

Review

Greenhouse gas mitigation in pasture-based dairy production systems in New Zealand: A review of mitigation options and their interactions



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ABSTRACT

Reducing greenhouse gas (GHG) emissions from dairy farming is crucial for mitigating climate change and enhancing the environmental credentials of New Zealand's dairy exports. This paper aims to explore potential GHG mitigation measures and their interactive effects when combined within New Zealand context, emphasising the practicality of these combinations, particularly focusing on recent studies of pasture-based dairy systems. The review assesses various mitigation options across animal, manure management, feed-based, soil-related, and system-related interventions and identifies immediately applicable mitigation options based on specific criteria. It also discusses the implementation costs, implications on emissions, and the combined effects of these options when applied as bundles in pasture-based systems using a combination matrix. It is indicated that mitigation options on New Zealand's dairy farms can yield diverse outcomes and costs based on farming characteristics. By analysing different combinations of short-listed, it was found that although most mitigation options are compatible, some may have a lower overall reduction potential because of interaction effects. Integrating lower N fertiliser use, low-emission feed, and reduced stocking rates with high-performing animals provides a practical approach for GHG reductions and potential cost savings. However, implementing compatible mitigation bundles requires better quantification of their interactions, economic viability, and compatibility with existing farming systems which need further research.

1. Introduction

While striving to meet increasing demands for food, global agriculture has also brought about adverse environmental and social consequences, such as water pollution, soil degradation, depletion of natural resources, and a rise in greenhouse gas emissions (GHG). The gross GHG emission profile in New Zealand has increased by 13.7 % (9437.2 kt CO₂e) between 1990 and 2022. The agriculture sector, accounting for 53 % of New Zealand's gross GHG emissions in 2022, experienced a 12.4 % (4591.2 kt CO₂e) rise compared to the levels recorded in 1990 (37,121.5 kt CO₂e) [1]. Enteric methane (CH₄) emissions from ruminant livestock, including dairy cattle, beef cattle, sheep, and deer, comprise 78.2 % of New Zealand's agricultural emissions, with dairy livestock responsible for nearly half of all agricultural emissions [1].

New Zealand dairy farms are well-known for their pasture-based

systems. Since 1971, the number of dairy cattle on these farms has gradually increased from 3.2 million to 5.8 million (Fig. 1). Further, nitrogen (N) fertiliser use has increased by 465 % since 1990, contributing 915.8 kt CO₂e to agricultural emissions between 1990 and 2022. CH₄ and nitrous oxide (N₂O) are the primary sources of dairy emissions, accounting for 22 % and 3 % of the country's gross emissions, respectively [1]. New Zealand has committed to reducing GHG emissions in accordance with the Paris Agreement, working with other nations to limit global temperature rise [1].

In order to reduce New Zealand's GHG emissions, the dairy sector, accounting for a quarter of the total country's emissions (half of agricultural GHG emissions), is an obvious starting point. Lowering these emissions would enhance the environmental credentials of New Zealand's dairy exports and strengthen its standing as a reliable source of low-emission dairy products. Therefore, identifying potential mitigation

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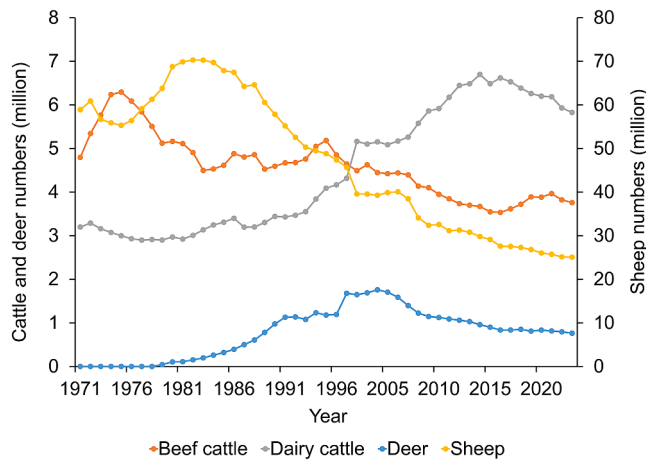


Fig. 1. New Zealand livestock numbers from 1971 to 2023 [2,3].

options is important. Since no single mitigation option is likely sufficient to meet the reduction targets, a multi-pronged approach is necessary. These options should be chosen with a focus on their capacity to reduce emissions while ensuring they align with farmers' technical capabilities and economic viability. Moreover, their practical implementation hinges on their alignment with existing policies and regulations. Further, the impact of adopting multiple mitigation options depends on their interactions with each other and can vary between farms [4].

This review advances beyond current literature by identifying farm system-specific and cost-effective abatement options for dairy farms in New Zealand. Although recent studies have identified potential mitigation options for reducing agricultural GHG emissions in New Zealand [5], it is important to acknowledge that only a few studies [6,7] have addressed the interaction effects among these measures and the variations in their effectiveness across different farming systems and also there is a void remains concerning their practical application within specific farm systems. This work distinguishes itself by exploring potential GHG mitigation measures and their interaction effects when combined, with a focus on their applicability in the New Zealand context. Furthermore, it examines the costs of implementing selected mitigation options, their implications on emissions, and their effects when applied to pasture-based dairy systems. This review provides the first comprehensive assessment of compatibility and interactions among immediately applicable mitigation options for New Zealand dairy farms, evaluating how different options work together based on literature findings. The findings of this review could aid New Zealand dairy farmers in making informed decisions and contribute to a more sustainable future.

2. Method

2.1. Literature search

The literature search was conducted using the Discover, Google Scholar, and ScienceDirect databases. An advanced search was performed with the keyword phrase “(dairy) AND (GHG OR greenhouse gas) AND (mitigation) AND (technology OR options)” to ensure the inclusion of the most relevant search terms. The search results were filtered using the following criteria that focused on implementation in New Zealand.

- I. Papers based on dairy GHG mitigation in pasture-based systems.
- II. Identifying options applicable to New Zealand dairy systems.

Between 2010 and 2025, 116 articles related to countries with pasture-based dairy systems were selected based on the above criteria.

Of these, 79 were published in peer-reviewed journals, while the remaining articles included published reports and book chapters. Further, a backward citation search was conducted to find other relevant literature. Grey literature, such as conference proceedings and dissertations, were excluded. However, government reports were included as they provided unique information related to the dairy industry in New Zealand. Fig. S1 in the supplementary material presents the flowchart summarising the literature screening process.

2.2. Identify the most appropriate mitigation options

To identify immediately applicable measures, we first screened approximately 20 mitigation options in the initial stage. In this review, these options were categorised into five categories: Animal interventions, Manure management interventions, Feed-based interventions, Soil-related interventions, and System-related interventions, considering the specific aspects of the dairy farm that contribute to emissions. Section 3.1 provides recent research developments of the initially screened mitigation options.

In the subsequent step, to shortlist the most appropriate measures for combined approach, we used the set of criteria, described by Pellerin et al. [8], to evaluate each option's effectiveness in addressing the identified challenges. The first criterion is on-farm implementation, which prioritises measures that can be seamlessly integrated into existing agricultural practices without requiring significant modifications to the production system or causing excessive yield reduction. The second criterion is abatement potential, which excludes measures that exhibit low or uncertain abatement potential or have limited applicability in the New Zealand agricultural context. The third criterion is technological readiness, which prioritises measures supported by available technologies with validated scientific knowledge demonstrating their efficacy over research-stage measures or unproven technologies. Under the fourth criterion, which is feasibility and compliance, measures that pose large-scale feasibility issues, known or suspected health or environmental risks, non-compliance with regulations, or low social acceptability are excluded from consideration. The fifth criterion is synergies and trade-offs, which consider the potential synergistic or antagonistic effects of each measure with other major agri-environmental objectives.

These criteria served as the basis for shortlisting the most suitable options for further analysis and recommendation in the context of dairy farming in New Zealand. Fig. 2 shows the process used to select mitigation options.

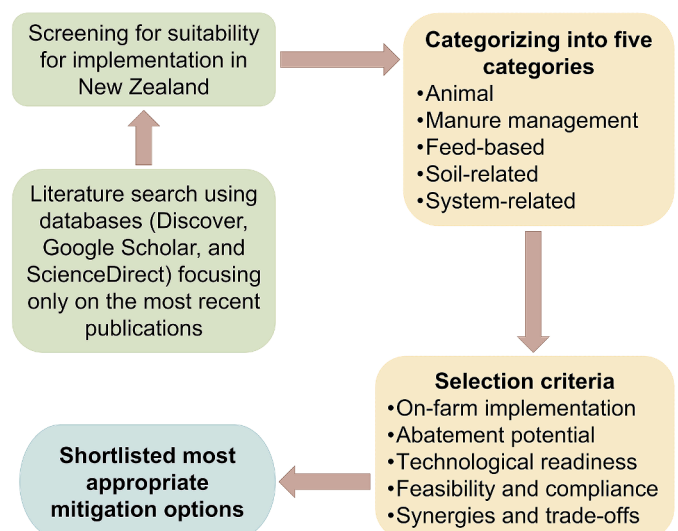


Fig. 2. Identification of immediately applicable mitigation options.

3. Results and discussion

3.1. Mitigation options for GHG emissions

3.1.1. Animal intervention

3.1.1.1. Improving feed conversion efficiency through animal breeding. Feed efficiency is a genetically complex trait [9] that denotes an animal's capacity to convert feed nutrients into products such as milk or milk components, and selecting for feed efficiency can result in fewer, higher-producing cows to suffice for equivalent milk volume, thus curbing emissions. This reduction in cow number lessens feed requirements, decreasing CH₄ emissions and urinary-N deposition [10]. DairyNZ [11] reports that 1 kg less DM (dry matter) consumption for the same level of milk solids saves \$85 year⁻¹ cow⁻¹. However, increased feed conversion efficiency may encourage farmers to increase stocking rate, potentially raising total CH₄ emissions [12]. Improved feed conversion efficiency allows animals to produce more output (weight gain, milk, etc.) with less feed. This efficient feed utilisation reduces overall feed demand and can lead to an increased carrying capacity of the land, which may lead to increased farm emissions.

3.1.1.2. Methane vaccine. A methane vaccine triggers the animal's immune system to generate antibodies in saliva and inhibits the growth of methanogens in the rumen [13]. A methane vaccine would be ideal for New Zealand's pasture-based systems as it requires no farm system change and leaves no residues in products [14]. However, once a prototype vaccine is successfully demonstrated, it could take 7–10 years for the vaccine to become commercially available [15]. The efficacy of methanogen vaccines and their impact on food quality and safety require further exploration as well [16].

3.1.1.3. Methane inhibitors. Methane inhibitors are targeted chemical compounds with a specific inhibitory effect on rumen archaea, methanogenic single-celled organisms. Inhibitors like Bromochloromethane (BCM) and Chloroform have been found to inhibit rumen methanogenesis [17]. However, these compounds have been banned since 2002 due to their ozone-depleting effect and 3-nitrooxypropanol (3-NOP) was developed which breaks down to form sugars, fat and proteins and is removed as CO₂ [18]. Recent studies have shown that 3-NOP can decrease CH₄ emissions for high-producing dairy cows without affecting milk production or feed intake [19] and increases body weight gain, implying that the reduction in CH₄ emissions increases energy availability to animals. van Gastelen et al. [20] found that 3-NOP increased the yields of energy-corrected milk, fat, and protein-corrected milk by 6.5 %. However, 3-NOP must be present in every mouthful of feed to achieve full efficacy, which is impractical to use in New Zealand's pasture-based systems [15]. The Environmental Protection Authority has approved a feed additive that contains 10–25 % of 3-NOP to be used in New Zealand [21].

Further, a halogenated molecule called Bromoform (tribromo-methane) has the ability to prevent CH₄ production by methanogens [22]. Some studies have indicated either no notable rise in bromoform levels in milk or considerable variability in residue amounts among the treated animals [23,24]. Current evidence suggests that bromoform used at very low doses does not have measurable bioavailable levels, indicating a low risk of residue transfer or adverse effects in other animals and humans [25]. Kelly et al. [26] identifies regulatory limits for bromoform in drinking water, but Codex Alimentarius has not established a maximum residue limit for milk or animal products, which could create a gap for international food trade. It also identifies consumer hesitancy as a key public perception barrier to this adoption. New Zealand has developed a bolus technology, which is a capsule that facilitates controlled slow-release of methane inhibitors that are present in the rumen for six months and has the ability to reduce daily CH₄ emissions

by 70 % from ruminant digestion over 3 months [27]. This solution could address certain barriers that hinder the dosing process in New Zealand pasture systems, including health issues, and it is expected to launch in the New Zealand market in 2025 [22]. The bromoform is present in red seaweed and according to RNZ [28], there are plans to manufacture this particular seaweed in an industrial plant in New Zealand.

3.1.2. Manure management interventions

3.1.2.1. EcoPond effluent treatment systems. The EcoPond system curbs CH₄ emissions from dairy effluent by making conditions unfavourable for methanogens. Treatment with poly-ferric sulphate reduces total CH₄ emissions (g CO₂e day⁻¹) by up to 99 % compared to untreated dairy effluent [29]. A specified amount of poly-ferric sulphate is added to the effluent as it moves through a mixing coil, creating conditions in the pond that prevent microorganisms from producing CH₄ gas [30]. Applying poly-ferric sulphate-treated effluent on drained pasture soils reduces phosphorus and E. coli concentrations in drainage water without impacting plant growth [31]. EcoPond has the potential to reduce total annual agricultural emissions by 1.4 % and total annual CH₄ emissions from dairy manure by 36.8 % if half of dairy farms adopt this technology [32], and the cost would be around \$143 per t CO₂e [33].

3.1.2.2. Anaerobic digesters. An anaerobic digester is a closed system that uses microorganisms to break down organic matter in an anaerobic condition. In the dairy industry, anaerobic digesters are typically used to treat manure and other dairy waste products, reducing emissions by capturing CH₄ produced for use as a fuel source, as an alternative to fossil fuels. Additionally, the residual solid material produced by the anaerobic digester can be used as fertiliser, reducing the need for synthetic fertilisers. However, the application of anaerobic digestate leads to a 23 % increase in the emission of N₂O compared to urea, according to Verdi et al. [34].

Milet et al. [35] found that in New Zealand, installing an anaerobic digestion system becomes economically viable with a herd size of 1000 cows. The economic analysis conducted by Nleya et al. [36] revealed that installing a digester system in a New Zealand farm of 900 cows would cost approximately NZ\$ 2.5 million (capital + operating) per year while generating \$331,607 of revenue per year. Maintaining the minimum size of herds necessary for the anaerobic digestion system is the key constraint to making this approach cost-effective as 95 % of the country's dairy farms are too small to install a digester by themselves [37]. A centralised digestion facility [38,39] could enable smaller farms to collaborate and share infrastructure, significantly reducing individual financial burdens.

3.1.3. Feed-based interventions

3.1.3.1. Low-emissions feeds. Researchers have shown that some supplemental feeds ferment differently in the rumen, reducing CH₄ emissions per unit of feed consumed. Feeds with lower nitrogen concentrations also decrease N excretion on grasslands, thereby reducing N₂O emissions. In New Zealand low-emission feeds like forage rape and fodder beets are more digestible, fermentable, and contain fewer structural carbohydrates, resulting in lower rumen fluid pH [40]. Methanogens are sensitive to pH, with pH levels below six decreasing CH₄ production [41]. Cows fed fodder beet with silage emitted 28 % less CH₄ than cows grazing forage kale with straw, and lactating cows fed with fodder beet produced 16 % less CH₄ than cows grazing pasture alone [40]. However, its effectiveness as a CH₄ mitigation option in New Zealand's pasture-based systems requires diet inclusion rates over 75 %, which can pose animal welfare risks due to rumen acidosis [42], needing careful feed management to avoid this condition, which can be fatal if not managed properly. Fodder beet's high yields lead to increased

stocking densities and urine deposition [43], contributing to elevated N leaching. However, the preliminary findings suggest that winter-grazed fodder beet may result in lower leaching losses than winter grazing on kale, based on trials at the Southern Dairy Hub in Southland, New Zealand [44].

Plantain (*Plantago lanceolata*) sown on dairy farms, especially where summer feed quantity and quality limit milk production. Plantain can reduce N excretion from cattle, lowering the N₂O emissions [45,46]. Furthermore, non-lactating dairy cows fed a 100 % plantain diet showed 23 % lower CH₄ compared to those on a 100 % perennial ryegrass diet [47]. However, maintaining the required plantain proportion in the diet poses challenges under practical farming conditions and up to 30 % plantain in the sward is needed for the environmental benefit [48].

3.1.3.2. Low-emissions grasses. Perennial ryegrass dominates dairy pastures in New Zealand due to its high yields, high nutritional value, and prolonged growth period. Varieties like high sugar cultivars (HSG) and tetraploid ryegrass, bred for increased water-soluble carbohydrates (WSC) content, improve energy availability for rumen microbes to use more N in the rumen thus reducing N excretion [49]. Research based on pasture-based systems indicates that high-sugar ryegrass is an economical short-term option for reducing emissions [50]. Jonker et al. [51] found that cows fed with rye grass and white clover generated lower CH₄ yield (g kg⁻¹ DMI) compared to the cows fed with diverse pasture yet no difference in gross CH₄ emissions.

Recent research in New Zealand has focused on developing a variety of perennial ryegrass with high lipid content using GM technology called high metabolizable energy (HME) [52], which can increase its growth [53]. Bowatte et al. [54] found that HME ryegrass has greater N uptake and emits lower N₂O from the cow urine deposited on the mesocosm of HME ryegrass compared to its wild type. Further, current research has developed a white clover breed with soluble condensed tannins (CT) and many recent studies have proved its ability to reduce CH₄ and N losses [55,56].

3.1.4. Soil-related interventions

3.1.4.1. Use of nitrification inhibitors. Nitrification inhibitors, applied in autumn and winter, retard the nitrification process, reducing N₂O emissions and promoting soil N retention, thus lessening the need for fertilisers. They can be added to fertilisers or directly onto grazed pasture. Dicyandiamide (DCD) is a nitrification inhibitor, and a national series of trials across New Zealand further highlighted the potential for DCD to reduce N₂O emissions from dairy systems by, on average, 50 % [57–60]. However, DCD withdrawal from the market due to trace residues in milk has prompted research into alternative, widely applicable, and less costly inhibitors. Adhikari et al. [61] proposed 3,4-dimethyl pyrazole phosphate and 2-chloro-6-(trichloromethyl) pyridine (Nitrapyrin) as potential options for reducing N₂O emissions from urine patches in New Zealand pastures. Additionally, Aucubin, a potential nitrification inhibitor found in plantain (*Plantago lanceolata*), was evaluated by Gardiner et al. [62] for its effectiveness in reducing urine patch NO₃⁻ accumulation and N₂O emissions. However, while it acted as a brief nitrification inhibitor after soil application, its effects were insufficient to reduce overall urine patch N₂O emissions significantly.

3.1.4.2. Reduced N fertiliser and urease inhibitors use. The frequency and timing of N fertiliser application significantly impact pasture growth and N losses. Suter et al. [63] found that increasing N fertiliser rates led to increased N₂O emissions. They suggested strategic N application in response to plant needs, particularly during cooler, wetter months, to lower N₂O emissions. Vogeler et al. [64] observed N losses from N fertiliser application can be avoided by not applying it during late autumn or winter months. However, indirect N losses can increase due to more urine patches from higher stocking rates resulting from increased

pasture growth. Reducing N fertiliser usage could decrease pasture productivity, necessitating additional purchases of off-farm feeds, which could reduce profitability on pastoral farms [65].

To mitigate NH₃ loss, and thus indirect N₂O emissions, from urea, fertilisers with urease inhibitors are increasingly used in New Zealand to enhance N availability for plant uptake and reduce emissions. As Saggart et al. [66] mentioned, N-(n-butyl) Thiophosphoric Triamide, which is sold under the trade name Agrotain®, effectively reduces NH₃ emissions by 45 % from urea and 53 % from urine at an application rate of 0.025 % w/w. Further, using urease inhibitors with N fertiliser can reduce fertiliser needs while maintaining the same pasture production, leading to cost savings for farmers [67].

3.1.4.3. The addition of biochar. Biochar is a solid material rich in C, produced through pyrolysis of materials such as wood, prunings, crops, food, or animal residues. In New Zealand, studies have examined the impact of biochar soil amendment on N₂O emissions from urine patches, but to date, the results have been inconclusive [68]. According to a New Zealand study conducted by Knowles et al. [69], the incorporation of biochar into biosolids-amended soil mitigates nitrate leaching and, thus, indirect N₂O emissions over the short term. A study conducted by Whitehead et al. [70] concluded that biochar addition is not yet an economical option for large-scale application in New Zealand, even though it could possibly increase soil C stocks.

Biochar significantly influences soil properties and microbial activity, making it challenging to predict its effects on N₂O emissions and NO₃⁻ leaching in arable and grazed pasture soils [71]. A critical review indicates that biochar should be used cautiously [72], as excessive application can harm the environment, negatively affecting microbial abundance and activity. Currently, biochar costs about AU\$1000 per tonne, with expectations to drop to around AU\$400 per tonne for larger quantities, including transportation [73].

3.1.4.4. Using off-paddock facilities. Off-paddock facilities, such as stand-off pads or animal housing systems, enable livestock to be kept off pasture when conditions are unsuitable. They help to protect the pasture from pugging by preventing cows from standing on wet paddocks [74]. Pugging can reduce pasture production for several months afterwards and, as a result, lower milk production. Also, off-paddock facilities offer an option to reduce N loss by stopping the deposition of urine patches and, therefore, reducing the risk of N leaching or N₂O emissions [75].

Research studies have been carried out in New Zealand on stand-off pads and housing systems. For example, Doole and Romera [76] found that using stand-off pad on medium or high-intensity farms can reduce leaching at a manageable cost. The stand-off pad system can be cost-effective for reducing nitrate leaching, and without stand-off pads, it would be more costly to reduce N pollution through de-intensification [77]. In contrast, van der Weerden et al. [7] estimated that total emissions per cow per year were 10–35 % higher for systems with off-paddock facilities, compared with a typical grazing system, and there is a reduction in emissions per unit of product when the standing cows are off wet paddocks and wintering cows are in an animal shelter.

3.1.5. System-related interventions

3.1.5.1. Once-A-day milking. Dairy producers using Once-A-Day (OAD) milking may decrease total CH₄ emissions and the need for supplementary feed, leading to lower N excretion and potentially reduced N₂O emissions [78]. OAD can also reduce effluent volumes, energy consumption, and the number of tanker visits for milk transportation [37]. OAD milking could reduce the total GHG emissions of an average farm by 5 % depending on animal performance, stocking rate, and feed adjustments. However, in terms of emission intensity, it could increase the emissions per unit product due to reduced production [79]. Currently, 5 %–10 % of dairy farmers in New Zealand use this method [37]. While

suitable for low-intensity farms, it is unlikely to be adopted in high-input systems due to potential economic losses from reduced production [37]. However, Edwards et al. [80] mentions that the cost saving from OAD practices can compensate for the milk income loss, though the degree of this offset varies by farm.

A financial analysis revealed that switching to OAD from twice-a-day (TAD) milking increased profitability by 23 % in the least efficient farms by improving labour efficiency [81]. But, the cows in the OAD population produce less milk solids than those in the TAD population, which may result from long-term changes in mammary functions in OAD cows [79]. The amount by which productivity per animal can drop while maintaining overall profitability depends on the payout per kg of milk solids. When the milk payout is low, a farm can sustain a greater drop in productivity and still break even with a farm that uses TAD milking. Conversely, if the payout is high, the breakeven drop in productivity can be much smaller. Therefore, the incentives for adopting OAD milking depend on longer-term expectations about milk prices [42]. One major concern regarding emissions is that any reductions may not be sustainable in the long run. Selecting cows for OAD milking can eventually increase feed demand and return them to their previous productivity levels. If cow numbers rise to maintain production, emissions may also increase. While OAD cows should be fed similarly to TAD cows to improve body condition, this could limit potential emission reduction [37].

3.1.5.2. Reduce stocking rate. Reducing stocking rates in dairy systems can effectively lower GHG emissions while maintaining overall production through increased animal productivity. As Kristensen et al. [82] stated, this is the most promising mitigation measure that decreased the carbon footprint of the dairy sector. Transitioning to fewer cows, each producing more milk, is a necessary mitigation step [83].

In the New Zealand context, the profitability and productivity of pasture-based dairy farm systems are influenced by stocking rates, which increase pasture utilisation and production per hectare [7]. Reducing the stocking rate can minimise the farm profit [84]. Using high genetic merit animals allows farmers to maintain lower stocking rates with minimal productivity loss. The Biological Emissions Reference Group [42] suggests that reducing stocking rates by 5 %–15 % (and thus proportionally increasing per-animal productivity) can achieve 3 %–9 % emissions reductions while boosting profitability. Modelling studies indicate that reduced stocking rates with high genetic merit animals caused emission reductions with improved milk production [83,85]. Additionally, lower stocking rates can decrease feed requirements, allowing for reduced N inputs [7]. Beukes et al. [83], using a farm-systems model, estimated that combining reduced or no N fertiliser application with lower stocking rates significantly reduced GHG emissions by 20 % and 28 %, respectively, compared to the baseline. Clark et al. [86] compared a typical Waikato farmlet with a farmlet that had a lower stocking rate, higher genetic merit cows, lower N fertiliser use, and stand-off pads. The researchers found that while the modified farm reduced N leaching by 43 %, it was around 13 % less profitable than a typical farm.

Maintaining adequate stocking rates is crucial for grassland management to sustain pasture quality [87] and animal performance. Simply reducing stocking rates without improving individual animal performance may lead to decreased emissions, but could also lower profits and compromise grassland quality [87]. Therefore, the adaptation of faster rotations, more subdivision, and the topping of pastures could be beneficial [88].

3.1.5.3. Tree planting. Planting trees offsets livestock emissions through C sequestration [89]. This could involve natural reversion on paddock margins, riparian strips, and planting for erosion control, amongst others. Beyond carbon sequestration, trees offer various environmental benefits such as reducing soil erosion, providing windbreaks,

minimising pollutant runoff into waterways, boosting pasture production, enhancing pollination, and controlling pests [90]. Even though large-scale planting of exotic trees on farmlands, reduces livestock production, it can create additional income streams and help maintain farm profitability [37]. Integrating more trees into the pastoral area should consider their potential impact on overall livestock production. Planting trees may not be economically feasible on New Zealand's most productive and fertile agricultural lands classified as LUC (Land Use Capability) Class 1. These lands are primarily used for dairy farming and horticulture due to their high productivity and economic returns [91]. In those areas, growing fruit or nut trees could offer a dual benefit of sustainable land use and economic value, thereby enhancing both environmental and economic potential.

3.2. Selection of the mitigation options

The selected mitigation options after evaluating under key criteria are: reduce the use of N fertilisers, reduce stock number while increasing performance, once-a-day milking, low emission feed, anaerobic digesters, tree planting, urease inhibitor, eco pond, and biochar. Table S1 in the supplementary material summarises how each mitigation option was evaluated under key criteria.

3.3. Interaction among mitigation options

Mitigation measures can interact when implemented together at the farm system level. These interactions potentially enhance or diminish each other's effectiveness depending on farm structure, management system and specific regional factors [92]. Due to the interactions between mitigation measures, the total emission reduction potential is not equal to the sum of the abatement potentials of individual measures [93]. Understanding these interactions is crucial for optimising combined mitigation effectiveness and not accounting for interactions may result in an overestimation of the total potential for GHG emissions [94]. According to Eory et al. [4], this can be achieved by assuming that the measures are mutually exclusive or by adjusting the abatement potential of each measure when determining the total abatement. It is essential to consider the entire farm system and evaluate the cumulative effects of implementing multiple mitigation options [85]. A comprehensive assessment of these interactions enables farmers to make informed decisions to reduce emissions while preserving productivity, profitability, and environmental sustainability. Table 1 shows how interactions between different GHG mitigation options impact the GHG mitigation potential and cost-effectiveness. (see supplementary material, Table S2 for the effects of mitigation options at the farm system level and the implications on emissions).

3.4. Cost of mitigation

The abatement cost of GHG mitigation refers to the expenses incurred in reducing emissions, which encompass the investment needed to adopt various mitigation options and operational and maintenance expenses, as well as potential reductions in revenue. Further, the cost would consider potential cost savings from increased efficiency, such as reduced input use, increased yield and energy generation from biogas. Assessing mitigation costs helps to identify cost-effective measures and design support mechanisms to facilitate the adoption. Table 2 shows the cost of implementing some mitigation options in New Zealand based on real inputs from actual farm systems.

The cost of emission reduction depends on efficiency, the cost of mitigation options, farm input and output prices, trade-offs, and synergies among mitigation options. Further, New Zealand's dairy farms exhibit heterogeneity due to size, location, soil type, vegetation, livestock mix, management practices and climate. Consequently, identifying effective strategies to reduce GHG emissions depends on the objective of

Table 1
Effect of interactions between GHG mitigation options.

Reference	Location	Mitigation options combined	Observation
Beukes et al. [95]	New Zealand	Reduce low protein supplements, low replacement rates, standing cows off	The combined effect of mitigation measures reduced the N leaching compared to baseline with no mitigation practice.
Vogeler et al. [96]	New Zealand	Low replacement rate, low stocking rate, standing-off, low-protein feed, nitrification inhibitors, low N fertiliser	The combined effect of mitigation measures reduced the N leaching compared to baseline farms with no mitigation strategy.
Beukes et al. [83]	New Zealand	Low replacement rate, introduce high genetic merit cows, improve pasture management, less imported supplements	The combined effect of these options could decrease emissions per ha by 27–32 % without reducing milk production while increased profitability.
Beukes et al. [85]	New Zealand	Low replacement rate, increased genetic merit, loafing pad, growing low protein crops, reducing N fertiliser	The combination of these options reduces total GHG emissions by 15–20 % while increasing milk production ha ⁻¹ by 15–20 %.
Carroll and Daigneault [97]	New Zealand	Low-N feed, selective breeding, N inhibitors CH ₄ inhibitor, CH ₄ vaccine, N inhibitor CH ₄ vaccine, N inhibitor	20 % reduction of gross GHG emissions 51 % reduction of gross GHG emissions
Chikazhe et al. [98]	New Zealand	Reduced N fertiliser, including Italian ryegrass in pasture sward, including plantain in pasture sward, earlier calving and drying off, wintering on pasture and baleage	8 % reduction of GHG emissions
Adler et al. [99]	New Zealand	Feed pad, reduced replacement rate	2 % reduction in GHG emissions per hectare, while 1 % increase in profit per hectare (High-intensity Waikato farm) 1.5 % reduction in GHG emissions per hectare while 4 % increase in profit per hectare (High-intensity Canterbury farm)
van der Weerden et al. [7]	New Zealand	Reduced stocking rate, low replacement rate, higher genetic merit cows	16 % reduction in GHG emissions per hectare, 13 % reduction in GHG emission intensity

the farmer, regulations in place, farm economic situation, commodities market prices, and the expertise needed to implement specific mitigation options, considering each farm's distinct circumstances. This diversity presents both challenges and opportunities for emission reduction. The cost of different mitigation options can vary greatly depending on factors such as the size and location of the farm, the practices and technologies used, and the scale of implementation. For example, New Zealand's dairy industry is made up of approximately 11,034 herds with an average herd size of around 450 cows, ranging from 100 to 1000 cows [103]. Smaller farms may find low-tech solutions like improved grazing management, reduced fertiliser use, or OAD milking more feasible, while larger farms may benefit from investing in high-tech solutions like anaerobic digesters.

Table 2
An assessment of the cost of selected greenhouse gas mitigation measures when implemented on pasture-based dairy production systems in New Zealand.

Mitigation measure	Farm region	Cost of mitigation (NZ \$/tCO ₂ e)	Comment
Reducing stocking rate with higher-performing cows, reduced N fertiliser, reduced replacement rate, use of low N feeds and use of stand-off pads	Waikato	\$127 [6]	Introducing stand-off pads caused a greater reduction in profitability. The authors suggested that without stand-off pads, the farm could be made more profitable with emissions reductions without needing extra investments.
Reducing stocking rate with higher-performing cows, reduced N fertiliser and use of low N feeds	Canterbury	\$71 [6]	Operating profit and emissions reductions are higher compared to Waikato regions also represented higher profits than other surrounding commercial farms.
Reduced N fertiliser, changing calving data and type of home-grown feed	Otago	\$59.9 [6]	Operating profit is higher compared to Waikato and Canterbury.
Reduce N fertiliser, reduce stocking rate	Waikato	\$60-\$81 [100]	Production reduction of 54–117 kgMS ha ⁻¹ compared to baseline farm.
Reduce stocking rate, reduce N fertiliser, reduce supplement use	Manawatu Northland Waikato	\$55 [101] \$8 [101] \$127 [101]	22 % production reduction compared to medium intensity farm 30 % production reduction compared to medium intensity farm 28 % production reduction compared to high intensity farm
Methane inhibitors	Waikato	\$145 [102]	1 % increase in production compared to baseline farm

Source: Beukes et al. [6], van der Weerden et al. [7]. The results are based on modelling assessments. For the assumptions used, please refer to the original publications.

3.5. Combinations of selected mitigation options and their practical applicability

Implementing bundled mitigation options is crucial for achieving a significant reduction in emissions at a farm level [104,105], as each option has its strengths and limitations. When combining options, it is important to consider their compatibility, synergies, and potential trade-offs [85]. By bundling complementary mitigation options, synergistic effects can be harnessed. Assessing compatibility with farm-specific conditions, including size, location, climate, operations, and financial situation, is important for selecting the most practical combination of options to ensure that the chosen bundle aligns with the farm's capacity, minimizes economic risks, and effectively contributes to GHG mitigation efforts.

Interactions between measures can impact both farm finances and the emission reduction potential. For example, when implemented together, the adoption of one measure might eliminate the need for a similar investment in another measure, resulting in cost reduction [106]. Based on the author's experience and analysis, Fig. 3 qualitatively visualises the intersections of selected mitigation options through a combination matrix. Our assessment is that most of the selected mitigations are compatible, but for some, the combined reduction potentials

	Reduce the use of N fertilisers	Reducing stock number while increasing performance	Once-A-Day (OAD) milking	Low emission feed	Anaerobic digesters	Tree planting	Urease inhibitor	EcoPond	Biochar
Reduce N fertiliser use	Can be implemented together as less feed required to sustain the herd.	Can be implemented together due to reduced feed intake.	Low N feed (maize and fodder beet) reduces N excretion onto pastures, which may increase the need for N fertiliser.	Possible to implement with reduced N fertiliser as manure digestate can be used as an alternative to N fertiliser.	Compatible	Compatible	Compatible but where the reduction potentials may be less than the sum of the individual reduction potentials of N fertiliser reduction and urease inhibitors.	Implementation is challenging as reduced N fertiliser affects fed intake, causing a reduction of effluents.	Compatible
			The need for N fertiliser may increase if the stocking rate increases to maintain the production.						
Reducing stock number while increasing performance		Farmers who shifted to OAD may increase the stocking rate to keep the production level unchanged.	Compatible	Not enough manure generated to be utilised in the digester.	Land can be freed up to be repurposed for tree planting.	Compatible	Reduced effluent quantity may compromise the cost-effectiveness of building and maintaining the EcoPond.	Compatible	
Once-A-Day (OAD) milking			Due to the reduced feed intake, OAD cows may not consume enough.	OAD milking reduces manure production, which could affect digester efficiency and cost-effectiveness.	Compatible	Compatible	Reduced effluent volumes may compromise the EcoPond's size, efficiency, and treatment capabilities, impacting cost-effectiveness.	Compatible	
Low emission feed				Compatible	Compatible	Compatible	Compatible	Compatible	
Anaerobic digesters					Compatible	Compatible	Incompatible Economically may be impractical.	Biochar can be added to composting of solid dairy manure from anaerobic digesters.	
Tree planting						Compatible	Compatible	Compatible	
Urease inhibitor							Compatible	Compatible	
EcoPond								Compatible	
Biochar								Compatible	

Fig. 3. Combination matrix of selected mitigation options.

may be lower than the sum of the individual options due to the overlaps (antagonistic). Some mitigation options that may not (always) be compatible include the combined use of reduced N fertilisers with urease inhibitors [107]; combined implementation of reducing the stock number and once-a-day milking [37]; feeding once-a-day cows with low emission feeds [79] & implementing anaerobic digester/EcoPond in the once-a-day milking system [79]. Further, compatible mitigation bundles such as reduced N fertilisers with reduced stocking rates and reduced N fertiliser with low-emission feed harness synergistic effects.

Implementing the reduced N fertiliser strategy alongside reducing the number of cows with high-performance animals can reduce the environmental footprint while maintaining overall productivity [99, 100]. This integrated approach enhances better pasture management because lowering N application can help balance the reduction in animal numbers, which in turn enables the allocation of more land for other purposes, such as diversification. Farmers can allocate excess pasture-land resulting from reduced demand for grazing due to lower cow numbers, for tree planting or growing cash crops. While tree planting can provide ecosystem benefits, it can also decrease pasture productivity if overdone. It's vital to ensure that expanding tree planting or cash crop

cultivation on dairyland does not hinder its primary function or negatively impact dairy farming operations. These activities should also be in line with national policy for highly productive lands as lands categorised as LUC 1,2 and 3 are recognized as highly productive lands and should be protected for land-based primary production [91]. Further, tree planting initiatives require initial investments and often take considerable time before the financial and environmental benefits are fully realised. Further, when harvesting trees, it could be a source of emissions.

In Fig. 3, blue cells denote combinations that are incompatible, while green cells indicate combinations that are compatible. Yellow cells indicate interaction effects, where the reduction potential of the combined options is likely to be lower than the sum of the reduction potentials of the individual options (antagonistic).

In addition, a challenge arises when considering the potential increase in milk production associated with improved animal performance or genetic merit. If farmers lack the necessary knowledge or understanding of how these factors influence milk production, then the implementation of this combination of options in real farm systems may be challenging. Furthermore, it is essential to employ skilled grazing

management and strategic supplementary feeding when implementing reduced stocking rates with high-performance cows [42]. Therefore, knowledge transfer and support mechanisms that provide farmers with the required expertise and guidance are needed to fully capitalise on the benefits of reduced fertiliser application and lower stocking rates of higher genetic merit cows.

In New Zealand conditions, Beukes et al. [6] compared normal regional farms with experimental farms that had implemented combinations of feasible mitigation options by conducting small-scale farm trials covering three dairy regions: Waikato, Canterbury, and Otago. They found that the economic and environmental impacts after implementing mitigation options were specific to each region. Lower emissions from the farms in the Waikato and Canterbury regions were mainly driven by reduced N fertiliser and lower stocking rates. According to Beukes et al. [108], the combined implementation of reduced N fertiliser, reduced stock number with high-performance cows, incorporating low protein supplements into the diet, adding dedicated maize block and introducing off-paddock facility such as feed or stand-off pad is cost-effective than standalone implementation where expensive additives or infrastructure (nitrification inhibitors and stand-off pads) are required. Introducing stand-off pads could reduce the N leaching; however, this could generate considerable profit loss [6,108]. Therefore, using a lower-cost feed pad could reduce the negative impact on profitability while achieving considerable leaching reduction [108]. According to the modelling study by Vibart et al. [109], using a system 4 (70–79 % of total feed is home-grown feed) farm showed reduced N leaching losses at a low cost per N-loss mitigated when the dairy cows are excluded from water bodies, with a slight reduction of N fertiliser and inclusion of a feed pad. System 4 farm imported 20–30 % of the total feed for the dry and milking cows.

In New Zealand, integrating reduced N fertiliser and cow numbers while improving cow performance and using low-emission feeds can create a powerful and comprehensive approach to reducing emissions in the dairy sector. Reducing the cow number can be implemented synergistically with reduced N fertiliser application. Reducing N fertiliser leads to less feed available for the herd, which would allow farmers to reduce their stock number synergistically. However, farmers could choose to maintain their current farm area or reduce it for horticultural activities in line with national policy for highly productive lands [91]. Incorporating low-emission feed options, such as replacing palm kernel extract with maize silage, into this mitigation option bundle can significantly reduce off-farm emissions and save farm costs. A dedicated maize block can be introduced to the farm by utilising the excess pastureland. Further, maize should be followed by a catch crop to replenish the soil with nutrients and grown on the same farm to reduce the risk of N mineralisation [108]. A challenge could arise with the risk of losing pasture quality along with reduced stocking rate [87]. However, this risk could be lowered by reducing the stocking rate with high BW animals [42]. Further, it is important to consider the suitability of low-emission feed options like fodder beet, as high inclusion rates may not be suitable for CH₄ mitigation in pasture-based systems [42].

The combined application of reduced N fertiliser with OAD can offer potential benefits by reducing the overall feed intake of the dairy herd. However, this requires accurate feed budgeting. A crucial factor in successfully implementing OAD milking is understanding how the feed intake of the herd will change and how to appropriately adjust the replacement rate when transitioning from traditional TAD milking. If farmers lack the necessary knowledge or expertise to assess these changes accurately, then the implementation of this combination in real farm systems may be challenging.

Integrating the reduced stocking rate with an anaerobic digester can potentially address the issue of emissions in the farming system. However, this combination may not be suitable due to various challenges. Firstly, anaerobic digesters are capital-intensive investments that require significant financial resources. Secondly, collecting manure on an extensive farm can be practically challenging, though anaerobic

digesters can still work by using the manure captured on concrete surfaces like milking sheds and holding yards. Additionally, farmers need specialised knowledge and expertise to properly maintain and operate these digesters to obtain the desired environmental benefits. Moreover, implementing capital-intensive technology on farms often requires several years to generate returns on investment, which can pose financial risks for farmers. However, reducing the stocking rate would decrease manure production, making it challenging for the operation of digesters. Considering these factors, integrating the reduced stocking rate with anaerobic digesters may not be a favourable combination.

The combination of N fertiliser reduction and urease inhibitors can be a compatible option [63]. However, the reduction potentials may be less than the sum of individual emission reduction potentials (antagonistic) [107]. Further, in order to get this combination to be effective and feasible in farm systems, it needs to be implemented with measures that increase milk production or overall profitability, such as efficiency improvement with higher BW animals. By incorporating strategies that enhance milk production or profitability, farmers can offset any potential economic challenges associated with reduced N fertiliser use and urease inhibition, such as reduced milk production caused by pasture yield reduction, while maintaining sustainability and environmental benefits.

Implementing reduced N fertiliser along with an EcoPond could reduce emissions with some practical challenges. Installing and maintaining an EcoPond requires considerable capital investment, which may take several years to generate returns. Further, reduced N fertiliser can affect the feed intake of the animals, which may reduce the effluent available for EcoPonds. These factors present barriers that make this combination less feasible.

Integrating reduced N fertiliser application and incorporating biochar into the fields are not mutually exclusive, making it possible to implement them together. Biochar, known for its soil-improving properties, has the potential to promote pasture growth and offset the potential reduction of pasture growth caused by reduced fertiliser application. When biochar is co-applied with fertiliser, it increases pasture yield while increasing the profitability of fertilisers [110]. However, it is important to note that biochar production typically incurs additional costs, particularly if it needs to be transported from off-farm sources. To mitigate this challenge, promoting on-farm biochar production could help reduce transportation costs and ensure a more cost-effective implementation. Encouraging farmers to establish biochar production systems on their farms would not only lower transport expenses but also create opportunities for utilising on-farm organic waste streams and improving resource efficiency. Furthermore, the successful integration of multiple mitigation options needs effective policies to manage synergies and trade-offs between them [111] and stakeholder involvement [112].

3.6. Emission reduction policies

New Zealand aims to reduce agricultural emissions through several policies, including the Climate Change Response (Zero Carbon) Amendment Act 2019 [113] and He Waka Eke Noa - Primary Sector Climate Action Partnership [114,115]. The Climate Change Response (Zero Carbon) Amendment Act 2019 establishes a target for achieving net-zero greenhouse gases (except biogenic CH₄) by 2050 and reducing biogenic CH₄ to 24–47 percent below 2017 levels by 2025. He Waka Eke Noa was a collaborative effort between the government and industry to devise effective strategies for lowering on-farm emissions. The proposed farm-level split gas levy system recognises on-farm efficiencies and reinvests revenue into research and development in the primary sector. Additionally, the government's emission reduction plan [27,116] encourages landowners to engage in afforestation through various conservation projects, including the One Billion Trees Fund (1BT), Crown Forestry joint ventures, the Hill Country Erosion Programme, and the Erosion Control Funding Programme (ECFP). Although the 1BT and

ECFP are no longer accepting new funding, planting activities will continue for several more years with the already approved grants. Furthermore, emissions reduction plans demonstrate the government's commitment to supporting farmers in their practical implementation. This approach intends to support farmers to utilise current practices and further innovations to reduce emissions rather than imposing a regulatory burden. Table S3 in the supplementary material provides a comparison of different emission reduction policies, including an overview of policy objectives and focused mitigation strategies under each regulation.

4. Conclusion and recommendation

Dairy farming is a pivotal part of New Zealand's economy, and mitigating GHG emissions from this sector is important to enhance the environmental credentials of New Zealand's dairy exports. The commonly used GHG mitigation options in pasture-based dairy systems were discussed by categorising them into five categories: animal, manure management, feed-based, soil-related, and system-related interventions. Then, immediately applicable mitigation options were short-listed within the New Zealand context, considering a specific set of criteria, namely, on-farm implementation, abatement potential, technological readiness, feasibility and compliance, and synergies and trade-offs. Further, the review examined the interactions between short-listed mitigation options through a combination matrix, highlighting which are compatible and incompatible and their interaction effects. It indicated that while most selected mitigation options are compatible, some may have combined reduction potential that is lower due to overlaps. For example, using reduced N fertilisers with urease inhibitors or implementing measures such as reducing the stock number in conjunction with once-a-day milking can lead to diminished effectiveness. Additionally, feeding once-a-day cows with low-emission feeds and implementing an anaerobic digester/EcoPond in the once-a-day milking system could reduce overall effectiveness. The combinations of reduced N fertiliser, reduced number of cows with high-producing animals, and low-emission feed provide a compatible and promising opportunity for farmers to reduce GHG emissions. However, the adoption of these combinations relies on the specific conditions of each farm, including geographical and financial characteristics. The mitigation bundles should be customised to fit the farm's capacity, helping to reduce economic risk while reducing emissions for practical implementation. Implementation of these mitigation strategies is facilitated by supportive policy frameworks that provide farmers with tools and innovations for emissions reduction.

In summary, the practical applicability of mitigation options in the New Zealand dairy sector depends on the quantification of their interactions, economic feasibility, and compatibility with existing farming systems, which require evaluation before adoption. By considering these factors, dairy farmers can significantly contribute to GHG emission reductions and promote environmental sustainability in the agriculture sector.

CRedit authorship contribution statement

Erandi Kalehe Kankanamge: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Thiagarajah Ramilan:** Writing – review & editing, Supervision, Conceptualization. **Peter R. Tozer:** Writing – review & editing, Conceptualization. **Cecile de Klein:** Writing – review & editing, Conceptualization. **Alvaro Romera:** Writing – review & editing, Conceptualization. **Simone Pieralli:** Writing – review & editing.

Data availability statement

Data availability is not applicable to this article as no new data were created or analysed in this study.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author used the ChatGPT only to improve the grammar and readability. After using this tool, the author reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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