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Meta-Analysis and Ranking of the Most Effective Methane Reduction Strategies for Australia's Beef and Dairy Sector

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Abstract: Although Australia remains committed to the Paris Agreement and to reducing its greenhouse gas emissions, it was late in joining the 2021 Global Methane Pledge. Finding suitable methane (CH_4) mitigation solutions for Australia's livestock industry should be part of this journey. Based on a 2020–2023 systematic literature review and multicriteria decision approach, this study analyses the available strategies for the Australian beef and dairy sector under three scenarios: baseline, where all assessment criteria are equally weighted; climate emergency, with a significant emphasis on CH_4 reduction for cattle in pasture and feedlot systems; and conservative, where priority is given to reducing costs. In total, 46 strategies from 27 academic publications were identified and classified as 'Avoid', 'Shift', or 'Improve' with respect to their impact on current CH_4 emissions. The findings indicate that 'Avoid' strategies of conversion of agricultural land to wetlands, salt marshes, and tidal forest are most efficient in the climate emergency scenario, while the 'Improve' strategy of including CH_4 production in the cattle breeding goals is the best for the conservative and baseline scenarios. A policy mix that encourages a wide range of strategies is required to ensure CH_4 emission reductions and make Australia's livestock industry more sustainable.

Keywords: avoid strategy; climate change; improve strategy; livestock; multi-criteria decision making; scenario; shift strategy; sustainability; systematic literature review; Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

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1. Introduction

Methane (CH_4) is a potent greenhouse gas (GHG) that contributes to climate change. For an extended period, CH_4 was not a focus in discussions about climate change. More recently, however, there has been a growing acknowledgment among scientists and policymakers that prioritizing CH_4 reduction is of paramount significance [1] in addressing climate risks. This includes averting potential threats of biodiversity loss, wildfires, extreme weather events, and sea level rise. Agriculture and the global food systems, particularly the beef and dairy sector, are major sources of CH_4 emissions [2]. Although estimates vary [3], cattle's contribution to GHG emissions is significant through gases produced in their digestive systems, the release of CH_4 during manure decomposition, and the land clearing required for grazing and feed production [4].

Identifying the most effective GHG reduction strategies is vital to mitigate the environmental impact of the beef and dairy sector, particularly as the atmospheric CH_4 concentration has experienced a staggering over twofold increase in the last two centuries [5–7]. Agriculture and food waste disposal are major contributors [8]. The impact of various GHGs on the climate is determined by two crucial characteristics: their atmospheric lifespan and their capacity to absorb energy [5]. Compared to carbon dioxide (CO_2), CH_4 stands out with a significantly shorter atmospheric lifetime, lasting approximately 12 years as opposed to the centuries-long persistence of CO_2 [1,5]. Despite its shorter duration, CH_4 possesses a higher energy-absorbing capability during its presence in the atmosphere. It exhibits an astonishing warming potency, surpassing CO_2 by over 80 times within the initial 20 years after entering the atmosphere [9]. This underscores the acute and immediate impact of CH_4 emissions on the greenhouse effect and climate change and the need for reduction strategies.

Many countries, including Australia, have committed to reducing their GHG emissions as part of the Paris Agreement [10]. Australia did not join initially the Global Methane Pledge launched in 2021 but has since taken steps to accelerate CH_4 mitigation from its liquified natural gas (LNG) operations [11]. Although livestock is a significant contributor to CH_4 emissions, Australia is yet to undertake any specific commitments. The Australian livestock industry, however, is looking at finding ways to reduce its CH_4 emissions in order to diminish its impacts on climate change.

Understanding the most effective CH_4 reduction strategies is essential for meeting the national commitments on the Paris Agreement and for contributing to the global efforts to combat climate change. Hence, governments and regulatory bodies need evidence-based information and insights to assess the livestock sector and develop targeted, impactful, and effective policies and regulations. Furthermore, the success of any mitigation strategy relies on its acceptance and implementation by the industry. Identifying and promoting strategies that are feasible, economically viable, and socially acceptable can encourage widespread adoption among farmers, consumers, and other stakeholders. As protein production efficiency varies with system design, factors, such as land use, enteric CH_4 production, and scientific progress must be considered in assessing the overall environmental footprint [12].

Australia holds the position of the second largest beef and beef exporter in the world, contributing 14% of all global beef exports [13]. To address the CH_4 emissions associated with ruminants and to boost production, animal nutrition models have evolved over the past six decades. The majority of research has focused on total mixed-ration diets typical of feedlot cattle, despite 96% of cattle in Australia grazing on pastures, and grazing breeding females constituting the largest source of CH_4 emissions in Australian agriculture [14–17].

According to Tedeschi [15], cattle are responsible for 10% of Australia's CH_4 emissions and 14.5% of human-induced GHG emissions, based on a global warming potential estimated over 100 years (GWP 100). Since 1990, CH_4 emissions from Australian beef cattle have risen 11.8% to 1.4 million tonnes of CH_4 per year in 2021 [18]. The Australian beef and dairy sector predominately rely on pasture-based cattle, with feedlot finishing accounting for 4% of Australia's herd consisting of 1 million beef cattle [19]. About 60% of the beef supply comes from extensive grazing [19] and 62% of the national herd grown in northern Australia primarily relies on native grasses with less than 5% of pastures sown with grass and legumes [13,20]. In the dairy industry, milk production has surged by 116% in the last 40 years resulting in a decrease in CH_4 intensity. This reduction is attributed to less seasonality and an increased reliance on fodder crops, supplements, and concentrates [14]. Australia's cattle sector holds national and global significance, with cattle grazing on sown pastures in the southern regions or native grasses in the north.

The aim of this research is to rank the most effective strategies to reduce CH_4 emissions in Australia's beef and dairy sector, in order to guide governments and decision-making processes for emission reductions in line with a 1.5 °C world, the desired outcome from the Paris Agreement. Ranking the most effective CH_4 reduction strategies for Australia's beef and dairy sector allows informed policy decisions while optimizing resource allocation, promoting industry adoption, fulfilling international commitments, ensuring economic viability, and advancing scientific understanding in the context of climate change mitigation. This can also guide future scenario building and scientific investigations in CH_4 reduction.

2. Materials and Methods

Two methods were used to analyse the current CH_4 reduction strategies available for the Australian beef and dairy sector. A systematic literature review (SLR) was undertaken to determine the latest strategies available, and then a multi-criteria decision making (MCDM) approach was used to assess and rank them.

The tool used for the MCDM is the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Developed in the 1980s by Yoon and Hwang and further refined in 1995, this method [21] has proven successful in managing complex decision making with objectivity and transparency across a variety of areas, including environmental management, sustainable development, energy sustainability assessments, mega projects, and supply chain logistics, as well as smaller-size initiatives, such as sustainable hotel construction, and sector-specific solutions, such as reducing the carbon footprint of Brazilian beef exports [22–29]. According to TOPSIS, the best alternative is the one geometrically closest to the positive ideal solution and the farthest away from the negative ideal solution. As a technique to implement MCDM, TOPSIS has become a sound mathematical tool capable of guiding ideal solutions to challenging situations [16]. The application of MCDM through TOPSIS has resulted in a more efficient use of resources, improved decisions, and better risk management [22–24].

Given the multi-faceted nature of CH_4 reduction solutions and their different impacts and effects, TOPSIS was used to assess and rank the various alternatives available to policymakers. In the MCDM, specific weightings were assigned for the assessment categories based on various criteria to accommodate three scenarios (Table 1). Firstly, in the baseline scenario, all indicators were equally weighted. Secondly, in the climate emergency scenario, a significant emphasis was placed on CH_4 reduction for all cattle, including both pasture and feedlot production systems. Lastly, in the conservative scenario, a prioritization was given to reducing costs.

Table 1. Indicator weighting of three scenarios to assess effectiveness of methane (CH_4) reduction strategies in the beef and dairy sector.

Scenario	Main Indicator Weighting	Remaining Indicator Weight
Baseline	None	All 8 indicators weigh 12.5%
Conservative	80% cost reduction	7 remaining indicators weigh 2.9%
Climate Emergency	40% CH_4 reduction 40% all production systems	6 remaining indicators weigh 2.9%

A range of CH_4 reduction strategies for the Australian beef and dairy sector were classified using the conceptual framework recommended by the Intergovernmental Panel on Climate Change (IPCC), categorizing mitigation strategies or measures as 'Avoid', 'Shift', or 'Improve' (ASI) [30]. The ASI framework places emphasis on providing services for well-being and maintaining decent living standards for all, while concurrently addressing emissions reduction. It serves as a conceptual guide to categorize the finding of possible solutions based on the strategies identified through the SLR.

2.1. Systematic Literature Review

The Scopus database was used to compile the list of strategies employing the search terms 'methane' or 'CH_4' or 'short-lived climate pollutant' or 'mid-term climate pollutant' in combination with 'reduction' or 'reduce' or 'strategy' or 'plan' or 'avoid' or 'shift' or 'improve' or 'lower' or 'solution' and 'meat' or 'bovine' or 'cattle' or 'dairy' or 'cow' or 'meat and dairy' or 'ruminant animal' or 'animal protein'. The geographical area was limited to Australia, and the time period was from 2020 to 2023. All abstracts of the publications resulting from the search were reviewed for relevance and only full-text, peer-reviewed publications in English were included. Publications focusing on sheep, nutritional content of plants, and increasing biogas potential were excluded. The resulting 27 publications (see Figure 1) were further categorized based on the treatment and control measuring CH_4 reduction in cattle. This categorization aligned with IPCC's ASI framework for GHG mitigation [30].

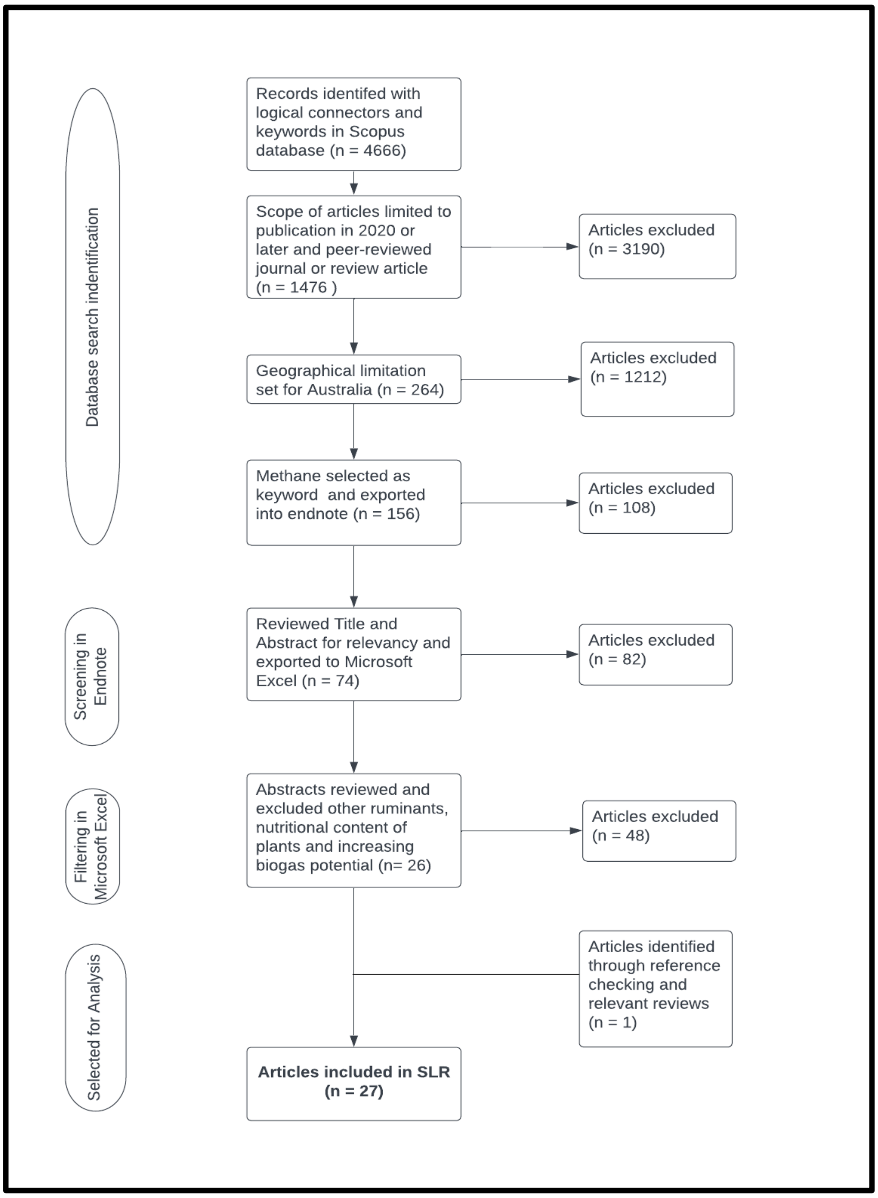

Figure 1. Steps undertaken to select articles for inclusion in the systematic literature review (SLR) based on Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram [31].

'Avoid' measures are seen to be the most effective yet most challenging to implement as avoiding emissions requires significant behaviour changes and the establishment of political and institutional structures that facilitate and enable supporting low-carbon lifestyle actions, ultimately reducing the demand for beef and dairy products. 'Shift' measures are generally easier and more accessible to adopt and involve shifting or redirecting consumer demand away from remnant products through easily manageable changes, such as incorporating more meat-free days or opting for consuming cell-based cultured meats. 'Improve' measures focus on strategies which reduce emission intensity by increasing the yield of a meat or dairy product and therefore diminishing emissions per kilogram of product while also contributing to an overall reduction in emissions. Examples of 'Improve' measures include the manipulation of rumen, feed formulation, dietary supplements, feed consistency, feed additives, selective breeding, farm management, and GHG breeding indexes.

2.2. MCDM and TOPSIS

The CH_4 reduction strategies contained within the 27 SLR-identified articles are assessed through a MCDM using TOPSIS. This section includes an explanation of TOPSIS, highlighting the development of a set of indicators and metrics to build a decision matrix to assess the strategies. It then details the formulas used to calculate the rank of each CH_4 reduction strategy with respect to the ideal solution in the beef and dairy sector. As secondary data are being used, a sensitivity analysis is undertaken to scale weightings according to the three scenarios described above (see Table 1).

Required steps in TOPSIS are identification of indicators, selection of metrics and the development of a decision matrix. This allows for the extracted data to be analysed.

2.2.1. Indicator Development and Metrics

A search of the literature found a lack of assessment criteria or indicators targeting reduction in agricultural CH_4 emissions. Much of the MCDM research available relates to transportation and energy choices, such as the EU's 2030 plan to step up climate ambition [32], energy efficiency, and conservation [33] or focus on corporate sustainability [34,35]. Nevertheless, parallels apply for this study. For example, assessment indicators are provided by UNEP [33] for governments to choose energy saving and energy-efficient energy systems, carbon capture, and storage and to reduce human health impacts and risks. Furthermore, overarching indicator themes have been obtained from sustainability assessment handbooks and MCDM guidelines [24,36].

Typically, indicators for assessing policy-making decisions include measurements for environmental, economic, social, global impact-related, technical, and other aspects. For example, UNEP [33] suggests a comprehensive set of indicators, comprising minimizing spending on technology, other types of spending, allowing for easy implementation, adhering to required timing of policy intervention, reducing GHG and black carbon emissions, enhancing resilience to climate change, stimulating private investments, improving economic performance, generating employment, contributing to fiscal sustainability, protecting environmental resources, preserving biodiversity, supporting ecosystem services, reducing poverty incidence, reducing inequality, improving health, preserving cultural heritage, contributing to political stability, and enhancing governance. Meanwhile, the European Commission [37] recommends policy assessment indicators such as air pollution impacts, synergies and trade-offs, capital and variable costs revenues gained, investment challenges, energy supply security, and impact on employment and households when assessing sustainable energy and transport options. Other indicators include social criteria, such as social acceptability, and the globalized impact of policy, including resource depletion [24].

These resources provide the context for applying the relevant parallels from energy and transport policy assessment in the context of reducing CH_4 in the beef and dairy industry. Table 2 shows the criteria adopted for this study under the following categories:

- Environmental impact—CH_4 reduction;
- Economic impact—estimated intervention costs;
- Technological readiness—research development stage;
- Policy and regulatory landscape—compliance with existing laws, new policy required;
- Scalability and replicability—applicable across production systems, climatic zones, and seasons.

Table 2. Assessment categories and indicators for assessment of CH_4 reduction strategies in the beef and dairy sector in Australia.

Categories	Indicators (Value in Brackets)	Supporting Information
Environmental Impact	CH_4 reduction per litre of energy-corrected milk, per kilogram of trimmed boneless beef or baseline (%)	Energy-corrected metric, industry standardized unit of measurement in dairy industry [38]. Trimmed boneless beef according to Saner and Buseman [39].
Estimated Implementation Costs	Estimated AUD upfront capital costs for strategy implementation and/or operating expenditures Relative comparison of strategies scaled between 1 and 10	Similar to UNEP's [33] Practical Framework for Planning Pro-Development Climate policy. Example indicators for energy efficiency, carbon capture and storage, and reducing human health impacts.
Technological Readiness	Research development stage: emerging (1) or established (2)	Based on Federal Agriculture Department [40].
Policy and Regulatory Landscape	Compliance with existing laws: No (1), Yes (2) New policy required: No (1), Yes (2)	Similar to UNEP's [33] indicators for energy efficiency regarding easy institutional implementation. Data sourced from the systematic literature review (SLR) and secondary evidence.
Scalability and Replicability	Applicable production system: Feedlot (1), pasture-based (2), both (3) Applicability to both northern and southern regions: No (1), Yes (2) Applicability to all seasons: No (1), Yes (2)	Similar to UNEP's [33] indicators for energy efficiency regarding easy institutional implementation. Data sourced from SLR and secondary evidence.

Environmental Impact

The environmental impact is measured by calculating the percentage reduction in CH_4 emissions per litre of energy-corrected milk (ECM) or kilogram of boneless beef values, where available. This approach ensures standardized consistency between feed inputs and product yields. The formula for calculating cost of kilogram of boneless trimmed beef is based on 63% of live animal as Hot Carcass Weight (HCW), and 65% of HCW is assumed to be measured in kilograms of trimmed boneless beef [39].

Economic Cost

The economic category is quantified by estimating the cost of the intervention in Australian dollars (AUD), assuming government subsidization or support upon adoption. As the research articles reviewed do not provide calculation for upfront capital or ongoing costs related to implementing CH_4 reduction strategies, relevant data are drawn from secondary sources, identified during this literature review. Given that most strategies are based on improving feed, a significant component of the financial cost and the metabolizable energy of cattle, the choice of feed can affect yield and the quality and quantity of outputs subject to variables such as the prevailing milk pricing. As such this cost element considers only the upfront or ongoing costs of supplying the chosen feed/supplement with the assumption that the government will absorb these costs if the intervention is adopted. After the calculation of the estimated pricing for all strategies, a comparative scale of 1–10 was established. For example, establishing a new industry and genetic research requiring more than AUD 100 million in grants and funding, was considered the highest cost, resulting in a score of '10'. By comparison, changes in farm management practices, such as alterations to feed, composting or increasing milk production targets were assigned a score of '1' due to their comparatively lower cost.

Technological Readiness

Technological readiness highlights the developmental stage of a strategy, which is particularly relevant when investing in innovation. Drawing upon Australia's efforts to determine a strategy for net zero emissions in the agriculture sector, two distinct categories transpired regarding new technologies and practices, namely established and scalable, and emerging [40]. In such a context, strategies undergoing 'in vitro' lab testing, which have yet to transition from the laboratory setting to real-world application, are classed as not being technologically ready or assigned a '1' for this indicator. A '2' was assigned to strategies, or close variations, which are considered to be technologically ready for implementation if they have been previously established and demonstrated elsewhere.

Policy landscape

The policy landscape was assessed using a scale of 1 or 2. A scope of '2' was assigned if a strategy complied with current legislation and/or regulations, while a '1' was assigned for non-compliance or when a new policy was required.

Scalability

Scalability is an assessment of the applicability of the strategy across both feed and forage systems for beef and dairy systems, as well as across various climatic zones and seasons. A scale of 1 to 3 was employed for the production system, where '1' represents application to only feedlot production, '2' represents application to only grazing production, and '3' indicates application for both production systems. Similarly, a '1' or '2' was assigned for applicability to both Northern and Southern production zones or seasons, where '1' represents only limited applicability to specific seasons or production zones.

2.2.2. Decision Matrix

Using the 46 strategies identified in the 27 articles analysed, data on CH_4 reduction and other assessment categories were extracted to formulate the decision matrix. The creation of the decision matrix (outlined as the first step Equation (A3) in Appendix A) aims to assess the most effective available solution for CH_4 reduction in the beef and dairy sector and is shown in Appendix B. Where data regarding cost, policy landscape, and technological readiness were not available in the original articles, secondary sources were used.

2.2.3. TOPSIS Formulations

The TOPSIS formulas are used to calculate each strategy's Euclidian distance to the most ideal solution, according to the assessment categories in Table 2 and data from Appendix C. These Euclidian distances are then used to create a ranking of the 10 most effective strategies [21]. In order to determine the most effective CH_4 reduction strategy in the beef and dairy sector, a decision matrix was constructed (refer to Appendix B). Equations (A1)–(A12) in Appendix A describe the process of decision matrix formulation, vector normalization, integration with baseline, conservative and climate emergency scenario weighting, determination of positive and ideal negative solutions, separation value calculation, and the final preference score calculation. Full results are located in Appendix D, and the results are discussed in the next section.

3. Results

This section presents the results derived from the systematic literature review and the MCDM through TOPSIS ranking. The top-ranking strategies for effective CH_4 reduction in the beef and dairy sector are revealed under the baseline, conservative, and climate emergency scenarios. They are informative for policymakers when considering effective CH_4 reduction policies in the beef and dairy sector.

3.1. Systematic Literature Review

The literature highlights the challenges associated with measuring CH_4 accurately and consistently due to a variety of methods and options available for modelling CH_4 production. Pryce and Haile-Mariam [41] state that the accuracy of CH_4 measurement varies on the chosen technique for capturing CH_4 data, ranging in affordability from enclosed respiration chambers, SF6 tracer techniques, handheld laser CH_4 detection, automated head chambers, or sensors in automated milking systems. Measurement of CH_4 in the industry also shows discrepancies as the reported direct value is 30% lower than that calculated by national inventory standards [19]. Furthermore, a more accurate representation of CH_4 environmental impact is debated in the literature with alternative CH_4 metrics such as GWP* [42]. This metric replaces the 100-year carbon equivalation with the calculated lifespan of CH_4 and other short-lived GHGs, enabling a more accurate calculation of CH_4 impact over its 12-year life span [42]. In this literature review, GWP* is used as a way to increase the contribution of CH_4 reduction in feedlot cattle supplemented with additives to the overall national herd efforts [43] as the standardized use of GWP100 “may not provide suitable information for every decision-making context” [18].

Tedeschi [15] suggests the mathematical models do not capture the energy expenditure of grazing cattle and may need to be ‘re-engineered’ to accommodate a sustainable perspective combining modelling concepts to encapsulate a decrease in CH_4 emissions. Defining suitable breeding objectives is also a challenge, with a wide range of choices available to model CH_4, such as CH_4 intensity, CH_4 yield, or gross CH_4 emissions and variability in CH_4 produced during different life stages [41]. The literature also captured post-farm emissions associated with the dairy sector [44] where a review of 15 lifecycle assessments and carbon footprints of dairy products was undertaken and included the GHG emissions in post farm-gate processing. These further contribute to the impact of beef and dairy industries with butter and cheese having the highest global warming potential with an average of 20–36 kg of CO_2e and 6.7–9.47 kg CO_2e per kg of product, respectively, when including activities, such as packaging, transportation, different processing methods in industries, and energy consumption.

3.1.1. ‘Avoid’ Strategies

Only one article specifically assessed ‘Avoid’ strategies to reduce CH_4 in the beef and dairy sector by measuring CH_4 emissions resulting from land-use changes and the impact of converting agricultural land back to its original habitat. Iram et al. [45] measured GHG fluxes with a flame ionization detector with nitrogen as a carrier gas from the soil of various sites in an agricultural area located on the Herbert River basin in Queensland. The studied sites produced CH_4 fluxes of 209 g of CH_4 per square metre per year compared to natural habitats of mangrove, freshwater tidal forest and saltmarshes with 0.73 g, 0.15 g, and 0.04 g of CH_4 per square metre per year, respectively. With unstocked wet pastures emitting 200 times more CH_4 than any other site, management practices such as converting wet pasture back to original habitats, including salt marshes, wetlands, and tidal forest, would reduce soil based CH_4 emissions by 99.95%. This paper highlights the potential for ‘Avoiding’ emissions though rehabilitation of agricultural lands back to original habitats.

3.1.2. ‘Shift’ Strategies

Two articles highlighted carbon pricing and cellular agriculture as strategies to shift CH_4 emissions by financially incentivizing low-CH_4 cattle and shifting production of dairy protein to cellular protein. The first ‘Shift’ strategy was a national carbon price that aims to encourage producers and consumers to shift to low-carbon farming alternatives. Richardson et al. [46] measured the effect of including a GHG sub-index into the national breeding program, against carbon prices ranging from AUD 150 to 1000 per t CO_2e and high- and low-accuracy residual CH_4 traits. The results showed that the current low accuracy of CH_4 prediction would reduce CH_4 by 0%, 0.09%, 0.36%, and 0.71% with a carbon pricing of AUD 150, AUD 250, AUD 500, and AUD 1000 per t CO_2e, respectively. A future greater CH_4 accuracy could reduce CH_4 by 3.92%, 5.7%, 6.69%, and 8.03% with a carbon price of AUD 150, AUD 250, AUD 500, and AUD 1000 per t CO_2e, respectively. A carbon price of AUD 1000/t CO_2e reduced CH_4 emissions up to 8.03% when the assumed accuracy in phenotyping is more certain. Davison et al. [47] also reviewed the effect of a modest carbon price of AUD 16.14/t CO_2e and calculated benefits to farmers up to AUD 500 million in net present value until 2030 if *Asparagopsis* or *leucanena* (forage legumes) were eligible for carbon credits.

The second 'Shift' strategy was researched by Behm et al. [48], who compared the life cycle of a cultured protein with cellular agriculture to dairy protein through a life cycle analysis (LCA). This LCA compared the protein component of milk only and concluded that cellular agriculture is more sustainable from climate and water perspective only if the required protein purity is lower and there is no need for chromatographic purification. Otherwise, protein production through cellular agriculture is similar to the most efficient traditional dairy production in New Zealand. As the LCA of cellular agriculture did not specifically compare CH_4 emissions to traditional dairy farms, only the carbon pricing was included in the following quantitative assessment of strategies.

3.1.3. 'Improve' Strategies

'Improve' strategies dominated the literature with 21 articles focusing on improving the efficiency or emissions intensity of beef and dairy production. A number of strategies measured CH_4 reduction via feed supplements, feed formulation, genetic selection, improved fertility, manure management, post-farm gate processing, and heat stress reduction.

Feed formulation

The strategies regarding the formulation included feeds such as grass, grain, or legume-based diets and feed supplements such as *Asparagopsis taxiformis*. Thomas et al. [12] compared the net protein contribution of grass-fed and grain-finished cattle and found that grass-fed cattle produced a higher CH_4 intensity, approximately 22.5% higher than grain-finished beef. The ability of pasture to provide full nutrition to cattle was researched by Mahanta et al. [49], who calculated that cattle can no longer gain the nutrition needed from pasture alone. Yet cultivated cereals, such as maze and sorghum, reduce enteric CH_4; however, cultivation, fertilization, harvesting, and preservation of feed contribute to the overall GHG emissions, and grain-based diets need to be assessed through LCA. This has ramifications for the strategy proposed by Moate et al. [14] who studied the effect of increasing the proportion of wheat in the diet of dairy cattle and found that the higher it is, the greater the reduction in CH_4 and increase in protein, but reduced milk fat. For dietary inclusions of wheat at 15%, 20%, and 45% of dry matter intake (DMI), CH_4 was reduced per kilogram of energy-corrected milk by 12.35%, 14.71%, and 21.18%, respectively.

Several articles, namely Badgery et al. [16], Stifkens et al. [50], and Mwangi et al. [13], investigated a number of legumes and herbs for impact on CH_4 reduction in ruminant diets. Badgery et al. [16] found that *Biserrula pelecinus* has great potential to reduce enteric CH_4 emissions, similarly to clover *Trifolium subterraneum*. Stifkens et al. [51] found that increasing the proportion of legumes such as *Leucaena leucocephala* in feed reduces CH_4 due to condensed tannins acting as a bioactive compound that reduce methanogenesis. A 36% inclusion of *Leucaena leucocephala* in the diet of cattle reduced CH_4 by 25.09% per kilogram of boneless trimmed beef. Mwangi et al. [13] studied the effect of increasing the proportions of *Desmanthus* Spp. in the diet of feedlot cattle and the effect on weight gain, fermentation in the rumen, and plasma metabolites in cattle.

Feed supplements and additives

Seaweeds have proven to be effective at reducing enteric CH_4 emissions. Ridoutt et al. [43] explored the supplement of *Asparagopsis taxiformis*, a red seaweed, on feedlot cattle's CH_4 production and calculated a 1–4% reduction in Australia's cattle sector. Parra et al. [51] assessed a range of additives to reduce CH_4 in grazing cattle and found the addition of biochar and nitrate, biochar and *Asparagopsis*, and citral extract to significantly reduce CH_4 emissions by 22.83%, 19.82%, and 41%, respectively. Lean and Moate [20] reviewed CH_4 reduction strategies in Australia and found that nitrate supplementation reduced emissions by 10% and feed supplemented with 3-nitro-oxypropanol (3-NOP) reduced CH_4 by 22% in beef cattle and 39% in dairy cattle. Australian research has inspired researchers in the United States to study a locally produced seaweed grown in the waters of California to reduce CH_4 in cattle. Of note from this study is the 75% reduction in CH_4 production with *Asparagopsis taxiformis* and *Zonaria farlowii*. Research results from Kinley et al. [52], who supplemented beef cattle with a very low dosage of *Asparagopsis taxiformis*, found that the average daily weight gain increased by 26% and resulted in a reduction in CH_4 of 35% per kg of boneless trimmed beef.

Selective breeding

Pryce and Haile-Mariam [41] argue for genetic selection as a long-term permanent solution by selecting low-emitter cows and traits that have beneficial effects on emissions. Richardson et al. [53] studied the impact of direct CH_4 traits, reduction in replacements, and increase in productivity on CH_4 reduction. Another study [46] determined that the Estimated Breeding Values for Residual Methane Production (EBVRMP) phenotypically corrected for ECM (kg of CH_4/year) is currently the most inheritable trait to reduce CH_4 production in beef. The researchers note that dairy cows appear to have bodyweight and feed intake as the greatest effect on CH_4 production.

Residual CH_4 is stated to be the most inheritable trait to measure low-emissions cows [54]; yet Richardson et al. [46] argue more data are required to confirm residual CH_4 as an accurate measure of selective breeding programs. Currently, high-quality CH_4 phenotypes are less than 10% reliable which is insufficient for inclusion in selective breeding objectives.

Inclusion of sub-indexes in breeding standards

Richardson et al. [55] caution in choosing genetic traits due to potential for unfavourable correlations with energy-corrected milk or difficult to predict responses to genetic selection. Manzanilla-Pech et al. [54] compared dry matter intake and residual feed intake against CH_4 production as a sub-index in Australia's national breeding standards with CH_4 valued at various price points from nil to high and low negative values. Including residual food intake with a negative economic value in the breeding goal reduces the production of CH_4 compared to the base scenario. For example, this results in a 16.66% and 36.11% reduction in CH_4 based on DMI if CH_4 production is negatively valued at AUD 0.30 or AUD 0.60 per kg of CH_4, respectively. Pryce and Haile-Mariam [41] argue for inclusion of a heat stress/tolerance sub-index in the Balanced Performance Index as a way for the dairy industry to adapt to climate change.

Beef processing

Colley et al. [56] highlight the underreporting of CH_4 emissions generated from meat processing plants' wastewater. The researchers undertook an LCA and found that CH_4 generated from on-site wastewaters was responsible for 34% of climate change impacts in small to medium processors.

Farm management

Bai et al. [57] compared farm strategies regarding manure management and compared turning to stockpiling of manure. The researchers determined a 53.85%

decrease in CH_4 emission generated from manure after turning or windrow composting manure. Almeida et al. [17] argue for increased efficiency and production by triggering early puberty in breeding cows and reducing the post-weaning phase and associated feeding and emissions generated during non-productive times. Lean and Moate [20] found that providing ozonated water to cattle could reduce CH_4 by 20%.

3.2. MCDM/TOPSIS Results

In terms of the ASI framework, a mixture of 'Avoid' and 'Improve' measures were evident in the top ten ranked strategies for the baseline scenario and the climate emergency scenario. The conservatively weighted scenario, on the other hand, resulted in only 'Improve' strategies in the top ten. A breakdown of the strategies per scenario is presented in Figure 2. 'Avoid' strategies of land conversion pricing dominated the top four ranked strategies for the climate emergency and ranked 3rd and 4th in the baseline scenario. 'Improve' strategies, specifically those related to CH_4 being negatively valued in the breeding objective sub-index and citral extract supplementation ranked very highly for both baseline and conservatively weighted scenarios. Breeding indexes, supplementation with biochar and nitrates, and a greater proportion of wheat, grain, and legumes in dietary feed also ranked highly in the conservative and baseline top ten.

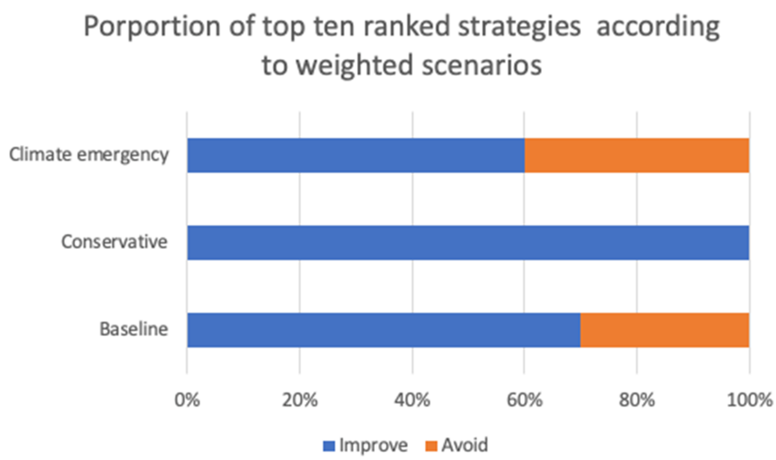

Figure 2. Proportion of strategies with ASI framework based on TOPSIS results from baseline, climate emergency, and conservative weightings.

3.2.1 Baseline Scenario

A combination of 'Improve' and 'Avoid' strategies dominated the top three ranked strategies under the equalized weighting scenario (Table 3). With all factors equally weighted, the best performing strategies were CH_4 negatively valued highly in sub-index of breeding standards based on DMI and conversion of ponded pastures to freshwater tidal forests or mangroves, resulting in a reduction in CH_4 by 58.33%, 99.93%, and 99.96%, respectively. High and low negative values of CH_4 included in breeding sub-index based on RFI reduced CH_4 by 47.22% and 27.78%, respectively, ranking 4th and 6th. Citral extract supplement in feed intake ranked 5th and reduced CH_4 emissions by 41%. The supplementation of feed with biochar and nitrates, provision of wheat at 45% of DMI, and grain-finished pasture cattle ranked 7th, 8th, and 10th, respectively, with 22.83%, 21.18%, and 22.25% reduction in CH_4. The 'Avoid' strategy converting ponded pastures to saltmarshes ranked 9th and reduced CH_4 by 99.98%. The performance scores ranged from 0.86 to 0.84 with rankings closest to 1 being the most effective solution.

Table 3. Ranked methane reduction strategies according to baseline equally-weighted indicators.

Ranking	Performance Ranking	Baseline Equally-Weighted Strategy
1	0.88414382	Methane included in breeding index and valued at 0.60 c per kg of CH_4 based on dry matter intake (DMI)
2	0.87393197	Conversion of land from ponded pasture to freshwater tidal forest
3	0.87387	Conversion of land from ponded pasture to mangroves
4	0.86826467	Methane production negatively economically valued at −0.60 c per kg CH_4 and resulting feed intake (RFI) included in breeding goals
5	0.86503572	Inclusion of citral extract at 0.1% of dry matter (DM)
6	0.85100814	Methane included in breeding index and valued at 0.30 c per kg of CH_4 based on RFI
7	0.84991771	Inclusion of biochar and nitrates at 8% of DM
8	0.84673888	Wheat 45% of DMI
9	0.84619539	Conversion of land from ponded pasture to salt marsh
10	0.84062149	Grain-finished pasture cattle

3.2.2. Climate Emergency Scenario

As the IPCC's mitigation strategies [30] encourage urgent and effective action, the climate emergency weighting prioritized CH_4 reduction in all cattle, feedlot and grazing. The top four results were 'Avoid' strategies through conversion of agricultural land to natural habitat. Conversion of wet pastures to freshwater tidal forests, mangroves or salt marshes reduced CH_4 emissions by 99.93%, 99.65%, and 99.98%, respectively. Conversion of dry pastures to salt marshes reduced CH_4 by 73.3%, ranked fourth, and feedlot cattle supplemented with *Asparagopsis taxiformis* ranked 6th with an 81% CH_4 reduction for 4% of the national herd's population. Inclusion of CH_4 as a subindex in breeding objectives and negatively valued at 60 c ranked fifth and seventh for DMI and RFI values reducing CH_4 by 58.33% and 47.22%, respectively. Supplementing feed with citral extracts, manure management strategies, and a low negative value of CH_4 in GHG subindex reduced CH_4 by 41%, 53.85%, and 36.11%, respectively, ranking 8th, 9th, and 10th (Table 4). The performance ranking ranged from 0.94 to 0.86.

Table 4. Ranked methane reduction strategies according to climate emergency-weighted indicators.

Ranking	Performance Ranking	Climate Emergency-Weighted Strategy
1	0.94687926	Conversion of land from ponded pasture to freshwater tidal forest
2	0.94684681	Conversion of land from ponded pasture to mangroves
3	0.94637256	Conversion of land from ponded pasture to salt marsh
4	0.92307151	Conversion of land from dry pasture to salt marsh
5	0.89979906	Methane production negatively economically valued at −0.60 c per kg CH_4 and DMI included in breeding goals
6	0.88987446	Feed lot cattle supplemented with Asparagopsis taxiformis
7	0.88001861	Methane production negatively economically valued at −0.60 c per kg CH_4 and RFI included in breeding goals
8	0.87954682	Inclusion of citral extract at 0.1% of DM
9	0.86121429	Composting manure vs. stockpiling
10	0.85934594	Methane production negatively economically valued at −0.30 c and DMI included in breeding goals

3.2.3. Conservative Scenario

When cost is weighted as the dominating indicator, 'Improve' strategies occupied all of the top ten most effective strategies (see Table 5). The most effective solution in the conservative scenario is the inclusion of CH_4 at a high negative value as a national breeding subindex based on DMI, or RFI followed by the supplementation of feed with citral extract, reducing methane by 58.33%, 47.22%, and 41%, respectively. The inclusion of biochar and nitrates in feed ranked fourth, following by a low negative value of CH_4 included in national breeding subindex based on DMI, and cattle diet consisting of 45% wheat reducing CH_4 by 22.83%, 36.11%, and 21.18%. The remainder of 'Improve' relating to feed supplementation ranked 7th, 8th, and 10th with grain-finished pasture cattle, supplementation of *Leucaena leucocephala*, and cattle diet consisting of 20% wheat reduced CH_4 by 22.25%, 25.09%, and 14.71%. The ninth ranked strategy was a lower negative value of CH_4 included in the national breeding index based on the resulting feed intake (RFI) reducing CH_4 by 27.78%. The performance ranking of all 'Improve' strategies were within the 0.98 performance range (see Table 5).

Table 5. Ranked methane reduction strategies according to conservatively-weighted indicators.

Ranking	Performance Ranking	Conservatively-Weighted Strategy
1	0.98219361	Methane production negatively economically valued at −0.60 c per kg CH_4 and DMI included in breeding goals
2	0.97988897	Methane production negatively economically valued at −0.60 c per kg CH_4 and RFI included in breeding goals
3	0.9794944	Inclusion of citral extract at 0.1% of DM
4	0.97761249	Inclusion of biochar and nitrates at 8% of DM
5	0.97737908	Methane production negatively economically valued at −0.30 c and DMI included in breeding goals
6	0.97714331	Proportion of wheat is 45% of DMI
7	0.9761628	Grain-finished feed formulation
8	0.97558359	36% Leucaena leucocephala feed formulation
9	0.97540405	Methane production negatively economically valued at −0.30 c and RFI included in breeding goals
10	0.97530739	Proportion of wheat is 20% of DMI

4. Discussion

Focusing on research in Australia, this study seeks to answer how the beef and dairy sector can address CH_4 emissions. Global CH_4 levels are rising despite many attempts to control them, including through the Global Methane Pledge signed by over 150 countries [58], which was eventually supported by Australia. The food system is responsible for up to 37% of global GHG emissions and affects nearly every planetary boundary [59,60]. Ruminant animals are the main sources of CH_4 emissions through enteric fermentation and CH_4 levels are predicted to increase as global population grows to over 9.7 billion with rising consumption of meat and dairy per person as a dietary trend globally [61]. With food systems being called to be compliant with a 1.5 °C world, this research seeks to address what are estimated to be the most effective strategies to reduce CH_4 emission in the beef and dairy sector.

This literature review's findings suggest two main concerns requiring CH_4 as a GHG, namely, metric and measurement challenges. They are discussed first before outlining the reduction strategies and interpreting the research findings regarding the ASI scenarios.

4.1. Methane Metric Challenges

All GHGs, including CH_4, are made equivalated to carbon dioxide's molecular structure and lifespan of approximate 100 years represented as Global Warming Potential of 100 (GWP100) [62]. The IPCC's 6th Assessment Report states that CH_4 emissions are equivalated to 27 times more potent than CO_2 over a 100-year timescale. This report also confirms the lifetime of CH_4 is 11.8 years in the atmosphere, making the potency much closer to 84 times as potent as carbon dioxide over the relevant approximately 20-year lifespan [63]. The argument for GWP* is supported in the literature, where the "*" represents the lifespan of the GHG in question [18,20].

Perez-Dominguez et al. [64] highlight the value of reflecting the true lifespan of CH_4 which can reverse temperature increases by 2070 if carbon pricing is adequately high enough. The universal application of GWP* raises risks according to Rogelj and Schleussner [65], who argue that implementing GWP* will create equality issues due to the unfair allocation of greater emissions to lower income countries that are agriculture-based, yet have not historically contributed to climate change. As the scope for this research is within the advanced economy of Australia, the application of GWP* to GHG metrics is deemed appropriate.

4.2. Measurement of Methane

The literature highlights the difficulty in measuring accurate CH_4 emissions which creates uncertainty regarding CH_4 production and impact [18,42,57]. This is supported in the wider literature, especially in agricultural settings where whole-of-farm activities are not included in national GHG inventories [66] and measurement of CH_4 differs dependent upon the stage of lactation as well as measurement method [67,68]. Given the projected 90% rise in CH_4 emissions attributable solely to meat production, coupled with an anticipated 1.8% growth in milk production by 2031 [69], CH_4 has historically been overshadowed by carbon in policy discussions until the global policy landscape changed with the adoption of the Global Methane Pledge in 2021 [58]. Australia also signed the methane pledge in October 2022 but has yet to develop a national strategy for its implementation [70].

Ruminants are animals with a rumen which contains a complex anaerobic microbial ecosystem that can ferment plant matter [71]. A rumen's microbiome consists of bacteria, archaea, protozoa, bacteriophage, and fungi that produce CH_4 as a by-product of enteric fermentation [72]. The cattle population in Australia exceeds 24 million, and with each animal emitting an estimated average of 56 kg of CH_4 annually, this results in 1.3 million tonnes of CH_4 produced solely from cattle [53,73] or 105 million tonnes of CO_2e based on a twenty-year half-life (GWP20) of CH_4. These emissions are anticipated to rise, as global beef and dairy production is projected to increase by 6% in 2031, driven by consumer demand stemming from population growth and dietary trends [69]. Despite recent attention on CH_4 reduction following the Global Methane Pledge, no national CH_4 reduction strategy for Australia currently exists.

4.3. Methane Reduction Strategies

In the TOPSIS context, "most effective" is defined as the strategy closest to the positive ideal solution and farthest from the negative ideal solution [25]. For example, the most effective strategy could be one which reduces the highest amount of CH_4 emissions, incurring the smallest cost, with minimal detrimental trade-offs and providing substantial environmental and social benefits. This effectiveness is subject to consideration of many factors across different strategic approaches. A literature search indicates the absence of existing frameworks published and/or available for national governments, industries, or the general public to assess the effectiveness of various CH_4 reduction strategies. The only exception is an assessment of the New South Wales's livestock sector, which considers the practicality, availability, risks, and barriers influencing the adoption of CH_4 reduction strategies [74].

Applying the novel indicator framework, a ranking of strategies using TOPSIS estimated that conversion of agricultural land to natural wetlands in the climate emergency scenario is the most effective strategy which favoured CH_4 reduction and both production systems. This 'Avoid' strategy measured a reduction in CH_4 emissions associated with soil up to 99%, excluding enteric CH_4, highlighting the significant of land use change in the agricultural sector. Rewilding, reforestation, and rehabilitation of natural habitat have been undertaken as a strategy by the Australian Department of Climate Change, Energy, the Environment and Water (DCCEEW) with a focus on restoring coastal wetlands, salt, and tidal marshes [75]. Whilst government funding for land rehabilitation is up to AUD 2 million dollars per site, a meta-analysis of successful land rehabilitation projects in developed economies determined the costs to be approximately AUD 40–50,000 per hectare for restoration of coastal wetlands and mangroves and approximately AUD 150,000 per hectare for restoration of salt marsh, which could be reduced significantly with volunteer and community support [76]. This strategy is limited to areas of coastal or river basins, but it applies to both Australia's northern and southern production zones and complies with existing legislation. No new policy is required to continue rehabilitation efforts; however, upscaling of existing efforts may require incentivizing policies for cattle farmers to restore agricultural lands to natural habitats within the property boundaries.

In the baseline and conservative scenarios, the inclusion of a GHG subindex into the national breeding standards of Australian cattle ranked first as the most effective CH_4 reduction strategy. The highest reduction in CH_4 by 58.33% and 47.33% occurred when CH_4 production was negatively valued at AUD 0.60 c per kg of CH_4 and based on dry matter intake or residual feed intake, respectively. Negatively valuing CH_4 emissions in breeding objectives has support within this literature search with a focus on the selection of the most suitable phenotype for low-emission cattle. The inclusion of a CH_4 trait in breeding values such as the Balanced Performance Index is considered as a low-cost strategy requiring an update to the Australian Breeding Values and that is readily scaled to all beef and dairy sectors nationwide. Habitat restoration and the inclusion of a GHG subindex into the national breeding standards were ranked as the most effective strategies.

The top ten strategies to reduce CH_4 in a conservative scenario indicate no presence of 'Avoid' strategies, which is indicative of an economic focus. Land restoration strategies ranked very low in the conservative scenario due to the higher cost of land restoration compared to feed formulations and additives in a cost-saving scenario. Australian federal departments acknowledge the social and cultural benefits of wetland restoration [75] and land restoration policies align with IPCC's mitigation of emissions approach to health and well-being typical of 'Avoid' scenarios.

No 'Shift' strategies ranked highly in any scenario in this study. When considering the IPCC's assessment of demand-side strategies, plant-based diets represent the greatest 'Shift' potential of all 'Shift' strategies whilst increasing human health and well-being [30]. The IPCC acknowledges that feedback loops between dietary shifts and demand for production are often overlooked in LCA studies of dietary changes [77]. No research in this literature review presented Australian CH_4 reduction strategies which highlighted human health impacts. This indicates disconnect between human and environmental well-being.

'Improve' strategies dominated the conservative scenario with 100% of 'Improve' strategies in the top ten, 70% in the baseline, and 60% in the climate emergency scenario. Feed supplements, feed formulations, GHG subindexes and manure management dominated high-ranking 'Improve' strategies for all scenarios.

4.4. Strategies in Perspective

The dominance of 'Improve' strategies in the top strategies of the conservative scenario highlights the research focus on feed supplements for feedlot cattle and reduced economic capital. This focus on efficiency and feed inputs refers to reducing product-based emissions without regard for absolute emissions as demand is expected to grow and is reflected in Australia's discussion paper about developing a net zero plan for agriculture [40]. The focus on improving breeding standards has highlighted the possibility of updating the Balanced Performance Index to include GHG emissions as a sub-index, but difficulties remain in determining an accurate genetic phenotype for low-emission cattle.

By comparison, the dominance of 'Avoid' strategies in the top strategies for climate emergencies highlights the focus to expand the narrow vision of efficiency per litre or kilogram of a product versus a whole-of-farm approach that includes overall emissions generated from the food system, including soil emissions, and can extend to processing and beyond-the-farm-gate processing. The Food and Agriculture Organization of the United Nations (FAO) [69] aligns with many of the 'Improve' strategies which contrast with IPCC's [30] low-carbon high-wellbeing societies and the outcome of the meta-analysis of over 400 CH_4 reduction studies in the beef and dairy sector. While Arndt et al. [78] analysed the impact of combining various effective strategies, the authors found that a reduction in breeding activities through shifting to plant-based diets will ensure the agriculture sector achieves the 1.5 °C target by 2050.

4.5. Limitations of the Study

This study is limited by a range of methodological and research factors. Firstly, there was a lack of comprehensive data for most of the strategies included in the study, namely relating to the true cost of upfront capital required and ongoing costs of each strategy. Similarly, environmental impacts are limited to only CH_4 reduction and a fuller understanding of a strategy's upstream and downstream effects via a lifecycle assessment would benefit the environmental categories greatly. Further limitations include the impacts of strategies on human health and social acceptability, which would align closer with the ASI framework and assessment of animal health as a result of any implemented strategies.

Also, this study is limited by the choice of methodology. Firstly, applying a ranking system does not allow a combination of strategies to be assessed, which may result in different outcomes. Additionally, this study is limited by reliance on secondary data and the lack of stakeholder engagement which could affect indicator attributes, weighting and social acceptability. Despite these limitations, this study still has value being the first and only available investigation to attempt ranking CH_4 reduction strategies in the Australian beef and dairy industry.

4.6. Recommendations and Future Research

By assessing the range of strategies available with robust qualitative evidence, supported by empirical data and robust methodology, this study can assist formulation of evidence-based targeted policies to address CH_4 emissions in Australia's agricultural sector, in an approach similar to energy and transport decisions. Policymakers can leverage the insights gained from this research to develop informed and data-driven strategies aimed at mitigating CH_4 emissions. By acting on these recommendations and undertaking a MCDM approach to methodology, policymakers can capture the full benefits of converting agricultural land to natural habitat, which aligns with the need to critically engage in climate action this decade.

Based on the research and methodology described in the previous sections, it is recommended that policymakers implement 'Avoid' measures where feasibly possible to complement 'Improve' measures to achieve deep emissions reductions across the beef and dairy sector. Such a policy mix could include prioritization of agricultural land conversion and continued investment in research to determine accurate genetic phenotyping for greater certainty of CH_4 heritability traits to be included in national breeding objectives.

The identified limitations in this study pave the way for opportunities for future research, particularly in the context of deeper financial and environmental implications of CH_4 strategies focusing on Australia's beef and dairy sector. Expanding the environmental assessment beyond CH_4 reduction to encompass a lifecycle assessment of strategies or content analysis to capture additional issues raised in the research would bolster the ecosystem-wide effects which can offer a more comprehensive view of the environmental impact, considering upstream and downstream effects and impact on planetary boundaries such as biodiversity impacts, land-use impacts, biogeochemical flows, water consumption, and resource consumption.

Methodologically speaking, future research could explore alternative evaluation frameworks that allow for the combination of strategies or assessment of data. This would address the limitation of the current ranking system and provide a more nuanced understanding of the synergies and trade-offs between different CH_4 reduction approaches. Additionally, narrowing the geographical scope of studies to a particular area or region would enhance the applicability of findings, ensuring a more convincing perspective to promote effective strategies.

Lastly, recognizing the importance of stakeholder engagement is vital and future research should incorporate views from all affected stakeholders to ensure a more accurate representation of concerns, priorities, perspectives and capture social acceptability. The co-creation of a decision-making framework can contribute to refining indicator attributes and weighting, making the assessment more reflective of the country's diverse and dynamic landscape. Despite the acknowledged limitations, this study serves as a foundational step in ranking CH_4 reduction strategies, making future research opportunities even more critical in advancing the field and shaping evidence-based policies for beef and dairy production.

5. Concluding Remarks

To address the key research problem of what are the most effective strategies to reduce CH_4 emissions in the beef and dairy sector in Australia, a TOPSIS ranking method was undertaken which allowed us to estimate the most effective strategies available since 2020. With CH_4 reduction being a significant part of keeping the world a habitable space, addressing enteric emissions from ruminant animals remains critical. This research highlights the potency and lifespan of CH_4 as a key reason why this GHG is essential to reducing near- and long-term climate change impacts. With consistent formal underestimation of CH_4's impact due to equivalating to carbon's 100-year lifespan, accurate metrics, such as GWP* and standardized measurement of CH_4 techniques are needed to be implemented.

In total, 46 strategies from 27 articles on CH_4 reduction in Australia were ranked under three scenarios, namely, baseline, conservative, and climate emergency. The most effective were 'Avoid' strategies of conversion of agricultural land to wetlands, salt marshes, or tidal forest in the climate emergency scenario. By comparison, the most effective for the conservative and baseline scenarios was an 'Improve' strategy, namely the inclusion of CH_4 production in breeding goals associated with a high negative economic value. A policy mix of both measures is recommended for the industry to ensure significant and sustained emission reductions in line with industry, national, and international targets.

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Appendix A. TOPSIS Equations Used in the Assessment of the Alternative Strategies (Yoon and Hwang [32])

The positive-ideal solution is represented as:

$$A* = (x * 1, \ldots, x * j, \ldots, x * n) \quad (A1)$$

where x ∗ j stands for the most optimal value for the jth characteristic among all possible alternatives. The positive-ideal solution is achieved by combining the highest ratings for each attribute

Likewise, the negative-ideal solution is represented as:

$$A- = (x - 1, \ldots, x - j, \ldots, x - n) \quad (A2)$$

where x − j stands for the worst value for the jth characteristic among all possible alternatives to enable a comparison between alternatives in relation to the best and worst value.

Equation (A3) demonstrates the decision matrix to evaluate the alternatives and criteria:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} \\ x_{21} & x_{22} & \cdots & x_{2j} \\ \cdots & \cdots & \cdots & \cdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} \end{bmatrix} \quad (A3)$$

which represents the value of the alternatives, such as CH_4 reduction strategies with criteria, such as percentage of CH_4 reduction.

The data was normalized with vector normalization according to Equation (A4) to calculate a value between 0 and 1 to compare easily.

$$y_{ij} = x_{ij} / \sqrt{\sum_{i=1}^{I} x_{ij}^2} \quad (A4)$$

The normalized data are given in the Y matrix as seen in Equation (A5).

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1j} \\ y_{21} & y_{22} & \cdots & y_{2j} \\ \cdots & \cdots & \cdots & \cdots \\ y_{i1} & y_{i2} & \cdots & y_{ij} \end{bmatrix} \quad (A5)$$

For the integration of weightings weighted according to the three scenarios, baseline, conservative, and climate emergency, Equation (A6) was used.

$$W = Wj \quad (A6)$$

where Wj represents the allocated weighting across criteria according to the relevant scenarios to produce a weighted normalized V matrix in Equation (A7)

$$V = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1j} \\ v_{21} & v_{22} & \cdots & v_{2j} \\ \cdots & \cdots & \cdots & \cdots \\ v_{i1} & v_{i2} & \cdots & v_{ij} \end{bmatrix} \quad (A7)$$

The weighting for the baseline scenario is spread evenly across all categories; it is weighted heavily to reduce economic costs in the conservative scenario and weighted heavily towards health benefits and CH_4 reduction in the climate emergency scenario. The results of weighted normalized performance values can be seen in Appendix D.

As TOSPIS is based on the understanding that the most ideal solution has the shortest distance to the most positive ideal solution and the longest distance from the most negative ideal solution, the ideal best and ideal worst values were found (Equations (A8) and (A9)). All categories were of benefit to the most ideal solution except for costs and new policy required which were deemed as non-benefits.

$$A^* = [v_1^*, v_2^*, \ldots, v_j^*] \quad (A8)$$

$$A^{-} = [v_1^{-}, v_2^{-}, \dots, v_j^{-}] \quad \text{(A9)}$$

where

$$v_j^{*} = \begin{cases} \max v_{ij}, if\ j\ is\ a\ benefit\ attribute \\ \min v_{ij},\ if\ j\ is\ a\ cost\ attribute \end{cases}$$

$$v_j^{-} = \begin{cases} \min v_{ij}, if\ j\ is\ a\ benefit\ attribute \\ \max v_{ij},\ if\ j\ is\ a\ cost\ attribute \end{cases}$$

A* denotes the positive ideal strategy, whereas A⁻ denotes the negative ideal strategy.

The next step is to calculate the separation distance, or Euclidean distance, of each strategy from the ideal best and ideal worst solutions (Equations (A10) and (A11)).

$$S_i^{*} = \sqrt{\sum_{j=1}^{J} (v_{ij} - v_j^{*})^2} \quad \text{(A10)}$$

$$S_i^{-} = \sqrt{\sum_{j=1}^{J} (v_{ij} - v_j^{-})^2} \quad \text{(A11)}$$

Finally, the performance score was calculated using the figure which divides the sum of the ideal best and ideal worst distance by the ideal worst position for each strategy in Equation (A12).

$$V_i = \frac{S_i^{-}}{S_i^{-} + S_i^{*}} \quad \text{(A12)}$$

The finalized performance values can be seen in Appendix D. The higher the V_i performance value, the higher the strategy's ranking.

Appendix B

Table A1. Decision matrix for the Australian beef and dairy sector.

Author(s)	Article Number	Methane Reduction Strategy	% Reduction CH_4/kg of ECM Milk or Boneless Trimmed Beef	Estimated Establishment Costs AUD	Technological Readiness	Compliance with Existing Laws and Regulations	New Policy Required	Feedlot and Grazing Systems	Applicable to Both Climatic Zones	Applicable to All Seasons
Thomas et al. (2021) [12]	1	Grain-finished feed formulation	22.25	1.00	2.00	2.00	1.00	2.00	2.00	2.00
Stifkens et al. (2022) [50]	3	36% Leucaena leucocephala feed formulation	25.09	1.00	2.00	2.00	1.00	3.00	1.00	2.00
Ridoutt et al. (2022) [43]	4	Feed lot cattle supplemented with Asparagopsis taxiformis	81.00	10.00	1.00	2.00	2.00	1.00	2.00	2.00
Richardson et al. (2022) [46]	7	Low accuracy residual methane trait included in breeding standards	1.78	1.00	2.00	2.00	2.00	3.00	2.00	2.00
	7	Higher accuracy residual methane trait included in breeding standards	8.92	10.00	1.00	2.00	2.00	3.00	2.00	2.00
	7	$150/t carbon tax + low accuracy residual methane trait included in breeding standards	0.00	8.00	1.00	1.00	2.00	3.00	2.00	2.00
	7	$250/t carbon tax + low accuracy residual methane trait included in breeding standards	0.09	8.00	1.00	1.00	2.00	3.00	2.00	2.00
	7	$500/t carbon tax + low accuracy residual methane trait included in breeding standards	0.36	8.00	1.00	1.00	2.00	3.00	2.00	2.00
	7	$1000/t carbon tax + low accuracy residual methane trait included in breeding standards	0.71	8.00	1.00	1.00	2.00	3.00	2.00	2.00
	7	$150/t carbon tax + higher accuracy residual	3.92	10.00	1.00	1.00	2.00	3.00	2.00	2.00

		methane trait included in breeding standards								
	7	$250/t carbon tax + higher accuracy residual methane trait included in breeding standards	5.17	10.00	1.00	1.00	2.00	3.00	2.00	2.00
	7	$500/t carbon tax + higher accuracy residual methane trait included in breeding standards	6.96	10.00	1.00	1.00	2.00	3.00	2.00	2.00
	7	$1000/t carbon tax + higher accuracy residual methane trait included in breeding standards	8.03	10.00	1.00	1.00	2.00	3.00	2.00	2.00
Parra et al. (2023) [51]	10	Inclusion of biochar and nitrates at 8% of DM	22.83	1.00	2.00	2.00	1.00	3.00	2.00	2.00
	10	Inclusion of biochar and Asparagopsis at 5% of DM	19.82	10.00	1.00	2.00	2.00	1.00	2.00	2.00
	10	Inclusion of citral extract at 0.1% of DM	41.00	1.00	1.00	2.00	1.00	3.00	2.00	2.00
Moate et al. (2020) [14]	12	Proportion of wheat is 15% of DMI	12.35	1.00	2.00	2.00	1.00	3.00	2.00	2.00
	12	Proportion of wheat is 20% of DMI	14.71	1.00	2.00	2.00	1.00	3.00	2.00	2.00
	12	Proportion of wheat is 45% of DMI	21.18	1.00	2.00	2.00	1.00	3.00	2.00	2.00
Manzanilla-Pech et al. (2021) [54]	13	Reduction of methane and DMI included in breeding goals	16.66	1.00	2.00	2.00	2.00	2.00	2.00	2.00
	13	Methane production negatively economically valued at -0.30c and DMI included in breeding goals	36.11	1.00	2.00	2.00	2.00	2.00	2.00	2.00
	13	Methane production negatively economically valued at -0.60c per kg CH4 and DMI included in breeding goals	58.33	1.00	2.00	2.00	2.00	2.00	2.00	2.00

	13	Reduction of Methane and RFI included in breeding goals	8.33	1.00	2.00	2.00	2.00	2.00	2.00	2.00
	13	Methane production negatively economically valued at -0.30c and RFI included in breeding goals	27.78	1.00	2.00	2.00	2.00	2.00	2.00	2.00
	13	Methane production negatively economically valued at -0.60c per kg CH_4 and RFI included in breeding goals	47.22	1.00	2.00	2.00	2.00	2.00	2.00	2.00
Lean and Moate (2021) [20]	15	Ozone addition to water troughs	20.00	4.00	1.00	2.00	2.00	3.00	2.00	2.00
		Nitrates supplementation	10.00	1.00	2.00	2.00	2.00	2.00	2.00	2.00
		3-nitro-oxypropanol	30.50	1.00	2.00	1.00	2.00	1.00	2.00	2.00
Iram et al. (2021) [45]	16	Conversion of land from ponded pasture to mangroves	99.65	4.00	2.00	2.00	2.00	2.00	1.00	2.00
		Conversion of land from ponded pasture to freshwater tidal forest	99.93	4.00	2.00	2.00	2.00	2.00	1.00	2.00
		Conversion of land from ponded pasture to salt marsh	99.98	6.00	2.00	2.00	2.00	2.00	1.00	2.00
		Conversion of land from dry pasture to mangrove	-386.67	4.00	2.00	2.00	2.00	2.00	1.00	2.00
		Conversion of land from dry pasture to freshwater tidal forest	6.67	4.00	2.00	2.00	2.00	2.00	1.00	2.00
		Conversion of land from dry pasture to salt marsh	73.30	6.00	2.00	2.00	2.00	2.00	1.00	2.00
Bai et al. (2020) [57]	21	Composting manure vs stockpiling	53.85	4.00	2.00	2.00	2.00	1.00	2.00	2.00
Almeida et al. (2023) [17]	24	Improving fertility by 10% with 50% adoption rate	2.97	1.00	2.00	2.00	2.00	3.00	1.00	2.00

		Improving fertility by 10% with 60% adoption rate	3.56	1.00	2.00	2.00	2.00	3.00	1.00	2.00
		Improving fertility by 10% with 70% adoption rate	4.16	1.00	2.00	2.00	2.00	3.00	1.00	2.00
		Improving fertility by 10% with 80% adoption	4.75	1.00	2.00	2.00	2.00	3.00	1.00	2.00
		Improving fertility by 5% with 50% adoption	1.56	1.00	2.00	2.00	2.00	3.00	1.00	2.00
		Improving fertility by 5% with 60% adoption	1.87	1.00	2.00	2.00	2.00	3.00	1.00	2.00
		Improving fertility by 5% with 70% adoption	2.18	1.00	2.00	2.00	2.00	3.00	1.00	2.00
		Improving fertility by 5% with 80% adoption	2.50	1.00	2.00	2.00	2.00	3.00	1.00	2.00
Kinley et al. (2020) [52]	27	0.05% inclusion of Asparagopsis in OM	0.20	1.00	1.00	2.00	2.00	1.00	2.00	2.00
		0.10% inclusion of Asparagopsis in OM	0.35	1.00	1.00	2.00	2.00	1.00	2.00	2.00
		0.20% inclusion of Asparagopsis in OM	0.82	1.00	1.00	2.00	2.00	1.00	2.00	2.00

Note: DM—dry matter; DMI—dry matter intake; ECM—energy-corrected milk; OM—organic matter; RFI—Residual feed intake.

Appendix C

Table A2. Summary of articles and strategies included in TOPSIS with extracted data and secondary sources.

Strategy Type	Authors	Title	Study Summary	Extracted Data
Improve	Thomas et al. [12]	Net protein contribution and enteric methane production of pasture and grain-finished beef cattle supply chains	Enteric methane emissions from grass-fed and grain-fed beef supply chains were compared using net protein calculations resulting in grain-finished beef producing a lower net protein contribution value of 1.96 compared to 1597.	Grass-fed beef cattle produced a methane intensity of 10.06 kg of CO_2e live weight compared to 7.82 kg of CO_2e [12] resulting in 22.5% reduction in methane per kilogram of boneless trimmed weight according to Saner and Buseman (2020)'s methodology [39]. Grain estimated to be AUD 500/t based on June 2023 prices [79]. Barley, cottonseed, and cereal hay are readily available, comply with existing laws and regulations, and are implementable across both climatic zones, in all seasons and applicable to pasture systems if beef cattle relocated to feedlot for finishing.
Improve	Stifkens et al. [50]	Increasing the Proportion of Leucaena Leucocephala in Hay-	Study compared impact of 36% inclusion of Leucaena leucocephala in diet of grazing cattle.	A 25.09% reduction in methane compared to control [50] based on boneless trimmed beef compared using Saner and Buseman (2020)'s methodology [39]. Cost considered based on industry pricing for AUD 250 per 500 mL of inoculum required plus AUD

		Fed Beef Steers Reduces Methane Yield		250–300 per hectare planting estimation [80,81]. Successfully tested in the field, yet needs fertile soils to grow, limiting applicability in northern region [81]. Toxic to all mammals [82] and considered invasive species [81]. Farmers can choose to plant Leucaena as a forage species without need for new regulations, legislations, or policy.
Improve	Ridoutt et al. [43]	Potential GHG emission benefits of Asparagopsis taxiformis feed supplement in Australian beef cattle feedlots	Lifecycle assessment of feedlot cattle supplemented with 71.5 mg of bromoform per kilo of DMI.	An 81% reduction in methane as per previous in vivo trials [52,83]. Cost considered to be the highest due to new industry required for commercialisation with estimated of USD 39.5 million plus USD 5 million yearly [84]. More research needed for applicability to grazing cattle [43]. Northern region farmers most likely to give supplements in dry season [85]. Approved active constituents in Australia [86], but new policy required for commercialisation and wide-scale adoption.
Shift	Richardson et al. [46]	Reducing greenhouse gas emissions through genetic selection in the Australian dairy industry	Study compared current and future genetic accuracy of inclusion of GHG index in Balanced Performance Index (BPI) based on carbon prices of AUD 150/t, AUD 250/t, AUD 500/t, and AUD 1000/t.	Based on Richardson, Nguyen et al. (2021)'s calculations of 0.183 g of methane produced per cattle per day [55], 0, 0.05, 0.2, and 0.4 kg of methane were reduced under current genetic accuracy for AUD 150, AUD 250, AUD 500, and AUD 1000 carbon pricing per year, respectively Future genetic accuracy reduced methane by 2.2, 2.9, 3.9, and 4.5 kg for carbon pricing of AUD 150, AUD 250, AUD 500, and AUD 1000 per year, respectively [46]. Cost considered to be the highest to achieve greater genetic accuracy due to genetic research ranging from USD 150 to 300 million [87,88]. Not considered to be technologically ready until expected genetic accuracy reaches 0.54 or higher. Applicable to all systems, climates, and seasons without the need for legislative change; only policy change required to update BPI standards [53].
Improve	Parra et al. 2023 [51]	In vitro screening of anti-methanogenic additives for use in Australian grazing systems	Study of methane reduction over 48 h of incubating rumen fluid in vitro testing with garlic powder, biochar and nitrates, biochar and *Asparagopis Taxiformis*, essential oil blend, citral extract, sandalwood essential oil, Bacillus probiotic additive, and sugar cane extract.	Based on a control of 19.32 mL/CH_4 per gram of digestible matter, biochar and nitrates, biochar and *Asparagopis*, and citral extract significantly reduced methane reduction by 22.83%, 19.82%, and 4%, respectively. Biochar assumed to cost AUD 800/t [89], calcium nitrate, ammonium nitrate, or potassium nitrate estimated to be in the form of loose licks are considered to be 'cost effective' [90]; citral extract is EUR 163 per 500 ml [91] and considered to be low. Inclusion of *Asparagopis* was the highest cost due to requirement for establishing new industry [84]. Supplementation with *Asparagopis* and with citral were considered to be not technologically ready due to requirements for *Asparagopis* commercialisation [78], and further research for citral at higher-than-recommended doses due to digestion effects is needed [51]. *Asparagopis* requires new policy to establish commercialisation process and is only available in feedlot systems.
Improve	Moate et al. [14]	Influence of proportion of wheat in a pasture-based diet on milk yield, methane emissions,	Study compared various proportions of wheat in diet of dairy cattle over 47 days.	Diet supplemented with 15%, 20%, and 45% of DMI reduced methane by 12.35%, 14.71%, and 21.18% based on 17 g/kg per ECM of no-wheat diet [14]. Wheat

		methane yield, and ruminal protozoa of dairy cows		estimated to be a low-cost feed supplement at AUD 485/t [92]. No compliance or readiness issues triggered.
Improve	Manzanilla-Pech et al. [54]	Breeding for reduced methane emission and feed-efficient Holstein cows: An international response	Study compared dairy genome databases from Australia, Canada, UK, US, and Denmark to determine genetic parameters of methane traits and response of including methane traits in breeding goals with negative economic values.	A 16.66%, 36.11%, and 58.33% reduction in methane based on methane production traits based on digestible matter intake, mean body weight, and energy-corrected milk included in breeding standards, valued at low and high economic values, respectively [54]. An 8.33%, 27.78%, and 47.22% reduction in methane based on methane production traits for residual feed intake, mean body weight, and energy-corrected milk for being included in breeding standards at no value, low value, and high value, respectively [54]. A new policy is required to update the national breeding objective to include methane traits [93]. Costs considered to be low, similarly due to minimal interventions being required, and the strategy applies to all systems, climates, and seasons.
Improve	Lean and Moate [20]	Cattle, climate and complexity: food security, quality and sustainability of the Australian cattle industries	Reviewed a number of strategies to reduce methane in the beef and dairy sector.	Strategies highlighted 20% reduction in methane with addition of ozonated water. Needs in vivo testing [20], not technologically ready, and costs to ozonate water troughs are expected to be higher than feed with commercial systems estimated around USD 3000 [94]. No policy, legislation, systems, or climate issues triggered. Nitrates decreased methane by 10%; considered to have low costs [90], and no policy, legislation, systems, or climate issues triggered. 3NOP reduced methane by 22% in beef cattle and 39% in dairy cattle, yet not currently available in Australia as approval is required as an animal feed from the government [20,95], and is low cost and applies to feedlot cattle.
Improve	Iram et al. [45]	Soil greenhouse gas fluxes from tropical coastal wetlands and alternative agricultural land uses	Study compared GHG fluxes from wet pastures, dry pastures, mangroves, freshwater tidal forest, salt marshes, and sugar cane fields in the Herbert Basin in Queensland, Australia.	Mangroves, salt marshes, and freshwater tidal forests existed naturally prior to agricultural pastures. Mangroves, freshwater tidal forests, and salt marshes produced 99.95%, 99.93%, and 99.98% less methane than wet pastures, respectively. Salt marshes and fresh water tidal forests produced 73.3% and 6.67% less than dry pastures while mangroves produced 386.67% more methane than dry pastures. Costs of restoration of land back to original habitat estimated at USD 40,000, USD 52,000, and USD 151,000 per hectare for coastal wetlands, freshwater tidal forests, and salt marshes, respectively [76]. Only applicable to pasture systems in any coastal region or river basin regardless of climate. Policy required for restoration of agricultural land.
Improve	Bai et al. [57]	Gas emissions during cattle manure composting and stockpiling	Study compared emissions from stockpiling emissions to windrow composting systems.	Total cumulative methane emissions were 53.85% less in windrow composting compared to stockpiling manure [57]. Costs estimated to be USD 62,000 upfront plus USD 31,000 yearly maintenance [96]. Only applicable to feedlot cattle and may require new policy to require non-static manure stockpiling.

Improve	Almeida et al. [17]	A regional-scale assessment of nutritional-system strategies for abatement of enteric methane from grazing livestock	This study simulated the impact of improving fertility on NSW's beef cattle's methane production.	A 5% increase in fertility by reducing age at joining reduced NSW emissions by 1.56%, 1.87%, 2.18%, and 2.5% for adoption rates of 50%, 60%, 70%, and 80%, respectively [17]. A 10% improvement in fertility reduced state emissions by 2.97%, 3.56%, 4.16%, and 4.75% subject to 50%, 60%, 70%, or 80% adoption rate [17]. With changes in feeding triggering early puberty, costs were considered to be low due to feed requirement, and can be implemented in any system or climate without need for policy or legislation.
Improve	Kinley et al. [52]	Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed	Low doses of *Asparagopis* were supplemented in the diet of feedlot beef cattle to compare various proportions of *Asparagopis* on methane production, feed intake, weight gain, and volatile fatty acid production.	Average daily weight gain was calculated for each of the dosages and used Saner and Buseman (2020)'s formula [39] to calculate methane production per kg of boneless trimmed beef. A 20%, 35%, and 82% reduction in methane was found, respectively, when *Asparagopis* doses of 0.05%, 0.10%, and 0.20% of organic matter were included in diet [52]. Commercialisation of *Asparagopis* is needed requiring new policies, legislation, and the highest level of funding to support development of new industry exceeding USD 40 million per farm [84]. Only applicable to feedlot cattle as part of total mixed rations [52], but can be applied in all seasons and production regions.

Appendix D

Table A3. Scenarios for methane reduction in the Australian beef and dairy sector.

a. Baseline scenario																
		Normalised Equalised Data		**0.125**	**0.125**	**0.125**	**0.125**	**0.125**	**0.125**	**0.125**	**0.125**					
	Author/s	**Article #**	**Methane Reduction Strategy**	**% Reduction CH_4/kg of ECM Milk or Boneless Trimmed Beef**	**Estimated Costs AUD**	**Technological Readiness**	**Compliance with Existing Laws and Regulations**	**New Policy Required**	**Feedlot and Grazing Systems**	**Applicable to Both Climatic Zones**	**Applicable to All Seasons**	**Si+**	**Si-**	**Si+ + Si-**	**Performance Score**	**Ranking**
Improve	Thomas et al. (2021) [12]	1	Grain-finished feed formulation	0.0061	0.0037	0.0212	0.0200	0.0098	0.0147	0.0212	0.0184	0.0225	0.1187	0.1412	0.840621487	10
Improve	Stifkens et al. (2022) [50]	3	36% Leucaena leucocephala feed formulation	0.0069	0.0037	0.0212	0.0200	0.0098	0.0221	0.0106	0.0184	0.0231	0.1197	0.1427	0.838355082	11

Improve	Ridoutt et al. (2022) [43]	4	Feedlot cattle supplemented with Asparagopsis taxiformis	0.0222	0.0368	0.0106	0.0200	0.0196	0.0074	0.0212	0.0184	0.0394	0.1288	0.1682	0.76579404	35
Improve	Richardson et al. (2022) [46]	7	Low accuracy residual methane trait included in breeding standards	0.0005	0.0037	0.0212	0.0200	0.0196	0.0221	0.0212	0.0184	0.0286	0.1138	0.1424	0.799093316	22
Improve		7	Higher accuracy residual methane trait included in breeding standards	0.0024	0.0368	0.0106	0.0200	0.0196	0.0221	0.0212	0.0184	0.0439	0.1102	0.1541	0.715070836	40
Shift		7	$150/t carbon tax + low accuracy residual methane trait included in breeding standards	0.0000	0.0295	0.0106	0.0100	0.0196	0.0221	0.0212	0.0184	0.0415	0.1076	0.1491	0.721728038	39
Shift		7	$250/t carbon tax + low accuracy residual methane trait included in breeding standards	0.0000	0.0295	0.0106	0.0100	0.0196	0.0221	0.0212	0.0184	0.0415	0.1076	0.1491	0.721851822	38
Shift		7	$500/t carbon tax + low accuracy residual methane trait included in breeding standards	0.0001	0.0295	0.0106	0.0100	0.0196	0.0221	0.0212	0.0184	0.0414	0.1077	0.1491	0.722222853	37

Shift		7	$1000/t carbon tax + low accuracy residual methane trait included in breeding standards	0.0002	0.0295	0.0106	0.0100	0.0196	0.0221	0.0212	0.0184	0.0414	0.1078	0.1492	0.722703108	36
Shift		7	$150/t carbon tax + higher accuracy residual methane trait included in breeding standards	0.0011	0.0368	0.0106	0.0100	0.0196	0.0221	0.0212	0.0184	0.0458	0.1084	0.1542	0.702979188	45
Shift		7	$250/t carbon tax + higher accuracy residual methane trait included in breeding standards	0.0014	0.0368	0.0106	0.0100	0.0196	0.0221	0.0212	0.0184	0.0456	0.1088	0.1544	0.70451813	44
Shift		7	$500/t carbon tax + higher accuracy residual methane trait included in breeding standards	0.0019	0.0368	0.0106	0.0100	0.0196	0.0221	0.0212	0.0184	0.0453	0.1092	0.1546	0.706703235	43
Shift		7	$1000/t carbon tax + higher accuracy residual methane trait included in breeding standards	0.0022	0.0368	0.0106	0.0100	0.0196	0.0221	0.0212	0.0184	0.0452	0.1095	0.1547	0.707998788	42
Improve	Parra et al. (2023) [51]	10	Inclusion of biochar and nitrates at 8% of DM	0.0062	0.0037	0.0212	0.0200	0.0098	0.0221	0.0212	0.0184	0.0211	0.1196	0.1407	0.849917713	7
		10	Inclusion of biochar and	0.0054	0.0368	0.0106	0.0200	0.0196	0.0074	0.0212	0.0184	0.0448	0.1122	0.1570	0.714676191	41

			Asparagopsis at 5% of DM												
		10	Inclusion of citral extract at 0.1% of DM	0.0112	0.0037	0.0106	0.0200	0.0098	0.0221	0.0212	0.0184	0.0193	0.1238	0.1431	0.865035721	5
Improve	Moate et al. (2020) [14]	12	Proportion of wheat is 15% of DMI	0.0034	0.0037	0.0212	0.0200	0.0098	0.0221	0.0212	0.0184	0.0240	0.1169	0.1409	0.829753499	16
		12	Proportion of wheat is 20% of DMI	0.0040	0.0037	0.0212	0.0200	0.0098	0.0221	0.0212	0.0184	0.0233	0.1175	0.1408	0.834288801	14
		12	Proportion of wheat is 45% of DMI	0.0058	0.0037	0.0212	0.0200	0.0098	0.0221	0.0212	0.0184	0.0216	0.1191	0.1407	0.846738883	8
Improve	Manzanilla-Pech et al. (2021) [54]	13	Reduction of methane and DMI included in breeding goals	0.0046	0.0037	0.0212	0.0200	0.0196	0.0147	0.0212	0.0184	0.0259	0.1169	0.1428	0.818690049	17
		13	Methane production negatively economically valued at -0.30c and DMI included in breeding goals	0.0099	0.0037	0.0212	0.0200	0.0196	0.0147	0.0212	0.0184	0.0213	0.1219	0.1433	0.851008137	6
		13	Methane production negatively economically valued at -0.60c per kg CH_4 and DMI included in breeding goals	0.0160	0.0037	0.0212	0.0200	0.0196	0.0147	0.0212	0.0184	0.0167	0.1277	0.1444	0.884143824	1
		13	Reduction of methane and RFI	0.0023	0.0037	0.0212	0.0200	0.0196	0.0147	0.0212	0.0184	0.0279	0.1147	0.1426	0.804312142	20

			included in breeding goals													
		13	Methane production negatively economically valued at -0.30c and RFI included in breeding goals	0.0076	0.0037	0.0212	0.0200	0.0196	0.0147	0.0212	0.0184	0.0232	0.1198	0.1430	0.83742916	12
		13	Methane production negatively economically valued at -0.60c per kg CH_4 and RFI included in breeding goals	0.0129	0.0037	0.0212	0.0200	0.0196	0.0147	0.0212	0.0184	0.0189	0.1248	0.1437	0.868264667	4
Improve	Lean and Moate (2021) [20]	15	Ozone addition to water troughs	0.0055	0.0147	0.0106	0.0200	0.0196	0.0221	0.0212	0.0184	0.0285	0.1153	0.1438	0.80212983	21
			Nitrates supplementation	0.0027	0.0037	0.0212	0.0200	0.0196	0.0147	0.0212	0.0184	0.0275	0.1152	0.1427	0.807213855	19
			3-nitro-oxypropanol	0.0083	0.0037	0.0212	0.0100	0.0196	0.0074	0.0212	0.0184	0.0278	0.1198	0.1476	0.811574982	18
Avoid	Iram et al. (2021) [45]	16	Conversion of land from ponded pasture to mangroves	0.0273	0.0147	0.0212	0.0200	0.0196	0.0147	0.0106	0.0184	0.0196	0.1359	0.1555	0.873869997	3
			Conversion of land from ponded pasture to freshwater tidal forest	0.0273	0.0147	0.0212	0.0200	0.0196	0.0147	0.0106	0.0184	0.0196	0.1360	0.1556	0.873931975	2
			Conversion of land from ponded	0.0274	0.0221	0.0212	0.0200	0.0196	0.0147	0.0106	0.0184	0.0245	0.1350	0.1595	0.846195394	9

			pasture to salt marsh													
			Conversion of land from dry pasture to mangrove	-0.1058	0.0147	0.0212	0.0200	0.0196	0.0147	0.0106	0.0184	0.1346	0.0275	0.1621	0.169513828	46
			Conversion of land from dry pasture to freshwater tidal forest	0.0018	0.0147	0.0212	0.0200	0.0196	0.0147	0.0106	0.0184	0.0322	0.1111	0.1433	0.77529276	31
			Conversion of land from dry pasture to salt marsh	0.0201	0.0221	0.0212	0.0200	0.0196	0.0147	0.0106	0.0184	0.0256	0.1278	0.1534	0.833110524	15
Improve	Bai et al. (2020) [57]	21	Composting manure vs stockpiling	0.0147	0.0147	0.0212	0.0200	0.0196	0.0074	0.0212	0.0184	0.0244	0.1239	0.1483	0.835554123	13
Improve	Almedia et al (2023)	24	Improving fertility by 10% with 50% adoption rate	0.0008	0.0037	0.0212	0.0200	0.0196	0.0221	0.0106	0.0184	0.0302	0.1136	0.1438	0.789851064	26
			Improving fertility by 10% with 60% adoption rate	0.0010	0.0037	0.0212	0.0200	0.0196	0.0221	0.0106	0.0184	0.0301	0.1137	0.1438	0.790851256	25
			Improving fertility by 10% with 70% adoption rate	0.0011	0.0037	0.0212	0.0200	0.0196	0.0221	0.0106	0.0184	0.0299	0.1139	0.1438	0.791867173	24
			Improving fertility by 10% with 80% adoption	0.0013	0.0037	0.0212	0.0200	0.0196	0.0221	0.0106	0.0184	0.0298	0.1140	0.1438	0.79286493	23
			Improving fertility by 5% with 50% adoption	0.0004	0.0037	0.0212	0.0200	0.0196	0.0221	0.0106	0.0184	0.0306	0.1132	0.1438	0.787456045	30
			Improving fertility by 5% with 60% adoption	0.0005	0.0037	0.0212	0.0200	0.0196	0.0221	0.0106	0.0184	0.0305	0.1133	0.1438	0.787983172	29
			Improving fertility by 5% with 70% adoption	0.0006	0.0037	0.0212	0.0200	0.0196	0.0221	0.0106	0.0184	0.0304	0.1134	0.1438	0.788509985	28

			Improving fertility by 5% with 80% adoption	0.0007	0.0037	0.0212	0.0200	0.0196	0.0221	0.0106	0.0184	0.0303	0.1134	0.1438	0.789053458	27
Improve	Kinley et al. (2020) [52]	27	0.05% inclusion of Asparagopsis in OM	0.0001	0.0037	0.0106	0.0200	0.0196	0.0074	0.0212	0.0184	0.0342	0.1119	0.1461	0.765801601	34
			0.10% inclusion of Asparagopsis in OM	0.0001	0.0037	0.0106	0.0200	0.0196	0.0074	0.0212	0.0184	0.0342	0.1119	0.1461	0.766036889	33
			0.20% inclusion of Asparagopsis in OM	0.0002	0.0037	0.0106	0.0200	0.0196	0.0074	0.0212	0.0184	0.0341	0.1121	0.1461	0.766770252	32
b. Conservative scenario																
		Conservatively Weighted Data		**0.029**	**0.8**	**0.029**	**0.029**	**0.029**	**0.029**	**0.029**	**0.029**					
	Author/s	**Article #**	**Methane Reduction Strategy**	**% Reduction CH_4/kg of ECM Milk or Boneless Trimmed Beef**	**Estimated Costs AUD**	**Technological Readiness**	**Compliance with Existing Laws and Regulations**	**New Policy Required**	**Feedlot and Grazing Systems**	**Applicable to Both Climatic Zones**	**Applicable to All Seasons**	**Si+**	**Si-**	**Si+ + Si-**	**Performance Score**	**Ranking**
Improve	Thomas et al. (2021) [12]	1	Grain-finished feed formulation	0.0014	0.0236	0.0049	0.0046	0.0023	0.0034	0.0049	0.0043	0.0052	0.2139	0.2191	0.9761628	7
Improve	Stifkens et al. (2022) [50]	3	36% Leucaena leucocephala feed formulation	0.0016	0.0236	0.0049	0.0046	0.0023	0.0051	0.0025	0.0043	0.0054	0.2139	0.2192	0.97558359	8
Improve	Ridoutt et al. (2022) [43]	4	Feedlot cattle supplemented with Asparagopsis taxiformis	0.0051	0.2358	0.0025	0.0046	0.0045	0.0017	0.0049	0.0043	0.2123	0.0299	0.2422	0.12340019	40

Improve	Richardson et al (2022) [46]	7	Low accuracy residual methane trait included in breeding standards	0.0001	0.0236	0.0049	0.0046	0.0045	0.0051	0.0049	0.0043	0.0066	0.2137	0.2204	0.9698875	16
Improve		7	Higher accuracy residual methane trait included in breeding standards	0.0006	0.2358	0.0025	0.0046	0.0045	0.0051	0.0049	0.0043	0.2123	0.0256	0.2379	0.10748597	42
Shift		7	$150/t carbon tax + low accuracy residual methane trait included in breeding standards	0.0000	0.1886	0.0025	0.0023	0.0045	0.0051	0.0049	0.0043	0.1652	0.0533	0.2186	0.24401494	39
Shift		7	$250/t carbon tax + low accuracy residual methane trait included in breeding standards	0.0000	0.1886	0.0025	0.0023	0.0045	0.0051	0.0049	0.0043	0.1652	0.0533	0.2186	0.24402428	38
Shift		7	$500/t carbon tax + low accuracy residual methane trait included in breeding standards	0.0000	0.1886	0.0025	0.0023	0.0045	0.0051	0.0049	0.0043	0.1652	0.0533	0.2186	0.24405232	37
Shift		7	$1000/t carbon tax + low accuracy residual methane trait included in breeding standards	0.0000	0.1886	0.0025	0.0023	0.0045	0.0051	0.0049	0.0043	0.1652	0.0534	0.2186	0.24408868	36

Shift		7	$150/t carbon tax + higher accuracy residual methane trait included in breeding standards	0.0002	0.2358	0.0025	0.0023	0.0045	0.0051	0.0049	0.0043	0.2124	0.0252	0.2375	0.10590553	46
Shift		7	$250/t carbon tax + higher accuracy residual methane trait included in breeding standards	0.0003	0.2358	0.0025	0.0023	0.0045	0.0051	0.0049	0.0043	0.2123	0.0252	0.2376	0.106201	45
Shift		7	$500/t carbon tax + higher accuracy residual methane trait included in breeding standards	0.0004	0.2358	0.0025	0.0023	0.0045	0.0051	0.0049	0.0043	0.2123	0.0253	0.2377	0.10662381	44
Shift		7	$1000/t carbon tax + higher accuracy residual methane trait included in breeding standards	0.0005	0.2358	0.0025	0.0023	0.0045	0.0051	0.0049	0.0043	0.2123	0.0254	0.2378	0.10687637	43
Improve	Parra et al. (2023) [51]	10	Inclusion of biochar and nitrates at 8% of DM	0.0014	0.0236	0.0049	0.0046	0.0023	0.0051	0.0049	0.0043	0.0049	0.2139	0.2188	0.97761249	4
		10	Inclusion of biochar and Asparagopsis at 5% of DM	0.0013	0.2358	0.0025	0.0046	0.0045	0.0017	0.0049	0.0043	0.2123	0.0260	0.2384	0.10919116	41
		10	Inclusion of citral extract at 0.1% of DM	0.0026	0.0236	0.0025	0.0046	0.0023	0.0051	0.0049	0.0043	0.0045	0.2140	0.2185	0.9794944	3

Improve	Moate et al. (2020) [14]	12	Proportion of wheat is 15% of DMI	0.0008	0.0236	0.0049	0.0046	0.0023	0.0051	0.0049	0.0043	0.0056	0.2138	0.2194	0.97463926	11
		12	Proportion of wheat is 20% of DMI	0.0009	0.0236	0.0049	0.0046	0.0023	0.0051	0.0049	0.0043	0.0054	0.2138	0.2192	0.9753074	10
		12	Proportion of wheat is 45% of DMI	0.0013	0.0236	0.0049	0.0046	0.0023	0.0051	0.0049	0.0043	0.0050	0.2139	0.2189	0.97714331	6
Improve	Manzanilla-Pech et al. (2021) [54]	13	Reduction of methane and DMI included in breeding goals	0.0011	0.0236	0.0049	0.0046	0.0045	0.0034	0.0049	0.0043	0.0060	0.2138	0.2198	0.97268086	12
		13	Methane production negatively economically valued at -0.30c and DMI included in breeding goals	0.0023	0.0236	0.0049	0.0046	0.0045	0.0034	0.0049	0.0043	0.0050	0.2140	0.2189	0.97737908	5
		13	Methane production negatively economically valued at -0.60c per kg CH_4 and DMI included in breeding goals	0.0037	0.0236	0.0049	0.0046	0.0045	0.0034	0.0049	0.0043	0.0039	0.2141	0.2180	0.98219361	1
		13	Reduction of methane and RFI included in breeding goals	0.0005	0.0236	0.0049	0.0046	0.0045	0.0034	0.0049	0.0043	0.0065	0.2137	0.2202	0.97059409	15

		13	Methane production negatively economically valued at -0.30c and RFI included in breeding goals	0.0018	0.0236	0.0049	0.0046	0.0045	0.0034	0.0049	0.0043	0.0054	0.2139	0.2193	0.97540405	9
		13	Methane production negatively economically valued at -0.60c per kg CH_4 and RFI included in breeding goals	0.0030	0.0236	0.0049	0.0046	0.0045	0.0034	0.0049	0.0043	0.0044	0.2141	0.2184	0.97988897	2
Improve	Lean and Moate (2021) [20]	15	Ozone addition to water troughs	0.0013	0.0943	0.0025	0.0046	0.0045	0.0051	0.0049	0.0043	0.0710	0.1439	0.2149	0.66960565	31
			Nitrates supplementation	0.0006	0.0236	0.0049	0.0046	0.0045	0.0034	0.0049	0.0043	0.0064	0.2138	0.2201	0.97101503	13
			3-nitro-oxypropanol	0.0019	0.0236	0.0049	0.0023	0.0045	0.0017	0.0049	0.0043	0.0065	0.2139	0.2204	0.9707102	14
Avoid	Iram et al. (2021) [45]	16	Conversion of land from ponded pasture to mangroves	0.0063	0.0943	0.0049	0.0046	0.0045	0.0034	0.0025	0.0043	0.0708	0.1449	0.2157	0.67158033	29
			Conversion of land from ponded pasture to freshwater tidal forest	0.0063	0.0943	0.0049	0.0046	0.0045	0.0034	0.0025	0.0043	0.0708	0.1449	0.2157	0.67158611	28
			Conversion of land from ponded pasture to salt marsh	0.0063	0.1415	0.0049	0.0046	0.0045	0.0034	0.0025	0.0043	0.1180	0.0993	0.2173	0.45711502	34

			Conversion of land from dry pasture to mangrove	-0.0245	0.0943	0.0049	0.0046	0.0045	0.0034	0.0025	0.0043	0.0773	0.1415	0.2188	0.64680551	33
			Conversion of land from dry pasture to freshwater tidal forest	0.0004	0.0943	0.0049	0.0046	0.0045	0.0034	0.0025	0.0043	0.0711	0.1437	0.2148	0.66906062	32
			Conversion of land from dry pasture to salt marsh	0.0047	0.1415	0.0049	0.0046	0.0045	0.0034	0.0025	0.0043	0.1180	0.0988	0.2168	0.45580272	35
Improve	Bai et al. (2020) [57]	21	Composting manure vs stockpiling	0.0034	0.0943	0.0049	0.0046	0.0045	0.0017	0.0049	0.0043	0.0709	0.1443	0.2152	0.6704453	30
Improve	Almeida et al. (2023) [17]	24	Improving fertility by 10% with 50% adoption rate	0.0002	0.0236	0.0049	0.0046	0.0045	0.0051	0.0025	0.0043	0.0070	0.2137	0.2207	0.96823999	20
			Improving fertility by 10% with 60% adoption rate	0.0002	0.0236	0.0049	0.0046	0.0045	0.0051	0.0025	0.0043	0.0070	0.2137	0.2207	0.96838489	19
			Improving fertility by 10% with 70% adoption rate	0.0003	0.0236	0.0049	0.0046	0.0045	0.0051	0.0025	0.0043	0.0069	0.2137	0.2207	0.96853209	18
			Improving fertility by 10% with 80% adoption	0.0003	0.0236	0.0049	0.0046	0.0045	0.0051	0.0025	0.0043	0.0069	0.2137	0.2206	0.96867666	17
			Improving fertility by 5% with 50% adoption	0.0001	0.0236	0.0049	0.0046	0.0045	0.0051	0.0025	0.0043	0.0071	0.2137	0.2208	0.96789304	24
			Improving fertility by 5% with 60% adoption	0.0001	0.0236	0.0049	0.0046	0.0045	0.0051	0.0025	0.0043	0.0071	0.2137	0.2208	0.96796939	23
			Improving fertility by 5% with 70% adoption	0.0001	0.0236	0.0049	0.0046	0.0045	0.0051	0.0025	0.0043	0.0071	0.2137	0.2208	0.96804571	22

			Improving fertility by 5% with 80% adoption	0.0002	0.0236	0.0049	0.0046	0.0045	0.0051	0.0025	0.0043	0.0070	0.2137	0.2207	0.96812444	21
Improve	Kinley et al. (2020) [52]	27	0.05% inclusion of Asparagopsis in OM	0.0000	0.0236	0.0025	0.0046	0.0045	0.0017	0.0049	0.0043	0.0079	0.2137	0.2216	0.96417621	27
			0.10% inclusion of Asparagopsis in OM	0.0000	0.0236	0.0025	0.0046	0.0045	0.0017	0.0049	0.0043	0.0079	0.2137	0.2216	0.96420965	26
			0.20% inclusion of Asparagopsis in OM	0.0001	0.0236	0.0025	0.0046	0.0045	0.0017	0.0049	0.0043	0.0079	0.2137	0.2216	0.96431385	25
c. Climate emergency scenario																
		Climate Emergency Weighted Data		**0.4**	**0.029**	**0.029**	**0.029**	**0.029**	**0.4**	**0.029**	**0.029**					
	Author/s	**Article #**	**Methane Reduction Strategy**	**% reduction CH_4/kg of ECM Milk or Boneless Trimmed Beef**	**Estimated Costs AUD**	**Technological Readiness**	**Compliance with Existing Laws and Regulations**	**New Policy Required**	**Feedlot and Grazing Systems**	**Applicable to both Climatic Zones**	**Applicable to All Seasons**	**Si+**	**Si-**	**Si+ + Si-**	**Performance Score**	**Ranking**
Improve	Thomas et al. (2021) [12]	1	Grain-finished feed formulation	0.0195	0.0009	0.0049	0.0046	0.0023	0.0471	0.0049	0.0043	0.0720	0.3590	0.4310	0.83287418	16
Improve	Stifkens et al. (2022) [50]	3	36% Leucaena leucocephala feed formulation	0.0220	0.0009	0.0049	0.0046	0.0023	0.0707	0.0025	0.0043	0.0656	0.3638	0.4294	0.84715733	11

Improve	Ridoutt et al. (2022) [43]	4	Feedlot cattle supplemented with Asparagopsis taxiformis	0.0709	0.0085	0.0025	0.0046	0.0045	0.0236	0.0049	0.0043	0.0507	0.4096	0.4602	0.88987446	6
Improve	Richardson et al. (2022) [46]	7	Low accuracy residual methane trait included in breeding standards	0.0016	0.0009	0.0049	0.0046	0.0045	0.0707	0.0049	0.0043	0.0860	0.3435	0.4296	0.79973606	37
Improve		7	Higher accuracy residual methane trait included in breeding standards	0.0078	0.0085	0.0025	0.0046	0.0045	0.0707	0.0049	0.0043	0.0802	0.3496	0.4298	0.81344855	21
Shift		7	$150/t carbon tax + low accuracy residual methane trait included in breeding standards	0.0000	0.0068	0.0025	0.0023	0.0045	0.0707	0.0049	0.0043	0.0879	0.3419	0.4297	0.79557007	42
Shift		7	$250/t carbon tax + low accuracy residual methane trait included in breeding standards	0.0001	0.0068	0.0025	0.0023	0.0045	0.0707	0.0049	0.0043	0.0878	0.3420	0.4297	0.79575262	41

Shift		7	$500/t carbon tax + low accuracy residual methane trait included in breeding standards	0.0003	0.0068	0.0025	0.0023	0.004 5	0.0707	0.0049	0.004 3	0.087 5	0.342 2	0.4297	0.7963002 4	40
Shift		7	$1000/t carbon tax + low accuracy residual methane trait included in breeding standards	0.0006	0.0068	0.0025	0.0023	0.004 5	0.0707	0.0049	0.004 3	0.087 2	0.342 5	0.4297	0.7970101 2	39
Shift		7	$150/t carbon tax + higher accuracy residual methane trait included in breeding standards	0.0034	0.0085	0.0025	0.0023	0.004 5	0.0707	0.0049	0.004 3	0.084 6	0.345 3	0.4299	0.8032599 3	31
Shift		7	$250/t carbon tax + higher accuracy residual methane trait included in breeding standards	0.0045	0.0085	0.0025	0.0023	0.004 5	0.0707	0.0049	0.004 3	0.083 5	0.346 4	0.4298	0.8057907 9	26

Shift		7	$500/t carbon tax + higher accuracy residual methane trait included in breeding standards	0.0061	0.0085	0.0025	0.0023	0.0045	0.0707	0.0049	0.0043	0.0819	0.3479	0.4298	0.80941461	23
Shift		7	$1000/t carbon tax + higher accuracy residual methane trait included in breeding standards	0.0070	0.0085	0.0025	0.0023	0.0045	0.0707	0.0049	0.0043	0.0810	0.3488	0.4298	0.81158057	22
Improve	Parra et al. (2023) [51]	10	Inclusion of biochar and nitrates at 8% of DM	0.0200	0.0009	0.0049	0.0046	0.0023	0.0707	0.0049	0.0043	0.0676	0.3618	0.4294	0.84264807	13
		10	Inclusion of biochar and Asparagopsis at 5% of DM	0.0174	0.0085	0.0025	0.0046	0.0045	0.0236	0.0049	0.0043	0.0850	0.3560	0.4410	0.8073001	25
		10	Inclusion of citral extract at 0.1% of DM	0.0359	0.0009	0.0025	0.0046	0.0023	0.0707	0.0049	0.0043	0.0517	0.3776	0.4293	0.87954682	8
Improve	Moate et al. (2020) [14]	12	Proportion of wheat is 15% of DMI	0.0108	0.0009	0.0049	0.0046	0.0023	0.0707	0.0049	0.0043	0.0767	0.3527	0.4294	0.82130814	20

		12	Proportion of wheat is 20% of DMI	0.0129	0.0009	0.0049	0.0046	0.0023	0.0707	0.0049	0.0043	0.0747	0.3548	0.4294	0.82611282	17
		12	Proportion of wheat is 45% of DMI	0.0185	0.0009	0.0049	0.0046	0.0023	0.0707	0.0049	0.0043	0.0690	0.3604	0.4294	0.8392876	14
Improve	Manzanilla-Pech et al. (2021) [54]	13	Reduction of methane and DMI included in breeding goals	0.0146	0.0009	0.0049	0.0046	0.0045	0.0471	0.0049	0.0043	0.0767	0.3541	0.4308	0.82193674	19
		13	Methane production negatively economically valued at -0.30c and DMI included in breeding goals	0.0316	0.0009	0.0049	0.0046	0.0045	0.0471	0.0049	0.0043	0.0607	0.3711	0.4318	0.85934594	10
		13	Methane production negatively economically valued at -0.60c per kilo ch4 and DMI included in breeding goals	0.0511	0.0009	0.0049	0.0046	0.0045	0.0471	0.0049	0.0043	0.0435	0.3905	0.4340	0.89979906	5
		13	Reduction of methane and RFI included in breeding goals	0.0073	0.0009	0.0049	0.0046	0.0045	0.0471	0.0049	0.0043	0.0837	0.3468	0.4305	0.80562209	28

		13	Methane production negatively economically valued at -0.30c and RFI included in breeding goals	0.0243	0.0009	0.0049	0.0046	0.0045	0.0471	0.0049	0.0043	0.0675	0.3638	0.4313	0.84346984	12
		13	Methane production negatively economically valued at -0.60c per kilo CH_4 and RFI included in breeding goals	0.0414	0.0009	0.0049	0.0046	0.0045	0.0471	0.0049	0.0043	0.0519	0.3808	0.4327	0.88001861	7
Improve	Lean and Moate (2021) [20]	15	Ozone addition to water troughs	0.0175	0.0034	0.0025	0.0046	0.0045	0.0707	0.0049	0.0043	0.0702	0.3593	0.4294	0.83661398	15
			Nitrates supplementation	0.0088	0.0009	0.0049	0.0046	0.0045	0.0471	0.0049	0.0043	0.0823	0.3483	0.4306	0.8089032	24
			3-nitro-oxypropanol	0.0267	0.0009	0.0049	0.0023	0.0045	0.0236	0.0049	0.0043	0.0770	0.3654	0.4425	0.82588596	18
Avoid	Iram et al. (2021) [45]	16	Conversion of land from ponded pasture to mangroves	0.0873	0.0034	0.0049	0.0046	0.0045	0.0471	0.0025	0.0043	0.0239	0.4266	0.4505	0.94684681	2

			Conversion of land from ponded pasture to freshwater tidal forest	0.0875	0.0034	0.0049	0.0046	0.0045	0.0471	0.0025	0.0043	0.0239	0.4268	0.4508	0.94687926	1
			Conversion of land from ponded pasture to salt marsh	0.0876	0.0051	0.0049	0.0046	0.0045	0.0471	0.0025	0.0043	0.0242	0.4268	0.4510	0.94637256	3
			Conversion of land from dry pasture to mangrove	-0.3386	0.0034	0.0049	0.0046	0.0045	0.0471	0.0025	0.0043	0.4268	0.0244	0.4512	0.05398409	46
			Conversion of land from dry pasture to freshwater tidal forest	0.0058	0.0034	0.0049	0.0046	0.0045	0.0471	0.0025	0.0043	0.0851	0.3453	0.4305	0.80219186	32
			Conversion of land from dry pasture to salt marsh	0.0642	0.0051	0.0049	0.0046	0.0045	0.0471	0.0025	0.0043	0.0336	0.4035	0.4371	0.92307151	4
Improve	Bai et al. (2020) [57]	21	Composting manure vs stockpiling	0.0472	0.0034	0.0049	0.0046	0.0045	0.0236	0.0049	0.0043	0.0622	0.3858	0.4480	0.86121429	9
Improve	Almeida et al. (2023) [17]	24	Improving fertility by 10% with 50% adoption rate	0.0026	0.0009	0.0049	0.0046	0.0045	0.0707	0.0025	0.0043	0.0850	0.3446	0.4296	0.80208616	33

			Improving fertility by 10% with 60% adoption rate	0.0031	0.0009	0.0049	0.0046	0.0045	0.0707	0.0025	0.0043	0.0845	0.3451	0.4296	0.80328586	30
			Improving fertility by 10% with 70% adoption rate	0.0036	0.0009	0.0049	0.0046	0.0045	0.0707	0.0025	0.0043	0.0840	0.3456	0.4296	0.80450592	29
			Improving fertility by 10% with 80% adoption	0.0042	0.0009	0.0049	0.0046	0.0045	0.0707	0.0025	0.0043	0.0835	0.3461	0.4296	0.80570567	27
			Improving fertility by 5% with 50% adoption	0.0014	0.0009	0.0049	0.0046	0.0045	0.0707	0.0025	0.0043	0.0863	0.3433	0.4296	0.79921918	38
			Improving fertility by 5% with 60% adoption	0.0016	0.0009	0.0049	0.0046	0.0045	0.0707	0.0025	0.0043	0.0860	0.3436	0.4296	0.7998495	36
			Improving fertility by 5% with 70% adoption	0.0019	0.0009	0.0049	0.0046	0.0045	0.0707	0.0025	0.0043	0.0857	0.3439	0.4296	0.80047982	35
			Improving fertility by 5% with 80% adoption	0.0022	0.0009	0.0049	0.0046	0.0045	0.0707	0.0025	0.0043	0.0854	0.3441	0.4296	0.80113049	34
Improve	Kinley et al. (2020) [52]	27	0.05% inclusion of Asparagopsis in OM	0.0002	0.0009	0.0025	0.0046	0.0045	0.0236	0.0049	0.0043	0.0993	0.3389	0.4382	0.7733089	45

			0.10% inclusion of Asparagopsis in OM	0.0003	0.0009	0.0025	0.0046	0.0045	0.0236	0.0049	0.0043	0.0992	0.3390	0.4382	0.7735823	44
			0.20% inclusion of Asparagopsis in OM	0.0007	0.0009	0.0025	0.0046	0.0045	0.0236	0.0049	0.0043	0.0989	0.3394	0.4383	0.77443471	43

Note: DM—dry matter; DMI—dry matter intake; ECM—energy-corrected milk; OM—organic matter; RFI—residual feed intake.

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