: Evidence in cattle and sheep shows higher fat can reduce NDF digestibility and sometimes reduce intake, risking productivity losses.

Fat type/form selection is non-trivial: Different lipid sources produce different methane and digestibility responses so "lipids" are not a single uniform intervention.

System-specific dose-response under Australian grazing/supplement patterns (intermittent feeding, variable intake) remains a key uncertainty in valorising emissions reductions. The [low emissions framework for feed technologies](#) stresses that robust dose-response relationships require datasets reflective of commercial conditions.

Whole-of-system economics (fat cost, handling, transport, labour, potential productivity effects) is context-specific and not resolved by experimental methane studies alone (de Ondarza et al 2024).

### Stacking Potential

Ranking: high

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

### 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.

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## Enabling Potential

Ranking: low

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

## Estimated Cost Range:

The cost per day will depend on fat used, market conditions and transport costs. For the purposes of calculation DMI per day for beef cattle is assumed 10kg/day and fat inclusion at 3% of diet DM; and for sheep DMI of 1.5kg DM/day and lipid added at 5% of DM due to higher fibre diet. Abatement effectiveness uses the following classification: High indicates reliable, repeatable direct reductions in enteric methane when fed at practical doses, with a clear rumen mechanism (e.g. unsaturated vegetable oils); Medium means consistent but moderate methane reductions, or reductions partly confounded by digestibility/intake effects (e.g. animal fats, oilseeds); Low is where no robust direct rumen effect; not suitable as a primary methane mitigation measure (e.g. rumen-protected fats like Megalac).

Table 1. Indicative prices for lipid sources from April 2026 searches (urls listed).

| Lipid source                                   | Indicative price (A\$/kg)                                                                                                                                                                                                                                                                                                                                                      | Beef cattle (A\$/hd/day) | Sheep (A\$/hd/day) | Abatement effectiveness | Rationale                                                                                                                                                                          |
|------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|--------------------|-------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Animal fats (tallow / poultry fat)</b>      | 1.20 – 2.00<br><small>source<br/><a href="https://view.agriculture.com.au/station-tallow-index">https://view.agriculture.com.au/station-tallow-index</a></small>                                                                                                                                                                                                               | 0.36 – 0.60              | 0.06 – 0.16        | Medium                  | Rumen-available; consistently reduces CH <sub>4</sub> at moderate inclusion (1–3% DM). Effect size is material but smaller than highly unsaturated oils.                           |
| <b>Vegetable oils (canola / sunflower oil)</b> | 1.80 – 3.00<br><small><a href="https://www.safinewsmac.com/insights/prices/australia/canola-oil">https://www.safinewsmac.com/insights/prices/australia/canola-oil</a><br/><a href="https://www.safinewsmac.com/insights/prices/australia/sunflower-oil">https://www.safinewsmac.com/insights/prices/australia/sunflower-oil</a></small>                                        | 0.54 – 0.90              | 0.09 – 0.24        | High                    | Rumen-available and more unsaturated; stronger inhibition of methanogenesis and protozoa. Upper end constrained by intake/fibre digestibility risks.                               |
| <b>Oilseeds (fat-equivalent basis)</b>         | 2.2 – 3.9<br><i>(per kg fat)</i><br><small><a href="https://www.agriculture.gov.au/bares/data/weekly-commodity-price-update">https://www.agriculture.gov.au/bares/data/weekly-commodity-price-update</a><br/><a href="https://www.safinewsmac.com/insights/prices/australia/rapeseed-canola">https://www.safinewsmac.com/insights/prices/australia/rapeseed-canola</a></small> | 0.66 – 1.17              | 0.11 – 0.31        | Medium                  | Mixed mechanism: some direct lipid effect, but part of observed CH <sub>4</sub> reduction often due to reduced fibre digestion or intake rather than true biochemical suppression. |

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|                                             |                                                                                                                                                                                                                                                                                                                |             |             |     |                                                                                                                                                                                  |
|---------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|-------------|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Megalac® (palm fat; rumen-protected)</b> | 2.80 – 4.00<br><small>Megalac® is a premium rumen-protected fat (calcium salts of palm fatty acids) sold at a substantial premium to commodity fat sources such as tallow; indicative costs of A\$2.8–4.0/kg were derived from commercial supplier information and Australian tallow market benchmarks</small> | 0.84 – 1.20 | 0.14 – 0.32 | Low | Rumen-protected (bypass) fat; minimal direct effect on rumen fermentation. Any CH <sub>4</sub> change is indirect via intake or productivity, not a reliable mitigation pathway. |
|---------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|-------------|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

**Estimated Benefits:**

The typical performance response in well balanced diets in beef is +0.05-+0.20 kg/day (Clary et al 1993; Foster et al 2024). For sheep Patra showed no overall effect on DMI. Therefore, range in beef likely to be gain of \$0.1 to 0.6/hd.day assuming liveweight value of \$3.5-5kg. Assume no return from liveweight change in sheep. If a typical steer emits 140 g CH<sub>4</sub> head/day and we get a 10% reduction in emissions at a carbon price of \$30 tonne then there is a carbon value of around \$0.012 per head per day and over a 100 day feedlot stay of \$1.20 per head.

**Investment in R&D and Commercialisation**

Australian investment RDC and CRCNZE: \$843,755

Practical grazing delivery formats: formulation and testing of lick blocks incorporating vegetable oils and other rumen modifiers (“Lick-blocks for methane mitigation and production in grazing cattle”

- 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:**

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 co-benefits 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 (Cardoso-Gutierrez et al. 2021; Badgery et al. 2023).

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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 8-14% depending on species and inclusion rate in the diet (after Badgery et al. 2023; Charmley 2025).

Justification: Meta-analyses and synthesis studies indicate a wide range of responses. Badgery et al. (2023) showed that temperate legumes and herbs typically achieve 8–14% reductions in methane yield (g CH<sub>4</sub>/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. Cardoso Gutierrez et al. (2021) reported reductions of 0–32% in enteric methane with tannin rich tropical plants, with a clear dose–response relationship. Charmley (2025) noted the 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

Estimated feasible abatement: 0.28–1.12 Mt CO<sub>2</sub>-e per year.

Justification: Once established, phytochemical-rich pastures are cost-effective and do not require supplementary feeding infrastructure. However, feasible abatement at scale is constrained by agronomic fit, persistence and animal productivity impacts. Badgery et al. (2023) highlight that only a subset of temperate pasture species deliver methane reductions *and* maintain productivity under grazing. Assuming suitability in ~20% of regions and due to partial adoption. Assume low adoption within target area of 36% and high of 80% after Cowie et al. (2025) adoption figures for herd management.

## Breadth of Application

Ranking: Medium

Justification:

Phytochemical-rich pasture species are applicable across both northern and southern grazing systems, but adoption is uneven. Species such as Leucaena are well established in northern Australia, whereas 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.

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*Co-Benefit Potential*

Ranking: medium

Justification: Co-benefits may include improved forage quality, higher protein and energy content, extended growing seasons, improved nitrogen use efficiency and reduced urinary nitrogen losses. Some tannins can provide anti-parasitic effects, while legumes improve soil nitrogen status. However, outcomes are inconsistent. For example, biserrula has demonstrated strong methane suppression but has also been associated with reduced liveweight gain in grazing studies (Vercoe 2016; Badgery et al. 2023). Leucaena carries weediness risks, although sterile hybrids are under development. Overall, benefits are system and management dependent.

*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. Charmely (2025) raises issues of leakage through increased animal productivity.

*Stacking Potential*

Ranking: Medium

Justification: Phytochemical-rich pastures can be combined with other mitigation strategies, including genetic selection, improved herd efficiency, and 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: 8

Justification: Multiple species have been validated in field trials and commercial grazing systems. Leucaena is widely used internationally, while temperate legumes and herbs have demonstrated methane reduction under grazing. However, performance remains variable across environments, requiring further validation and refinement.

*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 (0.02-0.05 per animal per day assuming 5-15% improvement in NUE), potential productivity gains (1-3% liveweight gain increase giving 0.01-0.04 per animal per day), and reduced fertiliser costs, trivial input from carbon price(\$0.02/animal/day))

### Investment in R&D and Commercialisation

Range:

- Australian investment RDC and CRCNZE:
  - CRCNZE Project 1020 Feedbase Solutions to reduce Enteric Methane in Southern Australia and 1010 Northern Australia Low Methane Feedbase Program – Phase 1 Discovery
- 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 CH<sub>4</sub> per kg DMI for every g/kg DMI added, consistent with the mid-range responses in the Almeida et al. (2021) meta-analysis.

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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.

#### Annual Abatement Potential (Technical)

Abatement potential of 10%

Justification: 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 phytogenic reviews (Kholif & Olafadehan 2021; Nastoh et al. 2024).

#### Abatement Potential – Economic/Feasible

National abatement potential 0.03–0.12 Mt CO<sub>2</sub>-e yr<sup>-1</sup>

Justification: Assume restricted in application to confined/TMR systems with an achievable methane reduction of 11% and to pulse-fed/supplemented pasture systems with an achievable reduction of 5% (highly speculative), but consistent with reduced efficacy under intermittent dosing and microbial adaptation (Patra and Saxena 2010, Kholif and Olafadehan 2021). Assume adoption as for 3NOP supplements in Cowie et al. 2025.

#### Breadth of Application

Ranking: Medium

Justification: Most suitable for feedlot systems with controlled feeding (TMR, PMR, or daily supplementation). Application in extensive grazing systems is constrained by delivery, persistence of effect, and microbial adaptation

#### Co-Benefit Potential

Ranking: low

Justification: Beyond methane reduction, phytochemicals may provide:

- Improved nitrogen-use efficiency (reduced rumen protein degradation and urinary N losses)
- Potential animal health benefits (antioxidant, antiparasitic, heat-stress resilience)

However, anti-nutritional effects (reduced DMI or fibre digestibility) can occur at higher doses, constraining achievable benefits (Patra & Saxena 2010; Almeida et al. 2021).

#### Barriers and Knowledge Gaps

Ranking: Medium

Justification: Variable *in vivo* efficacy; Microbial adaptation with continuous feeding known to occur needs clarification; Limited long-term data on optimal dose and persistence ; Risk of intake depression or digestibility loss at high inclusion rates

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## 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; 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.

## Enabling Potential

Ranking: Low

Justification: narrow range of application

## Estimated Cost Range:

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

## Estimated Benefit

Return of around \$0.14 per head per day for cattle and \$0.04 per head per day for sheep.

Justification: Assume feed efficiency gain 2% feed efficiency gain (from Almeida et al. 2021; Kholif & Olafadehan 2021; Nastoh et al. 2024) then for beef around \$0.07 per head per day (assume feed cost around \$3.50 per head per day and arpend \$0.03 per head per day for sheep. Total carbon price gain at \$30 per tonne if 10% methane abatement reduction is around \$0.07 per head per day for cattle (assuming 90kg CH<sub>4</sub>/head/yr) and around \$0.01 per head per day for sheep assuming 20kg CH<sub>4</sub>/head/yr.

## Investment in R&amp;D and Commercialisation

Range:

- Australian investment RDC and CRCNZE: \$1954668:
  - Efficacy, safety, and delivery as part of multi additive portfolios: bundled programs including essential oils (e.g., Agolin type additives) (“Lower emissions supplements for grazing at scale”
  - Delivery format development for extensive systems: lick block formulation projects

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combining tannins/saponins/oils and other rumen modifiers (“Lick-blocks for methane mitigation and production in grazing cattle”).

- International investment (itemised):
  -

## Nitrate supplementation in feed

### Summary:

Nitrate ( $\text{NO}_3^-$ ) supplementation reduces enteric methane emissions by acting as an alternative hydrogen sink in the rumen, diverting hydrogen away from methanogenesis toward nitrate and nitrite reduction to ammonia. Across beef cattle and sheep, nitrate has demonstrated moderate methane abatement under controlled feeding conditions, particularly in feedlots, backgrounding systems, and supplemented grazing systems where intake can be managed.

Nitrate can also function as a non-protein nitrogen (NPN) source, partially substituting for urea in low-protein diets, which is particularly relevant for northern Australian beef systems and supplemented sheep enterprises. However, risk of nitrite toxicity (methaemoglobinaemia) remains the key constraint, requiring careful dosing, gradual adaptation, and appropriate delivery systems.

In Australian pasture-based systems with moderate to high crude protein, nitrate use is more limited and requires caution, particularly for sheep, due to poisoning risk and practical delivery challenges. Consequently, nitrate is not broadly applicable across extensive grazing systems without supplementation infrastructure (Nolan et al. 2016; Cottle & Eckard 2014; NSW DPI 2025).

### Annual Abatement Potential (Technical)

Justification: Meta-analyses and controlled animal studies report methane yield reductions of 10–22% for beef cattle and sheep. Higher reductions (up to 30–35%) have been observed at higher nitrate inclusion rates or when nitrate is combined with other additives (stacking) (Almeida et al. 2021; van Zijderveld et al. 2011).

- Typical achievable range (technical): 15–20% reduction in  $\text{CH}_4$  yield
- Upper experimental values: up to 30–38% under tightly controlled conditions

However, technical potential exceeds what is considered practically feasible at scale due to intake variability, toxicity risk, and delivery constraints.

### Abatement Potential – Economic/Feasible

0.02–0.05 Mt  $\text{CO}_2$ -e per year

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Justification: Nitrate supplementation is technically feasible in: beef feedlots and backgrounding systems; sheep finishing or supplemented grazing systems; extensive beef systems already using urea-based supplements (e.g. lick blocks), where nitrate may substitute for urea. Adoption at scale is constrained by animal health risk and management complexity. Modelling and national assessments suggest that only a small fraction of the national herd or flock is realistically accessible for sustained nitrate feeding. Black et al. (2021) and subsequent national modelling indicate that ~3–5% of the Australian beef and sheep population could feasibly adopt nitrate supplementation under current systems, translating to approximately 0.02–0.06 Mt CO<sub>2</sub>-e per year of abatement at the national level. Whole-farm assessments indicate that nitrate reduces total farm emissions, but the magnitude is modest relative to higher-efficacy inhibitors (e.g. 3-NOP), and carbon revenue alone is insufficient to drive adoption (Alvarez-Hess et al. 2019; ZNE-Ag CRC 2025).

### 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: Provides a nonprotein nitrogen source, potentially reducing reliance on urea or other supplements in low protein diets (Villar et al. 2020). Generally, no adverse effects on dry matter intake or fibre digestibility when animals are appropriately adapted (Almeida et al. 2021). Some studies report improved nitrogen use efficiency, though production responses (growth rate, feed efficiency) are variable and system dependent.

### Barriers and Knowledge Gaps

Ranking: Medium

Justification:

- Risk of nitrite toxicity, including animal morbidity and mortality
- Need for gradual adaptation protocols and careful ration formulation
- High variability in individual intake under grazing conditions
- Regulatory, animal welfare, and social licence concerns
- Limited long-term field data for extensive Australian beef and sheep systems
- Potential offset of methane gains by N<sub>2</sub>O formation under some conditions, reducing net abatement (Nolan et al. 2016)

### 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

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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 /head/day

**Estimated Benefits:**

AU\$0.05–0.15/head/day

(Savings from reduced protein supplementation; potential carbon credits)

**Investment in R&D and Commercialisation**

Range:

- Australian investment (itemised): \$387,667
  - 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 (e.g. Mootral)****Summary:**

Garlic and citrus extracts are phytogetic feed additives designed to reduce enteric methane emissions by direct inhibition of methanogenic archaea and modification of rumen microbial pathways. Commercial formulations (e.g. Mootral / Enterix™) combine organosulphur compounds from garlic (notably allicin) with citrus flavonoids (e.g. naringin).

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*In vivo* evidence now exists for beef cattle and sheep, showing modest but consistent methane reductions when intake is controlled. Practical deployment remains largely confined to feedlot, dairy, or intensively managed systems, with limited applicability to extensive grazing due to delivery constraints and cost.

#### Annual Abatement Potential (Technical)

13-23%, with occasional higher short term responses under controlled intake.

#### Justification:

##### Beef cattle (feedlot):

13% average reduction across a 12-week period; 23% reduction in final week when pellets fully consumed (Roque et al. 2019).

##### Sheep:

Dose-dependent reductions up to 12–13% without adverse effects on intake or digestibility (Ahmed et al. 2021).

No detectable reduction in methane yield or hydrogen emissions at 4 g/day Mootral™, even after adaptation, and no interaction with *Asparagopsis armata* (Fennessy et al. 2025) when fed pasture like/high roughage diets

Reductions are highly sensitive to intake consistency, diet composition, and dose and evidence is that reductions not reliably achieved.

#### Abatement Potential – Economic/Feasible

Estimate: 0.04–0.20 Mt CO<sub>2</sub>-e per year

#### Justification:

Commercially available but relatively expensive. Feasible in feedlot systems with controlled feeding for cattle (maximum 1.4M head at any one time), assume no accessible sheep and given low evidence of abatement ignore anyway. Assume low technical potential of 12% and high of 23%. Assume adoption rates as for 3NOP in Cowie et al 2025 (low 3% high 73%)

#### Breadth of Application

Ranking: Low

Justification: Not effective in sheep on roughage-based diets at realistic supplementation levels; limited applicability to intensive beef feedlots where intake can be tightly controlled; no demonstrated benefit in grazing systems

#### Co-Benefit Potential

Ranking: low

#### Justification

No consistent effects on intake, growth, or rumen fermentation in sheep (Fennessy et al. 2025) ; Behavioural or welfare benefits observed in earlier sheep studies were

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associated with high inclusion rates unlikely to be adopted commercially ; Dairy milk-yield responses reported elsewhere are not transferable to sheep or beef

### Barriers and Knowledge Gaps

Ranking: high

Justification:

- Highly variable results across species, diets, and feeding duration
- High cost relative to abatement achieved
- Commercial uncertainty following Mootral receivership
- Absence of credible long-term (>6–12 month) grazing studies
- Meat and milk impacts, taste concerns
- Delivery in grazing systems

### Stacking Potential

Ranking: low

Justification: No interaction or additive effect with *Asparagopsis armata* in sheep (Fennessy et al. 2025); No robust evidence of synergy with other mitigation pathways (nitrate, oils, 3-NOP)

### Technology Readiness Level (TRL)

Ranking: 7

Justification: Technically proven as a feed additive, but efficacy is not robust across target systems, particularly sheep.

### Commercial Readiness Level (CRL)

Ranking: 4

Justification: Products have existed commercially; Adoption constrained by weak and inconsistent mitigation performance ; Business continuity and reformulation uncertainty

### Enabling Potential

Ranking: low

Justification: Does not enable or unlock other methane-mitigation technologies or system changes.

### 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\$0-0.05 per animal per day

Justification: Sheep: No measurable methane benefit at feasible doses; Beef: Small potential carbon value only in feedlot systems

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## Investment in R&amp;D and Commercialisation:

## Range:

- Australian investment RDC and CRCNZE: \$0
- 
- International investment (itemised):
- 

**Ionophore antibiotic (Monensin)**

## Summary:

Ionophores are antimicrobial compounds widely used in beef cattle and sheep production systems to improve feed efficiency and animal performance through modification of rumen fermentation. Monensin, the most commonly used ionophore, selectively inhibits gram-positive rumen bacteria, leading to reduced acetate and hydrogen production and increased propionate formation, which indirectly limits substrates available for methanogenesis (Marques and Cooke 2021; Appuhamy et al. 2013).

In beef cattle, monensin consistently reduces enteric methane emissions under controlled feeding conditions, particularly in feedlot, backgrounding, and other confined or semi-confined systems. However, methane mitigation effects are moderate and often transient, declining with prolonged supplementation as rumen microbial communities adapt (Appuhamy et al. 2013; Cooke et al. 2024).

In sheep, monensin induces similar shifts in rumen fermentation and short-term methane reductions, but responses are variable and generally not persistent, limiting its role as a scalable methane mitigation option in grazing-based systems (Marques and Cooke 2021; Appuhamy et al. 2013). Regulatory constraints and antimicrobial stewardship concerns further restrict broader application.

## Annual Abatement Potential (Technical)

Estimate: MY reduced by only 4%, with 95% CI 0.5–7.4%, and the effect is limited to the period before rumen microbial adaptation.

## Justification:

Meta-analyses indicate that monensin reduces methane emissions in beef cattle by approximately 10–20% on average, with substantial variability across studies depending

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on dose, diet composition, feeding management, and duration of supplementation (Appuhamy et al. 2013; Cooke et al. 2024).

Another comprehensive meta-analysis across beef and dairy studies reported methane yield ( $Y_m$ ) reductions ranging from 0.5–7.4%, with a mean reduction of approximately 4%, and highlighted strong heterogeneity and inconsistent responses across experiments and the effect being limited to the period before microbial adaptation (Almeida et al. 2021).

A recent beef-specific meta-analysis found an average methane reduction of 15% (17.5 g CH<sub>4</sub>/day), with the strongest effects observed during the first 30–80 days of supplementation and at recommended dose ranges (32–44 mg/kg DM) (Cooke et al. 2024).

Several studies report no significant methane reduction, particularly at low doses, under grazing conditions, or following extended supplementation periods, reflecting limited persistence of the antimethanogenic effect (Appuhamy et al. 2013).

#### Abatement Potential – Economic/Feasible

Estimate: 0.0-0.06 MT CO<sub>2</sub>-e per year over and above existing use

Monensin is already widely used in beef feedlots, backgrounding operations, and some sheep finishing systems primarily for improvements in feed efficiency, growth rate, and health. Methane reduction remains an incidental co-benefit, rather than a primary motivation for use (Marques and Cooke 2021; Cooke et al. 2024).

In Australia, monensin is regulated as a Prescription Animal Remedy (S4), requiring veterinary oversight. Its use is largely confined to intensive or semi-intensive systems and excluded from organic production. Given its limited applicability, short-lived methane effects, and absence of methane-specific formulations, the economically feasible methane abatement potential at scale is very low (Marques and Cooke 2021; Appuhamy et al. 2013). Numbers here assume no barriers and that reductions are additional (which they may not be). Adoption assumed 100% into feedlots.

#### Breadth of Application

Ranking: low

Justification: Restricted primarily to feedlots, backgrounding, and supplement-fed beef and sheep systems; Not applicable across extensive grazing systems that dominate Australian beef and sheep production; Excluded from organic systems and constrained by prescription-only regulation.

#### Co-Benefit Potential

Ranking: Moderate

Justification: Improves feed efficiency, average daily gain, and energy utilisation;

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Reduces risk of ruminal acidosis and improves rumen stability; Methane reduction remains secondary and inconsistent.

### Barriers and Knowledge gaps

Ranking: High

Justification:

- Microbial adaptation reduces long-term efficacy
- Limited evidence for sustained methane reductions under commercial grazing conditions, particularly in sheep
- Regulatory restrictions
- Public health concerns over antimicrobial resistance
- Lack of methane-specific formulations

### Stacking Potential

Ranking: Low-Medium

Justification: Limited synergy with other additives due to overlapping microbial targets. May be used with 3-NOP or oils, but stacking benefits are modest (Cooke et al. 2024).

### Technology Readiness Level (TRL)

Ranking: 6

Justification: Widely used and well-understood. Fully developed and deployed in commercial systems. However less clearly understood for anti-methanogenic application (hence lower TRL)

### Commercial Readiness Level (CRL)

Ranking: 7

Justification: Commercially available and adopted in conventional feedlot and dairy systems. Regulatory and social licence 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 RDC and CRCNZE:
  - Practical delivery development in grazing systems: lick block development programs explicitly including ionophores among candidate additives “Lick-blocks for methane mitigation and production in grazing cattle”
- International investment (itemised):

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**Probiotics & directed microbials****Summary:**

Live microbial feed supplements (probiotics or direct-fed microbials), including selected bacteria and yeasts (e.g. *Lactobacillus*, *Propionibacterium*, *Bacillus*, *Saccharomyces*), have been investigated as a strategy to modify rumen fermentation toward pathways that reduce methane production. Proposed mechanisms include diversion of hydrogen toward propionate or reductive acetogenesis, reductions in protozoal abundance, and indirect inhibition of methanogenic archaea (Jeyanathan et al. 2014; Doyle et al. 2019).

In beef cattle, results from in vivo studies are highly variable. Many trials report no significant effect on methane emissions, while others show small reductions or even increases, depending on strain, dose, diet composition, animal type, and duration of supplementation (Jeyanathan et al. 2019; Ncho et al. 2024). A recent meta-analysis concluded that, when considered across all studies, probiotics do not consistently reduce methane emission, yield, or intensity in cattle (Ncho et al. 2024).

In sheep, a broader range of in vitro and in vivo studies suggests that certain probiotic strains or multi-strain formulations can reduce methane production under specific conditions, particularly when they enhance propionate production or suppress protozoa. However, effects remain strain-specific and inconsistent, and robust long-term in vivo evidence under grazing conditions is limited (Jeyanathan et al. 2016; Saleem et al. 2025).

Overall, current evidence indicates that probiotics cannot yet be recommended as a reliable methane mitigation strategy for beef cattle or sheep, although targeted multi-strain formulations and longer supplementation periods show some promise (Ncho et al. 2024; Almeida et al. 2021).

**Annual Abatement Potential (Technical)**

Insufficient evidence for presumed effect

**Justification:**

Meta-analytical evidence indicates no significant overall reduction in methane emissions from probiotic supplementation in cattle:

Ncho et al. (2024) analysed 49 in vivo comparisons and found no significant effect on methane emission, methane yield, or methane intensity in cattle overall.

Subgroup analyses showed that multi-strain bacterial probiotics, particularly combinations targeting propionate production and reductive acetogenesis, achieved moderate methane reductions, whereas single-strain probiotics often had no effect or increased methane (Ncho et al. 2024).

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Meta-regression indicated that longer supplementation periods were associated with greater methane reductions, suggesting that microbial establishment time is critical (Ncho et al. 2024).

In sheep, individual studies have reported methane reductions of approximately 10–15% for specific strains (e.g. *Lactobacillus pentosus*), but these effects were not universal and were sometimes offset by increases from other strains (Jeyanathan et al. 2016; Saleem et al. 2025).

Overall, the technical methane abatement potential is low and uncertain, with high variability across studies.

#### Abatement Potential – Economic/Feasible

Estimate 0MT CO<sub>2</sub>-e per year

Justification:

Given the lack of consistent methane reductions, there is insufficient evidence to justify probiotics as a methane-specific abatement option in beef cattle or sheep systems at present (Ncho et al. 2024; Almeida et al. 2021).

Probiotics are already used in some beef feedlot, backgrounding, and sheep production systems for performance, health, and feed efficiency benefits, rather than for methane mitigation. Any methane reduction achieved is therefore likely to be incidental and not additional. Consequently, the feasible methane abatement potential at scale is very low.

#### Breadth of Application

Ranking: moderate

Justification:

Probiotics can be administered in TMR-based beef feedlots, backgrounding systems, and intensively managed sheep systems.

Application is limited in extensive grazing systems, where regular delivery and dose control are difficult (Ncho et al. 2024; Saleem et al. 2025).

#### Co-Benefit Potential

Ranking: high

Justification:

Probiotic supplementation has been shown to improve animal performance, feed efficiency, gut health, immune function, and product quality in beef cattle and sheep. Evidence suggests reduced reliance on antibiotics and improved nutrient utilisation (Ncho et al. 2024; Saleem et al. 2025).

#### Barriers and Knowledge Gaps

Ranking: High

Justification:

- Highly variable and strain-specific methane responses.

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- Inconsistent translation from in vitro to in vivo results.
- Uncertainty around optimal strain combinations, dose, delivery method, and duration.
- Limited long-term grazing studies, particularly for sheep (Jeyanathan et al. 2019; Ncho et al. 2024).

*Stacking Potential*

Ranking: High if it did work

Justification:

In principle, probiotics could be combined additively with other mitigation strategies (e.g. lipids, nitrates, 3-NOP).

However, given the current uncertainty around methane efficacy, stacking benefits remain theoretical rather than demonstrated (Almeida et al. 2021; Ncho et al. 2024)

*Technology Readiness Level (TRL)*

Ranking: 5 for methane

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

*Commercial Readiness Level (CRL)*

Ranking: 7

Justification: Commercial products marketed for general use but targeting other uses. Products are not designed or validated specifically for methane abatement (Saleem et al. 2025).

*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 RDC and CRCNZE: \$978,864:
  - Meta omics discovery and prototype synbiotic development: early stage development of pro /pre biotic combinations to divert energy from methane into productivity;

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measurement and validation components to quantify methane and production outcomes as candidates progress “Precision bovine microbiome modulation - Phase 1 - 3).

- International investment (itemised):

- 

### Anti-methanogen vaccine (in development)

#### Summary:

Anti-methanogen vaccines aim to reduce enteric methane emissions by stimulating the host immune system to generate antibodies against rumen methanogenic archaea, particularly *Methanobrevibacter* spp., which dominate methane production in ruminants (Baca-González et al. 2020; Khanum et al. 2022). Antibodies produced in serum and secreted into saliva are intended to enter the rumen, bind to surface-exposed antigens on methanogens, and inhibit their growth or metabolic activity, thereby reducing methanogenesis (Wedlock et al. 2010; Subharat et al. 2015).

Over more than two decades of research, key mechanistic steps have been demonstrated, including antigen identification, induction of methanogen-specific antibodies, salivary transfer of immunoglobulins, antibody stability in rumen fluid, and inhibition of methane production in vitro (Baca-González et al. 2020; Khanum et al. 2022). However, translation to consistent and durable in vivo methane reduction has not been achieved, and no commercial vaccine is currently available (Baca-González et al. 2020; Global Methane Hub 2024).

Recent prototype studies, including those led by ArkeaBio, demonstrate renewed momentum, with short-term reductions in methane emissions reported under controlled conditions in beef cattle (Muntari et al. 2025; Frontiers in Animal Science 2025). Despite this progress, antimethanogen vaccines remain at an early development stage, with efficacy, durability, and scalability still uncertain (Global Methane Hub 2024).

#### Annual Abatement Potential (Technical)

In vitro and early in vivo studies suggest potential methane reductions of 10–20%, but results are inconsistent and not yet replicated at scale.

#### Justification:

In vitro studies frequently demonstrate methane inhibition when methanogens are exposed to vaccine-induced antisera, with reductions ranging from 20% to >40% depending on antigen and assay conditions (Wedlock et al. 2010; Baca-González et al. 2020).

Early in vivo sheep trials reported methane reductions of 7–13%, but these effects were inconsistent and often not replicated in follow-up studies (Wright 2004; Williams et al. 2009; Baca-González et al. 2020).

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A recent beef cattle study using a prototype vaccine reported 10–15% reductions in methane production, yield, and intensity over an 84-day measurement period without negative effects on growth performance (Muntari et al. 2025).

Reviews emphasise that methane suppression has generally been transient, with antibody titres declining over time and methanogen communities showing resilience or compositional shifts rather than sustained suppression (Baca-González et al. 2020; Khanum et al. 2022).

### Abatement Potential – Economic/Feasible

Range 0-3.0MT CO<sub>2</sub>-e/yr

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

For calculations assume range abatement 10-20%, relevant to all livestock and maximum adoption in 10 years is 30% to allow for development time and adoption process.

### Breadth of Application

Ranking: High

Justification:

Vaccines could theoretically be applied across beef, sheep, and dairy systems, including extensive pasture-based enterprises that are difficult to reach with feed additives (Baca-González et al. 2020; Global Methane Hub 2024).

Integration into existing animal health programs (e.g. routine vaccinations) would be straightforward if efficacy and regulatory approval were achieved (Malyugina et al. 2025).

### Co-Benefit Potential

Ranking: unclear/low

Justification:

Most studies report no negative impacts on growth or feed intake, but evidence for productivity gains or health co-benefits is limited (Williams et al. 2009; Muntari et al. 2025).

Altering rumen methanogen populations could theoretically affect fermentation efficiency, but consistent improvements in animal performance have not been demonstrated (Baca-González et al. 2020).

### Barriers and Knowledge Gaps

Ranking: High

Justification:

Lack of consistent in vivo efficacy and limited replication across environments and species (Baca-González et al. 2020; Global Methane Hub 2024).

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

Antibody delivery constraints, including limited IgG transfer to saliva and degradation of antibodies in rumen fluid (Subharat et al. 2015; Baca-González et al. 2020).

Long development timelines (>10 years) and regulatory complexity, with vaccines likely regulated as biologicals and requiring inclusion on the Australian Register of Therapeutic Goods (Global Methane Hub 2024).

### Stacking Potential

Ranking: High

Justification:

Vaccines could be combined with genetic selection, feed additives (e.g. 3-NOP), and pasture strategies to deliver cumulative methane reductions (Baca-González et al. 2020; Global Methane Hub 2024).

Because vaccines would not directly alter diet, they are theoretically compatible with most other mitigation approaches.

### Technology Readiness Level (TRL)

Ranking: 3

Justification:

Proof-of-concept demonstrated in vitro and limited in vivo trials.

No validated, durable prototype demonstrated under commercial conditions (Baca-González et al. 2020; Global Methane Hub 2024).

### Commercial Readiness Level (CRL)

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

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### Estimated Cost Range:

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

Industry claims suggest potential abatement costs < AU\$150 per tonne CO<sub>2</sub>-e, contingent on successful commercialisation (Muntari et al. 2025).

### Estimated Benefits:

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

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

### Investment in R&D and Commercialisation

Range: RDC and CRCNZE: \$0

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

## Early-life rumen programming

### Summary:

Early-life rumen programming aims to reduce lifetime enteric methane emissions by modifying rumen microbial colonisation during early developmental windows, when the rumen microbiome is plastic and not yet fully resilient (Yáñez-Ruiz et al. 2015; Kolathingal-Thodika et al. 2025). Interventions explored in beef cattle and sheep include early dietary manipulation, antimethanogenic compounds (notably 3-nitrooxypropanol; 3-NOP), maternal–offspring treatment strategies, and early management practices.

Recent grazing-based evidence substantially strengthens the biological plausibility of this approach. In a large Australian study under extensive grazing conditions, Martinez-Fernandez et al. (2024) demonstrated that treating calves with 3-NOP from birth to weaning resulted in persistent alterations to rumen microbial structure for up to 28 weeks post-weaning, with 10–15% lower methane emissions sustained for around 7 months after treatment withdrawal in one calving cohort. Importantly, this was achieved without adverse effects on growth or health.

However, responses were not uniform across cohorts, and methane suppression diminished as animals matured and diets changed. Consistent with earlier studies, microbial changes were more persistent than methane reductions, highlighting ongoing uncertainty about lifetime abatement durability (Meale et al. 2021; McSweeney et al. 2024).

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**Annual Abatement Potential (Technical)**

10–15% methane reduction, persisting months rather than years, with durability highly sensitive to timing, intake consistency, and post-weaning diet.

Justification:

Under grazing conditions, Martinez-Fernandez et al. (2024) reported 10–15% lower methane emissions for up to 20 weeks (around 5 months) posttreatment, extending to 28 weeks postweaning 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 pre-weaning state accounting for ~60–65% of the yearling microbiome.

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 months-scale persistence, but not lifelong abatement (Abecia et al. 2013; Abecia et al. 2014).

**Abatement Potential – Economic/Feasible**

Effects are creditable but require further evidence. Assume lower of 0 Mt CO<sub>2</sub>-e/yr and upper of 0.1 Mt CO<sub>2</sub>-e/yr

Justification:

Early-life programming requires short-duration intervention (birth to weaning), implying low additive cost relative to lifetime feeding strategies.

Martinez-Fernandez et al. (2024) demonstrated successful voluntary delivery of 3-NOP under grazing conditions, materially improving feasibility compared with earlier controlled-feeding studies. However, abatement persistence is insufficiently consistent to support reliable lifetime methane reduction accounting.

No approved early-life methane-reduction protocols currently exist for beef or sheep, and abatement cannot yet be confidently monetised.

For maximum level:

- Assume only targeted at animals where controlled feeding possible
- Maximum methane reduction: 12.5% (as mean value of Martinez-Fernandez et al. (2024) ),
- Duration: 1 year of a 1.5 yr lifespan for beef steer,
- Adoption ceiling: adoption analogous to feed-additive uptake (Cowie et al 2025).

**Breadth of Application**

Ranking: Moderate

Justification: Most effective in systems with controlled calf-rearing environments. Less practical in extensive grazing systems without early-life intervention infrastructure.

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## Co-Benefit Potential

Ranking: Moderate

Justification:

Applicable to managed beef systems (studs, backgrounding operations, intensive cow-calf systems).

Significantly constrained in extensive rangeland systems where early-life intake control and dosing uniformity remain challenging, despite improved delivery demonstrated by Martinez-Fernandez et al. (2024).

## Barriers and Knowledge Gaps

Ranking: High

Justification:

Inconsistent methane persistence across cohorts, even when microbial changes persist (Martinez-Fernandez et al. 2024).

Uncertainty around optimal timing, dose, duration, and intake uniformity under grazing.

Microbiome resilience post-weaning: dietary and environmental drivers eventually dominate (McSweeney et al. 2024).

Lack of commercial products, standardised protocols, and verification frameworks.

Need for stronger evidence on maternal programming and combined parent-offspring strategies.

## Stacking Potential

Ranking: high

Justification:

Early-life programming could prime animals for enhanced response to later-life interventions (genetics, feed additives, pasture quality).

Empirical evidence of additive or synergistic effects is not yet available, but biological rationale is strong.

## Technology Readiness Level (TRL)

Ranking: 5

Justification:

Demonstrated in large-scale, grazing beef trials with methane measurement and post-treatment persistence (Martinez-Fernandez et al. 2024).

Remaining uncertainty relates to durability and reproducibility, not basic function.

## Commercial Readiness Level (CRL)

Ranking: 2

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

## APPENDIX C.1: Priorities for Low Emissions Agricultural Solutions Investment

## Enabling Potential

Ranking: low-moderate

Justification:

Evidence now suggests early-life programming can establish low-methane microbial traits that persist for months, potentially lowering the baseline for later interventions (Martinez-Fernandez et al. 2024).

Insufficient evidence yet that this amplifies lifetime abatement outcomes.

## 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&amp;D and Commercialisation

Range:

- Australian investment RDC and CRCNZE: \$0:
  - 
  -
- International investment (itemised):
  -

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**Selective breeding for low methane****Summary:**

Selective breeding for lower methane-emitting beef cattle and sheep offers a permanent, cumulative, and low-cost mitigation strategy for reducing enteric methane emissions. Methane-related traits such as residual methane production, methane yield ( $\text{CH}_4/\text{kg DMI}$ ), and methane intensity ( $\text{CH}_4/\text{kg product}$ ) are heritable in beef cattle and sheep, with estimates generally in the low-to-moderate range ( $h^2 \approx 0.10\text{--}0.35$ ), indicating potential for genetic improvement (Lassen and Løvendahl 2016; de Haas et al. 2021; Worku 2024).

To date, most reductions in GHG emissions achieved through genetic selection in beef and sheep systems have occurred indirectly, via improvements in growth rate, feed efficiency, fertility, and survival, leading to reduced emissions intensity rather than large absolute reductions (Capper et al. 2007; Bell et al. 2012; Bell 2024). As in dairy systems, modelling suggests that if methane traits are not explicitly included in breeding objectives, absolute methane emissions per animal may increase over time due to higher intake associated with improved productivity, even when emissions intensity declines (de Haas et al. 2021).

Incorporating methane traits directly into breeding objectives is expected to have little impact on production performance, with at most minor reductions in genetic gain for growth or carcass traits under realistic selection scenarios, because genetic correlations between methane traits and key economic traits are generally modest (González-Recio et al. 2020; Bell 2024; Worku 2024). This makes genetic selection an attractive long-term mitigation option that aligns with existing breeding goals in beef and sheep industries

*Annual Abatement Potential (Technical)***Estimated potential: low per year, moderate cumulatively**

Genetic selection for methane mitigation in beef cattle and sheep is expected to deliver annual reductions of 0.2–0.6%  $\text{CO}_2\text{-e}$  per year, reflecting lower selection intensity and longer generation intervals than in dairy systems (Bell et al. 2012; de Haas et al. 2021).

Over a 30-year breeding horizon, emissions intensity reductions of 15–25% are plausible, driven primarily by improved productivity and feed efficiency, with additional gains if methane traits are explicitly weighted (Capper et al. 2007; Bell 2024).

Modelling suggests that absolute methane reductions of 5–8% per animal over 30 years may be achievable without reducing herd size, provided methane yield or residual methane traits are incorporated into breeding objectives (de Haas et al. 2021; Richardson et al. 2022).

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Because beef and sheep systems are dominated by extensive grazing and natural mating, genetic progress is slower and more heterogeneous than in dairy systems, limiting short-term abatement but supporting steady long-term gains

#### Abatement Potential – Economic/Feasible

Estimate: 0.9 to 4.0 Mt CO<sub>2</sub>-e/yr by 2050 if productivity gains allow the same beef and sheep output with fewer animals.

Justification:

Assumptions: same output with fewer animals:

- Long-term emissions-intensity reduction per animal: 5–10%
- Output held constant; animal numbers fall
- Gross enteric methane baseline: 50 Mt CO<sub>2</sub>-e yr<sup>-1</sup>

Apply conservative adoption factor (36–80%) (after adoption rate for herd management in Cowie et al 2025)):

- Result 4 to 6.0 Mt CO<sub>2</sub>-e/yr

#### Breadth of Application

Ranking: High

Justification:

Genetic selection is applicable across all beef and sheep production systems, including extensive rangeland, mixed farming, and intensive finishing systems. Mitigation is delivered entirely through breeding decisions, requiring no changes to grazing management, supplementation, or infrastructure.

However, compared with dairy systems, dissemination is slower because beef and sheep industries rely predominantly on natural mating, use a larger number of sires, and have longer generation intervals. As a result, population-wide methane reductions occur over decades rather than within one or two generations (Bell 2024; de Haas et al. 2021).

#### Co-Benefit Potential

Ranking: low.

Justification:

Adding methane traits to breeding objectives slightly increases index complexity and can marginally reduce selection pressure on individual production traits. However, most studies indicate minimal adverse impacts on growth, fertility, or carcass traits under realistic weighting scenarios, with co-benefits arising through improved feed efficiency and lifetime productivity (Bell et al. 2012; Worku 2024).

#### Barriers and Knowledge Gaps

Ranking: Medium

Justification:

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Limited large-scale methane phenotyping in grazing beef and sheep systems

Need for cost-effective proxies (e.g. residual feed intake, methane yield predictions) suitable for extensive conditions

Slower genetic gain due to lower selection intensity and longer generation intervals

Uncertainty around optimal methane trait definitions and economic weights

### Stacking Potential

Ranking: High

Justification:

Genetic selection is fully compatible with feed supplements, pasture improvement, herd management, and reproductive strategies, providing a permanent baseline reduction that enhances the durability of stacked mitigation options (Bell 2024).

Technology Readiness Level (TRL)

Ranking: 6-7

Justification:

Methane traits are identified and heritable in beef cattle and sheep, and selection experiments and modelling are well established. However, routine large-scale implementation remains limited by phenotyping constraints (Lassen and Løvendahl 2016; de Haas et al. 2021).

### Commercial Readiness Level (CRL)

Ranking: 5

Justification:

Sustainability-oriented breeding objectives exist in some regions, but formal methane trait integration into mainstream beef and sheep breeding programs is still emerging and less advanced than in dairy systems (Bell 2024).

### Enabling Potential

Ranking: low

Justification: does not enable other practices

### 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 RDC and CRCNZE investment: \$30,965,762:
  - Trait/proxy development and phenotyping foundations: projects treating methane as an indirect or direct trait within broader efficiency/profitability genetic evaluation “Genetic Evaluation of Production Efficiency and Profitability”

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- New measurement tools to enable selection: development of screening tools to identify high/low emitters “LESTR” Low Emission Saliva Test”.
- Breeding values and selection tools for sheep: methane trait integration into breeding values for selection “Selecting for more methane efficient sheep”
- Large scale beef genetic programs: development of genomic breeding values for methane across northern beef herds (“Reducing methane emissions and improving profitability in Northern Australian beef” and “Genetic improvement pipeline to reduce methane and improve productivity in the Australian beef industry”
- International investment (itemised):
  -

**Covered anaerobic lagoons and anaerobic digesters (biogas capture)****Summary:**

Covered anaerobic lagoons and anaerobic digesters involve placing an impermeable cover over manure effluent ponds to capture biogas, predominantly methane (CH<sub>4</sub>), generated during anaerobic decomposition of manure. The captured methane can be flared or used for energy generation (electricity, heat, or upgraded biogas). In the Australian beef and sheep context, this technology is primarily applicable to intensive beef feedlot systems, where manure is collected and managed in liquid or semi-liquid systems.

**Annual Abatement Potential (Technical)**

86% range(70-90%) compared to uncovered ponds

**Justification:**

The technical methane abatement potential from covered anaerobic lagoons or digesters is fundamentally constrained by the proportion of total manure that is captured and directed to anaerobic storage or treatment. In intensive housed or feedlot systems, >70% and up to >90% of manure can be captured, depending on housing design, surface type, and cleaning systems (Grell et al. 2024; Pratt et al. 2014 ). Field and modelling studies indicate that even with covered systems, 10–20% of methane may be lost due to fugitive emissions through covers, pipework, or incomplete combustion in flares or generators (Rotz et al. 2025; Flesch et al. 2011).

Total manure-related greenhouse gas emissions can be reduced by close to 90% relative to uncovered anaerobic lagoons (Artrip et al. 2013; Pratt et al. 2014).

**Abatement Potential – Economic/Feasible**

0.026-0.065 MT CO<sub>2</sub>-e yr

**Justification:**

Total feedlot emissions 2MT Mt CO<sub>2</sub>-e yr<sup>-1</sup> and if manure methane share 15% (range10-20%, after Bail et al 2023) then feedlot manure derived emissions 0.3Mt CO<sub>2</sub>-e yr<sup>-1</sup>

Assume best case system wide capture at feedlot 86%

Technically capturable abatement then 0.26 MT CO<sub>2</sub>-e yr<sup>-1</sup>

Only a small subset of Australian feedlots will be able to instal such systems:

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- Very large (>10,000–15,000 head)
- Wet or semi-liquid manure systems
- Permanent anaerobic ponds
- Capacity to manage capital, approvals, and operations

This represents 20-30% of cattle on feed. So assume low case at 10% and high at 25% adoption

## Breadth of Application

Ranking: low

Justification:

Covered anaerobic lagoons and digesters are only viable for large-scale, intensive feedlot operations due to:

- the need for sufficient manure volume and continuity,
- high capital and operating costs,
- specialist operational and maintenance requirements,
- complex environmental approvals, planning and zoning constraints, and
- limited access to subsidies, feed-in tariffs, or stable energy markets for biogas in Australia

## Co-Benefit Potential

Ranking: moderate

Justification:

Where implemented, systems can:

- generate renewable energy (electricity or heat),
- reduce odour and local air quality impacts,
- provide digestate with altered nutrient characteristics suitable for fertiliser use,

although these benefits are secondary to methane abatement and highly dependent on site-specific integration and markets

## Barriers and Knowledge Gaps

Ranking: low

Justification:

The technology itself is well established and commercially mature. Remaining uncertainties relate primarily to:

- adequacy of national and regional accounting for manure methane emissions,
- quantification of fugitive emissions from biogas infrastructure, and
- applicability of default emission factors to Australian feedlot conditions

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**Stacking Potential**

Ranking: high

Justification:

Methane abatement from manure systems is largely additive with:

- pasture management improvements,
- animal productivity gains,
- enteric methane reduction strategies,

making it compatible with whole-of-system mitigation portfolio

**Technology Readiness Level (TRL)**

Ranking: 9

Justification: Covered anaerobic lagoons and digesters are commercially available and deployed internationally, including in Australia at limited scale

**Commercial Readiness Level (CRL)**

Ranking: 5

Justification: While technically proven, adoption in Australian beef and sheep systems remains low due to limited economic incentives, high capital costs, and lack of stable revenue streams for biogas energy (Baylis et al. 2015; McCabe et al. 2014).

**Enabling Potential**

Ranking: low

Justification: Although biogas could theoretically support on-farm energy uses (e.g. heating, stationary equipment), enabling broader system transformation (e.g. biogas-powered machinery) remains limited under current Australian conditions (McCabe et al. 2014).

**Estimated Cost Range:**

Assume capital costs AU\$2-6M scaled down from dairy range

Assume feedlot size 15000 head

Assume asset life 20 years

Assume operation and maintenance at 3-5% capital cost per year

Then total cost is around \$0.03-0.11 per head per day

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## Estimated Benefits:

## Assumptions

Electricity generation: 50–150 kW (feedlot-scale, lower per-animal yield than dairy due to drier manure streams)

Electricity value: \$0.15–0.25/kWh

Carbon credit value: \$20–40/t CO<sub>2</sub>-e

Abatement: 5,000–10,000 t CO<sub>2</sub>-e/yr at large, suitable feedlots (manure methane only)

Total benefit \$0.03–0.12 per head per day

## Investment in R&amp;D and Commercialisation

## Range:

- Australian investment RDC and CRCNZE: \$1,400,00
  - Feasibility pilots to lift confidence and improve performance: pilot trials aimed at improving biomethane productivity and accelerating adoption “Accelerating biogas productivity and adoption using pilots”.
  - Integrated techno economic feasibility and systems integration: studies combining heat recovery, electrification, solar PV and biogas integration “Closing the loop on renewable process heat - an integrated feasibility study”
  -
- International investment (not explored for this project):
  -

## Biochar feed supplementation

## Summary:

Biochar (charcoal) has been investigated as a feed additive to reduce enteric methane by modifying rumen fermentation and adsorbing hydrogen. In beef and sheep systems, experimental results are inconsistent and strongly dependent on biochar properties, dose, and feeding context.

Under controlled feeding conditions, selected or engineered (“fit-for-purpose”) biochars have demonstrated modest methane reductions (approximately 9–13%) in cattle, without adverse effects on intake or rumen fermentation (Martínez-Fernández et al., 2024; MLA, 2022). However, these reductions were not observed when the same biochars were tested under grazing conditions, where intake variability and pulsed supplementation dominate. Grazing trials in beef cattle showed no significant effect on methane emissions or productivity (Martínez-Fernández et al., 2024; Conlin, 2021).

In sheep, recent *in vivo* studies similarly report no significant reduction in enteric methane emissions, despite some changes in fermentation characteristics such as short-chain fatty acid profiles (Lind et al., 2024). While earlier studies in sheep and small ruminants have reported methane reductions under confined or experimental

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conditions (e.g. Al-Azzawi et al., 2021), these effects have not translated reliably to extensive grazing systems, which dominate Australian sheep production.

Major syntheses and reviews conclude that biochar cannot currently be expected to deliver meaningful or reliable methane abatement ( $\geq 10\%$ ) in grazing beef cattle or sheep systems, particularly where supplements are delivered intermittently rather than continuously in a total mixed ration (Hegarty et al., 2021; Martínez-Fernández and Joseph, 2022).

#### Annual Abatement Potential (Technical)

Nil for Australian beef cattle and sheep systems

Justification: Methane reductions observed under controlled feeding conditions do not persist under grazing; no reproducible or scalable abatement demonstrated at the enterprise or system level (Martínez-Fernández et al., 2024; Conlin, 2021; Hegarty et al., 2021).

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#### Abatement Potential – Economic/Feasible

Nil

Justification: Absence of consistent methane reduction and lack of productivity co-benefits preclude an economic case for adoption in beef or sheep enterprises (Hegarty et al., 2021; Martínez-Fernández and Joseph, 2022).

#### Breadth of Application

Ranking: low

Justification: Antimethanogenic effects are limited to specific biochars under controlled feeding and do not generalise to extensive grazing systems typical of Australian beef and sheep production (Martínez-Fernández et al., 2024).

#### Co-Benefit Potential

Ranking: low

Justification: No consistent improvements in liveweight gain, feed efficiency, carcass traits, or wool production have been demonstrated under grazing conditions (Conlin, 2021; Lind et al., 2024).

#### Barriers and Knowledge Gaps

Ranking: high

Justification:

Strong dependence on biochar characteristics (feedstock, pyrolysis temperature, surface chemistry additives such as nitrates) (Martínez-Fernández and Joseph, 2022).

Poor translation of in vitro and housed-animal results to grazing beef and sheep systems (Martínez-Fernández et al., 2024).

High variability in intake when biochar is delivered via supplements, licks, or blocks (Hegarty et al., 2021).

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No validated slow-release or long-acting delivery mechanism suitable for extensive grazing.

### Stacking Potential

Ranking: low

Justification: No evidence of additive or synergistic methane reductions when biochar is combined with other mitigation strategies in beef cattle or sheep (Hegarty et al., 2021).

### Technology Readiness Level (TRL)

Ranking: 7-8

Justification: Multiple laboratory, pen, and grazing trials have been completed; however, performance remains inconsistent and not fit-for-purpose for grazing systems.

### Commercial Readiness Level (CRL)

Ranking: 2

Justification: No widespread commercial adoption in beef or sheep industries due to weak, inconsistent, and non-persistent methane mitigation outcomes

### Enabling Potential

Ranking: low

Justification: no effect

### Estimated Cost Range:

Typical inclusion rates tested: 0.5–1% of dry matter intake (DMI).

- Beef cattle:  
8–12 kg DMI/head/day → 15–44 kg biochar/head/year  
Cost at \$1–2/kg: \$15–88 per head per year
- Sheep:  
1.5–2.0 kg DMI/head/day → 2.7–7.3 kg biochar/head/year  
Cost at \$1–2/kg: \$3–15 per head per year

No reliable methane abatement or productivity return has been demonstrated to offset these costs (Conlin, 2021; Hegarty et al., 2021).

### Estimated Benefits:

Nil benefits

### Investment in R&D and Commercialisation

Range:

- Australian investment: \$0
- 
- 
- International investment (itemised):

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**Low-emission farm machinery****Summary:**

Low-emission farm machinery involves replacing diesel-powered tractors, vehicles, and stationary equipment used in beef cattle and sheep production with lower- or zero-emissions alternatives. Options under development or early deployment include battery-electric and hybrid tractors, biomethane and biogas-fuelled engines, hydrogen internal combustion engines, and hydrogen fuel-cell electric machinery.

In Australian beef and sheep systems, on-farm machinery is primarily used for mustering, supplementary feeding, feedlot operations, fodder production, water pumping, and general station activities. While these emissions are small relative to enteric methane, fossil fuel use remains a material and addressable source of CO<sub>2</sub> emissions. Life-cycle assessments of Australian beef production show that direct fossil fuel use contributes approximately 3–5% of total GHG emissions, with higher shares in more intensive systems such as feedlots (Wiedemann et al., 2015).

Electric and hybrid farm machinery is at an early stage of adoption in beef and sheep systems, largely due to challenges associated with horsepower requirements, duty cycles, range, and regional service infrastructure. Biomethane and biogas-fuelled machinery offer nearer-term options where on-farm anaerobic digestion is feasible (e.g. feedlots), although combustion engines can generate NO<sub>x</sub> emissions during cold starts and warm-up phases (Kuranc et al., 2025). Scope 2 emissions from electricity generation are not considered here.

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## Annual Abatement Potential (Technical)

10–70%, assume mean 40%

Use of battery-electric machinery powered by renewable electricity could virtually eliminate on-farm machinery CO<sub>2</sub> emissions. Where biofuels or biomethane are used, emissions reductions of approximately 10–70% are achievable, depending on feedstock, production pathway, and life-cycle boundaries.

However, studies indicate that methane and biogas-fuelled tractors can produce elevated NO<sub>x</sub> emissions during engine warm-up, partially offsetting climate and air-quality benefits if not managed appropriately (Kuranc et al., 2025).

## Abatement Potential – Economic/Feasible

Range 6 to 0.88 MT CO<sub>2</sub>-e yr

Justification:

Energy use associated with farm operations and feedlots represents about 3% of total Australian red-meat sector emissions, equivalent to approximately 1.54 Mt CO<sub>2</sub>-e per year (derived from national LCA estimates in Wiedemann et al., 2015). Assume 40% abatement, use figures from Cowie et al 2025 for biodiesel of low adoption at 4% and high at 84%.

In practice, machinery replacement cycles are long, and adoption will be gradual, limiting short-term abatement.

## Breadth of Application

Ranking: high

Justification: With adequate supply chains, price competitiveness, and regional service support, low-emission machinery could be adopted across extensive grazing, mixed farming, and feedlot systems in both beef and sheep enterprises.

## Co-Benefit Potential

Ranking: low

Justification: substitution technology.

## Barriers and Knowledge Gaps

Ranking: moderate

Justification:

Battery-electric, hybrid, and fuel-cell tractors are commercially emerging but face horsepower, runtime, and duty-cycle constraints in extensive systems.

Biomethane and biofuel tractors are technically available, but fuel supply chains are limited in regional Australia.

Further life-cycle assessment (LCA) work is needed to confirm net emissions reductions, including upstream fuel production and NO<sub>x</sub> trade-offs 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 \$55-\$80,000 compared with \$135-\$155,000 for electric) and biofuel tractors are perhaps 10% more expensive than diesel.

## Estimated Benefits:

Electric machinery has lower operating costs than diesel, particularly where on-farm solar or renewable electricity is available.

Biofuels are generally more expensive than diesel ( $\approx 1.5-2\times$ ), but costs may be reduced where on-farm biomethane is produced.

- Biomethane:  $\sim \$10-27/\text{GJ}$
- Diesel:  $\sim \$30-35/\text{GJ}$

([DAFF analysis](#); [Energy Networks Australia](#)).

Maintenance costs may be lower for electric machinery due to fewer moving parts.

On-farm biomethane production requires high upfront capital investment, limiting uptake to larger or more intensive operations (e.g. feedlots).

*Breakdown of costs and benefits for a typical tractor operation on a mixed farm*

**Indicative 10-year total cost of ownership (75 hp class tractor, Australia 2025–26)**

Assumptions:

- 75 hp utility tractor class
- 400–1,200 operating hours/year
- 10-year life
- Diesel price A\$1.80–2.00/L
- Electricity price A\$0.15–0.30/kWh (grid and/or on-farm solar blended)
- Electric tractor represented by Monarch MK-V class machine
- Diesel tractor represented by John Deere 5075E class machine
-

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| Cost component                            | Diesel tractor (A\$)   | Electric tractor (A\$) |
|-------------------------------------------|------------------------|------------------------|
| Initial purchase price                    | 55,000–80,000          | 135,000–155,000        |
| Energy cost over 10 years                 | 57,600–288,000         | 16,000–96,000          |
| Maintenance cost over 10 years            | 20,000–40,000          | 10,000–25,000          |
| <b>Total cost of ownership (10 years)</b> | <b>132,600–408,000</b> | <b>161,000–276,000</b> |

## Underlying annual operating cost assumptions

| Component            | Diesel tractor  | Electric tractor |
|----------------------|-----------------|------------------|
| Energy cost per hour | A\$12–24/h      | A\$4–8/h         |
| Annual hours (range) | 400–1,200       | 400–1,200        |
| Annual energy cost   | A\$4,800–28,800 | A\$1,600–9,600   |

## Central-case comparison

A reasonable central case for an Australian mixed-farming business (800 ha/year) is:

| Cost component                            | Diesel (A\$)   | Electric (A\$) |
|-------------------------------------------|----------------|----------------|
| Purchase price                            | 65,000         | 145,000        |
| Energy cost (10 years)                    | 144,000        | 48,000         |
| Maintenance (10 years)                    | 30,000         | 18,000         |
| <b>Total cost of ownership (10 years)</b> | <b>239,000</b> | <b>211,000</b> |

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RDO Equipment Australia. 2025. *John Deere 5075E Utility Tractor*.

<https://www.rdoequipment.com.au/john-deere-5075e-3-cyl-utility-tractor/>

### *Investment in R&D and Commercialisation*

Range:

- Australian investment (itemised) RDC and CRCNZE: \$0
- Other Australian
  - Range of concessional loan systems through banks
  - 
  -
- International investment (itemised):
  -

## **Grape marc**

### *Summary:*

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<sub>4</sub>) 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:

- Beef cattle:
 

Inclusion of approximately 30% ensiled crimped grape marc in beef cattle diets reduced daily methane output by 14%, but this reduction was fully explained by lower ME intake. When methane was expressed per unit of ME intake or weight gain, no mitigation effect was observed. Growth performance declined due to reduced digestibility and energy availability (Caetano et al. 2019).

## APPENDIX C.1: Priorities for Low Emissions Agricultural Solutions Investment

- **Sheep:**  
Replacement of approximately 20% of a standard forage–grain ration with grape marc maintained liveweight gain while increasing feed intake and shifting nitrogen excretion from urine to faeces. Methane emissions were not directly measured; however, the absence of productivity loss at moderate inclusion levels indicates limited scope for large methane reductions without inducing energy trade-offs (Wu et al. 2022).
- **Contextual evidence from ruminants:**  
Controlled ruminant studies show methane reductions of 10–20% when grape marc replaces other forages, but these reductions are consistently linked to energy dilution rather than improved fermentation efficiency, a mechanism that applies equally to beef and sheep systems (Moate et al. 2014; Black et al. 2021).

Overall, grape marc provides modest reductions in absolute methane emissions, but does not deliver durable reductions in methane intensity in beef and sheep production systems.

#### *Abatement Potential – Economic/Feasible*

Minimal given restrictions and trade-offs. If assume maximum adoption 10% where grape marc low cost feed close to feedlot then potential maximum 0.024 MT Co<sub>2</sub>-e/yr

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:

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While grape marc enables utilisation of a viticulture by-product and can shift nitrogen excretion toward faeces in sheep, it commonly reduces growth performance at inclusion levels required for methane abatement in beef cattle, limiting net system benefits (Caetano et al. 2019; Wu et al. 2022).

## 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:

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, but processing, storage, and transport typically cost AUD \$50–100 t<sup>-1</sup>. At daily intakes of 2–5 kg head<sup>-1</sup> day<sup>-1</sup>, this equates to approximately: AUD \$0.10–0.30 per head per day (Moate et al. 2020).

## Estimated Benefits:

Assume: nil

Justification:

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Grape marc typically substitutes 10–20% of the diet. Where a total mixed ration costs \$300–500 t<sup>-1</sup>, 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 liveweight gain when grape marc replaces higher-energy feeds (Caetano et al. 2019 pp. 168–170).

### Investment in R&D and Commercialisation

Range:

- Australian investment RDC and CRC NZEA: \$0
  - 
  -
- International investment (itemised):
  -

## Herd management

Summary:

Herd and flock management strategies reduce greenhouse gas emissions primarily by improving reproductive efficiency, growth rates, and feed-use efficiency, thereby lowering methane emissions intensity (emissions per unit of product). In both beef cattle and sheep systems, these strategies do not directly suppress methanogenesis, but instead reduce the proportion of unproductive, methane-emitting animals, particularly breeding females and replacements. Across Australian grazing systems, modelling and empirical studies consistently show that management interventions such as earlier joining, higher weaning rates, reduced mortality, improved growth rates, and more efficient grazing management can reduce emissions intensity by 10–30%, although net emissions at enterprise scale may remain unchanged or increase unless stocking rate or herd size is constrained (Hegarty et al. 2010; Harrison et al. 2014; Gebbels et al. 2022; Almeida et al. 2023).

In extensive beef and sheep systems, breeding females and replacement cohorts represent a large share of total enteric methane, so management that reduces unproductive days (e.g., earlier joining, improved weaning, reduced mortality) provides consistent intensity reductions. For beef enterprises with multiple properties (grower/backgrounder/feedlot), reconfiguring time spent in each stage can reduce emissions intensity by shortening low-gain grazing periods, but results depend on achieved liveweight gains and days carried (Taylor and Eckard 2016).

The Clean Energy Regular summarises this approach under the Beef Cattle Herd management method (2017) as follows. “Emissions from a beef cattle herd are related to productivity, which is influenced by feed composition and herd management practices. When cattle have access to sufficient high quality feed, they have better survival and growth rates. Improving breeding practices and removing less productive

## APPENDIX C.1: Priorities for Low Emissions Agricultural Solutions Investment

animals can also help enhance herd performance.” This method is no longer open to new projects and was closed on September 30, 2025, as the Emissions Reduction Assurance Committee for that the eligible activities were not always additional to what producers would do anyway, particularly when beef prices were strong. MLA are currently (May 2026) proponents of a new method being developed to replace the former Beef Cattle Herd Management method.

#### Annual Abatement Potential (Technical)

Estimate: 5-30% for emissions intensity however zero to low absolute emissions reductions unless herd/flock size is capped.

Justification:

Sheep systems (flock structure and reproduction)

- Earlier joining of maiden ewes reduces the proportion of non-productive females and lowers emissions intensity at flock level, particularly for self-replacing enterprises (Cottle et al 2016).
- Increasing reproductive output (e.g., higher conception/marking rates) reduces emissions intensity by spreading breeder methane “overhead” across more product, but may increase emissions per ewe if feed intake rises with productivity (Hegarty et al 2010)
- Systems modelling shows that stacking management and genotype interventions (e.g., earlier joining + improved feed-use efficiency + improved weaning rate) can reduce emissions intensity substantially more than single interventions (Cottle et al 2016; Martin et al 2024)
- However, productivity improvements can lower methane intensity while increasing net emissions, especially if producers use the efficiency gains to increase stocking rate or lamb output per hectare (Hegarty et al 2010; Martin et al. 2024).

Beef cattle systems (growth, finishing pathway, and grazing phase length)

- Grazing management that improves liveweight gain reduces methane per kilogram of gain (intensity), consistent with evidence that improved pasture utilisation can reduce methane per unit product. (Harrison et al. 2014, Kelliher et al 2014)
- Gate-to-gate LCA of a corporate northern Australian beef enterprise (Taylor and Eckard 2016) modelled three 5000-head herds and found emissions intensity reductions of:
  - 14% for steers when bypassing a low-gain “growing” property and spending more time backgrounding before feedlot finishing,

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- 29% for one heifer herd when bypassing a backgrounding property and moving earlier to feedlot grower/finisher rations,
- 4% for another heifer herd where backgrounding performance was higher (less benefit from bypass).
- The same study identified thresholds where baseline and alternative scenarios were equal: roughly 206 days on the growing property for steers, and 225–229 days on backgrounding properties for heifers (depending on daily liveweight gains). Above these thresholds, bypassing the grazing phase produced net reductions in emissions intensity; below them, bypassing could increase emissions.
- This demonstrates that “herd management” abatement is not just reproductive efficiency, but that production chain configuration (time-to-slaughter and time-in-stage) can deliver meaningful emissions intensity reductions, but only when the bypassed stage is sufficiently low productivity or long duration.

**Abatement Potential – Economic/Feasible**

0.03 to 7 Mt CO<sub>2</sub>-e/yr across beef and sheep (very strong influence of incentive).

Justification:

Across beef and sheep systems:

- 10–30% reductions in emissions intensity are technically feasible via:
  - earlier joining / reduced age at first reproduction,
  - improved reproductive rate and survival,
  - faster growth and reduced days alive,
  - improved feed-use efficiency,
  - re-configuration of beef production pathways (time in low-gain grazing stages).
- Absolute emissions reductions are much smaller unless producers:
  - hold output constant and reduce animal numbers, or
  - deliberately constrain stocking rate / herd size, or
  - combine management with land-use change or sequestration.

Low range scenario – business as usual with no incentives

Behavioural assumption

- Producers adopt management changes only where they increase profit or reduce risk.
- Productivity gains are largely reinvested into output or stocking rate.
- Result: emissions intensity falls, but net emissions fall only marginally.

Assume national absolute abatement fraction

- 3% of enteric emissions reduced in absolute terms.

This reflects:

- partial adoption,

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- limited willingness to reduce stock numbers,
- rebound effects from productivity gains.

High range scenario – with a policy incentive mechanism

## Behavioural assumption

An incentive mechanism (e.g. ACCUs, insetting premiums, supply-chain contracts, or regulated targets):

- Incentives are sufficient to change land use or stocking and cover overheads of projects (realistically \$150-350 per tCO<sub>2</sub>)
- Rewards absolute emissions reduction, not just intensity,
- Makes it rational to:
  - reduce breeder numbers while holding output,
  - cap stocking rates,
  - retire marginal animals or land,
  - restructure beef production pathways even where gross output is unchanged.

## Possible national absolute abatement fraction

- 18% of enteric emissions reduced in absolute terms (mean response observed).
- Assume maximum adoption 80% as per Cowie et al 2025

*Breadth of Application*

Ranking: High

Justification:

These strategies are applicable across:

- Sheep and beef systems,
- Temperate and tropical grazing regions,
- NSW, southern Australia, and northern rangelands.

They rely on management skill (and incentive payment) rather than technology access, making them broadly deployable (Hegarty et al. 2010; Almeida et al. 2023).

*Co-Benefit Potential*

Ranking: High

Justification:

Co-benefits (at least for emissions-intensity improvement actions) include:

- Increased profitability,
- Improved animal welfare,
- Reduced mortality and reproductive wastage,
- Improved resilience to climate variability.

*Barriers and Knowledge Gaps*

Ranking: Moderate

Justification:

While simple calculators are in place, some barriers to adoption exist including:

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Infrastructure investment in fencing, water infrastructure and yards and handling facilities to support more intensive management. This particularly presents a barrier to small enterprises. To calculate likely emissions changes requires more data collection on things like weaning rates, mortality and sale weights which again presents difficulties for smaller operators. Gains may require multiple years of practice change given the highly variable climate in northern Australia which can disrupt herd performance and cause variation in herd emissions.

*Stacking Potential*

Ranking: high

Justification:

Herd and flock management strategies:

- Stack effectively with genetic improvement,
- Enable higher efficacy of nutritional or additive interventions, and
- Can be combined with land-use change or carbon sequestration strategies to achieve absolute abatement (Harrison et al. 2014; Almeida et al. 2023).

*Technology Readiness Level (TRL)*

Ranking: 9

Justification:

- The method has been implemented across multiple commercial-scale projects in Australia.
- It relies on well-established livestock management practices, not experimental technologies.
- The method was formally approved under the Emissions Reduction Fund (ERF) and has generated Australian Carbon Credit Units (ACCUs) for several years, and has subsequently been revoked because not additional.

*Commercial Readiness Level (CRL)*

Ranking: 4

Justification:

In some regions larger producers have integrated the method into operations and aggregators have (prior to revocation) started to look at models to aggregate smaller users. Regulatory changes are slowing uptake

*Enabling Potential*

Ranking: moderate

Justification: Improved herd/flock management enables deeper abatement by creating a more efficient baseline system and improving the feasibility of complementary strategies (feed additives, genetics, land-use options).

*Estimated Cost Range:*

\$0-10 per head per year (management, planning, monitoring)

Justification:

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Most actions are management-led; costs rise only where extra supplementation or infrastructure is required. The cost will be highly variable depending on what capital and infrastructure works are undertaken but could run to \$50-100,000 for a modest size herd and property. Approach will need livestock management software, RFID tags etc for an additional \$1-10000 for a 1000 to 2000 head herd.

**Estimated Benefits:**

\$10-40 per head per year for cattle, \$2-10 per head per year for sheep

**Justification:**

Faster growth, earlier turn-off, and reduced time in low-gain phases improve capital turnover and reduce costs per kg beef. Assume no return from carbon as emissions intensity and not absolute reduction gains.

**Range:**

- Australian investment RDC and CRCNZE: \$0:
  - 
  -
- International investment (itemised):
  -

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