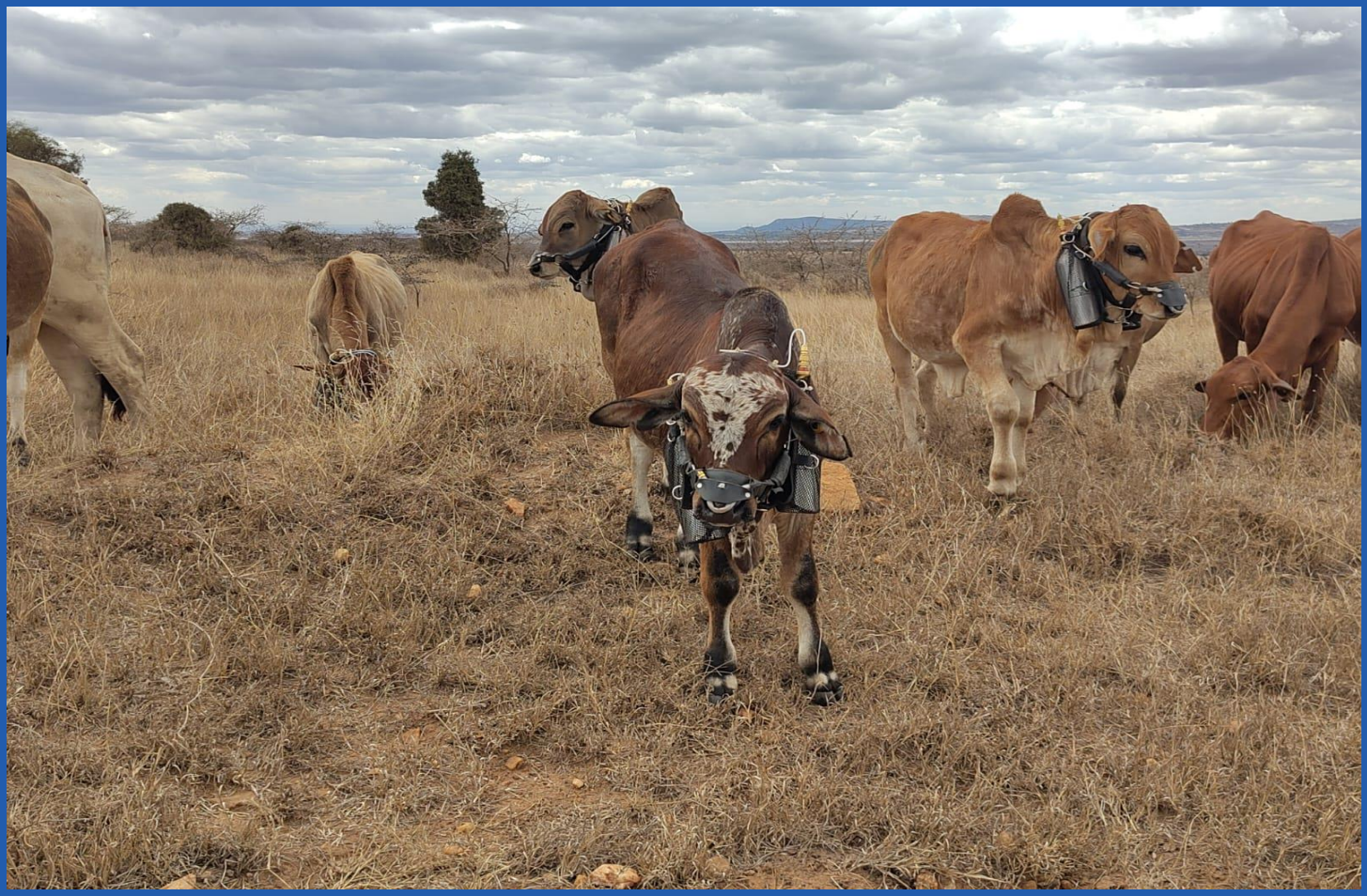
Mitigation Efficacy of Dietary Additives and Nutritional Strategies on Enteric Methane Emissions in Ruminant Livestock: A Systematic Review and Meta-Analysis

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Collaborating Centers

Abstract

Background

Ruminant livestock are a major source of enteric methane, a short-lived and potent greenhouse gas. In low- and middle-income countries, low-quality feed and low animal productivity raise the methane emitted per unit of milk or meat, yet most mitigation strategies were designed for developed countries. It is unclear how much feed and nutrition strategies reduce methane in these systems.

Objectives

To estimate the effect of dietary additives and nutritional strategies on enteric methane relative to productivity, feed intake and time in sheep, goats, dairy cattle, beef cattle and buffaloes, and to compare intervention types.

Methods

Studies came from evidence and gap map. We checked their full texts against pre-specified eligibility criteria, extracted arm-level data, appraised risk of bias and pooled log response ratios in random-effects models with Hartung-Knapp confidence intervals. Methane that was predicted or calculated from intake or rumen models was analysed only in sensitivity analyses.

Results

Thirty-three studies were included from 11 countries (Brazil 14, China 4, India 3, Kenya 3, Colombia 2, Ethiopia 2, and 1 each from Argentina, Bangladesh, Burkina Faso, Syria and Thailand) , of which 29 reported quantitative outcome data that could be extracted. Among studies that measured methane emissions, animals receiving the interventions produced, on average, 14.9% less methane per kg of feed eaten than animals in the control groups. This difference remained statistically significant after adjusting for the three outcomes tested.. Methane emissions per kg of milk produced, weight gained or carcass weight were 8.6% lower on average. However, this result was not statistically significant, meaning we cannot rule out the possibility that there was no real difference between the intervention and control groups. Studies that lacked variability data or were not controlled comparisons were not pooled and are described narratively. There were substantial differences in results across studies. Therefore, the pooled estimates represent the average effect across different interventions and should not be interpreted as the effect of any one intervention. We could not draw clear conclusions about which types of interventions were most effective, and the differences in results could not be explained by intervention type, animal species, measurement method, income group or trial duration. . Grazing and forage management showed no clear effect. Of the 29 critically appraised studies, 13 were rated High, 9 Medium and 7 Low confidence; no study reported a power calculation, which was recorded as a reporting item and did not lower the overall rating.

Conclusions

The evidence that feed and nutrition strategies reduce enteric methane in low- and middle-income countries is inconclusive. Methane per unit of feed intake was lower in pooled analyses, but results per unit of product and per day were uncertain, and effects varied widely between interventions. Future trials should measure methane directly, report outcomes per unit of product and report sample size calculation.nless scalable, locally viable nutritional interventions are successfully deployed (Steinfeld et al., 2006).

Background

Description of the problem

Ruminant livestock are a major source of anthropogenic greenhouse gas (GHG) emissions, with enteric fermentation being a major source of methane (CH_4) emissions from livestock systems (Food and Agriculture Organization of the United Nations [FAO], 2023). Enteric CH_4 is a short-lived but highly potent greenhouse gas, and reducing methane emissions can therefore contribute to near-term climate mitigation (FAO, 2023). Emissions accounting across agriculture is uneven, however, with important data gaps in livestock production systems, including limited information on production characteristics, animal health, manure management, and locally representative emission factors (Graham et al., 2022). This makes it important to identify where evidence is sufficiently dense and robust to support standardised, data-driven baselines for carbon accounting, emissions estimation, and agricultural policy. The problem is particularly acute in low- and middle-income countries (LMICs), where low-productivity livestock systems are widespread and where limited evidence across diverse production systems contributes to uncertainty in emissions estimates (FAO, 2023; Graham et al., 2022). In sub-Saharan Africa, for example, major gaps remain in evidence on pastoral and agropastoral systems, small ruminants, and geographically representative enteric CH_4 emission factors (Graham et al., 2022).

Three factors make enteric CH4 a disproportionate problem in LMICs. First, ruminants rely heavily on low-quality native pastures, crop residues and agro-industrial by-products (Gerber et al., 2013). These feeds are high in structural carbohydrates such as lignocellulose, which lengthen rumen retention time and shift microbial fermentation toward acetate. This pathway generates surplus metabolic hydrogen and yields high CH4 per unit of dry matter intake (Hristov et al., 2013). Second, animal health problems, heat stress and suboptimal feed allocation depress milk and meat productivity relative to high-income systems. An individual animal in an LMIC may emit less CH4 per day than a highly fed dairy cow in a high-income country, yet it emits far more per kilogram of milk or meat produced (Herrero et al., 2013; FAO, 2018). Third, population growth, urbanisation and rising incomes are increasing demand for animal-source protein, a trend described as the “livestock revolution” (Delgado, 2003). Because per-animal productivity gains are slow, LMICs largely meet this demand by enlarging herds. Unless scalable, locally viable nutritional interventions are deployed, this growth threatens to raise global agricultural emissions (Steinfeld et al., 2006).

Description of the intervention

The interventions in this review are technical changes to animal nutrition, which we term Feed and Nutrition Strategies. They fall into two categories, each with technical sub-categories.

Category A: Dietary additives. Specialised compounds are formulated into, or added directly to, the feed to alter rumen chemistry or microbial activity. Three sub-categories were distinguished:

- *Synthetic chemical inhibitors*: compounds engineered to disrupt a metabolic pathway, such as 3-nitrooxypropanol (3-NOP).
- *Alternative hydrogen or electron sinks:* compounds that introduce a competing pathway in the rumen, such as nitrates or sulfates, which accept electrons and divert metabolic hydrogen away from methanogenesis.
- *Natural bioactive compounds:* plant-derived extracts, secondary metabolites and biomass additions, including condensed tannins, saponins, essential oils, and macroalgae such as Asparagopsis taxiformis.

Category B: Nutritional manipulations. The physical formulation, component ratios or agronomic quality of the basal ration itself is changed. Three sub-categories were distinguished:

- *Lipid and fat supplementation*: dietary lipids, oils or oilseeds added to the ration to suppress protozoal and archaeal populations and reduce organic matter fermentation.
- *Concentrate-to-forage ratio adjustment*: a higher proportion of concentrate relative to structural forage, shifting volatile fatty acid production from acetate toward propionate.
- *High-quality or improved forage transitions*: a shift from low-quality native pasture or crop residues to highly digestible cultivated forages, improved pasture varieties or legumes, which lowers CH4 yield per unit of dry matter intake

How the intervention might work

Methane forms in the rumen when archaea use the hydrogen released as feed ferments to reduce carbon dioxide (Figure 1). Fermentation of fibre mainly yields acetate and releases hydrogen, whereas propionate formation takes up hydrogen, so the balance between the two sets how much hydrogen is left for methane (Janssen, 2010). Strategies can lower methane at four points along this chain, and the categories used in this review map onto them. The effects quoted below are those reported by earlier meta-analyses, not results of this review.

Changing the feed supply. Grazing management, the timing of paddock allocation and the choice of pasture system alter how much forage animals can eat and how digestible it is, which changes intake and the fermentation that follows. The global meta-analyses have focused on diet composition and additives (Almeida et al., 2021; Purba & Sangsawad, 2025), so the effect of these practices is less well quantified.

Making less hydrogen. Raising the concentrate share of the diet, moving animals to more digestible forages, adding supplements or processing feed shifts fermentation from acetate towards propionate. This shrinks the hydrogen pool and lowers methane per unit of dry matter intake (Janssen, 2010). Better feed can also raise growth or milk yield, so methane per unit of product can fall even if daily methane does not. In the global analysis by Arndt et al. (2022), a lower forage-to-concentrate ratio, less mature grass and a higher feeding level lowered methane per unit of product.

Diverting hydrogen. Nitrate is a preferred electron acceptor and outcompetes carbon dioxide for hydrogen, redirecting it away from methane formation (Latham et al., 2016). Purba and Sangsawad (2025) estimated that nitrate lowers methane yield by 16.0%.

Suppressing methanogens. Synthetic inhibitors such as 3-NOP bind methyl-coenzyme M reductase, the enzyme that catalyses the final step of methanogenesis in rumen archaea (Duin et al., 2016). Condensed tannins, saponins and dietary lipids are toxic or inhibitory to methanogenic archaea and to the ciliate protozoa associated with them, which interrupts hydrogen transfer between these organisms (Goel & Makkar, 2012). Reported effects on methane yield include −30.6% for 3-NOP, −51.0% for macroalgae, −14.7% for oils, −13.5% for phytochemicals and −10.2% for ionophores (Purba & Sangsawad, 2025). Almeida et al. (2021) reported −23.3% for 3-NOP, and Ku-Vera et al. (2020) reported falls of 10% to 25% with foliage and pods of tropical trees and shrubs. For daily methane, the five most effective strategies averaged a 21% fall (Arndt et al., 2022).

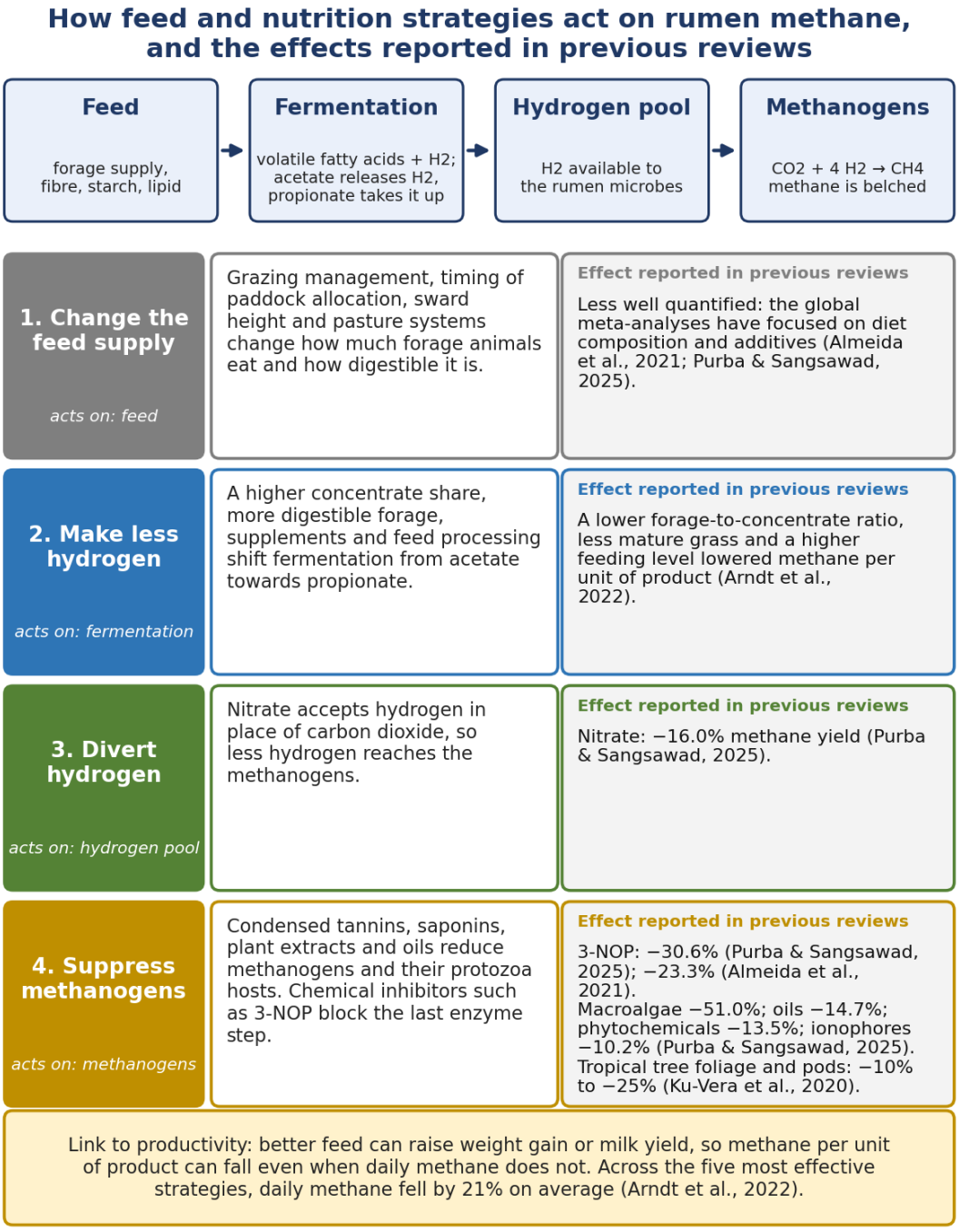


Figure 1. *How feed and nutrition strategies act on rumen methane, with the effects reported in previous reviews. 3-NOP, 3-nitrooxypropanol.*

The effects reported by earlier reviews are summarised in Figure 1. Whether similar effects occur in the low- and middle-income settings studied here is the question this review addresses

Why it is important to do this review

Several syntheses already quantify how dietary strategies change enteric methane. Global meta-analyses rank dietary additives and rumen modifiers by their effect on methane production, yield and intensity (Almeida et al., 2021), compare 98 mitigation strategies from 430 publications for product-based and absolute emissions (Arndt et al., 2022), and rank dietary interventions in cattle and sheep with network meta-analysis (Purba & Sangsawad, 2025). Regional and thematic syntheses cover the Latin America and Caribbean region (Congio et al., 2021), tannin-rich tropical plants (Cardoso-Gutierrez et al., 2021) and cattle fed tropical forages (Ku-Vera et al., 2020).

This review adds to that literature in four ways. First, it synthesises a fixed set of studies identified through an evidence and gap map of agricultural climate mitigation (Saran et al., 2026), not a new database search. The map identified 33 studies of Feed and Nutrition Strategies for ruminants that met the eligibility criteria. All 33 were done in low- and middle-income countries, where the evidence base is thin and most mitigation strategies were designed for developed countries (Harrison et al., 2021). Second, the primary outcomes are emission relative to productivity (per unit of milk, weight gain or carcass) and methane yield per unit of feed intake, with daily emission as a secondary outcome. The most recent global meta-analysis of dietary interventions used methane yield per kg of dry matter intake as its effect size (Purba & Sangsawad, 2025). Third, the scope is wider than dietary additives. It includes locally available feed resources and interventions that alter forage availability or quality, such as grazing management and the timing of paddock allocation, which some global meta-analyses excluded together with studies that estimated methane from equations (Purba & Sangsawad, 2025). Here, studies with predicted or calculated methane are analysed separately from those with measured methane. Fourth, every included study was appraised with a six-domain critical appraisal tool, and studies that could not be pooled are described in a narrative synthesis, so the review also shows how reliable the evidence from these settings is.

The review is smaller and less comprehensive than the global meta-analyses, and it does not aim to rank strategies worldwide. It asks what the experimental evidence from low- and middle-income countries shows about methane relative to productivity, and how far that evidence can be trusted. A systematic review and meta-analysis can pool these data, test conflicting results, and give policymakers estimates that a descriptive narrative cannot provide.

Objectives

The primary objective was to synthesise quantitatively the experimental evidence on the mitigation efficacy of dietary additives and nutritional strategies for enteric CH4 emissions across ruminant sub-systems: small ruminants, dairy cattle and beef cattle. Two review questions guided the work:

1. What is the mitigation efficacy of feed and nutrition strategies on enteric CH4 emissions in managed ruminant livestock?

2. How does mitigation efficacy differ between Category A (dietary additives) and Category B (nutritional manipulations)?

Method

Deviations from the protocol

The protocol (Saran et al., 2026) was published before the studies were assessed, and the changes below were all decided by the review team afterwards, so all are post hoc. The protocol referred to 42 studies in places and 39 in others. We checked the 42 studies coded under Feed and Nutrition Strategies in the evidence and gap map (EGM) against the eligibility criteria, and 33 met them. We added a full-text eligibility step for this, because the protocol described no separate check of the pre-identified studies and the cluster contained studies that did not meet the criteria. The protocol excluded observational studies, uncontrolled comparisons, field surveys, and it required a concurrent comparator. The EGM had broader design criteria and had already identified and coded six such studies in the cluster: two field surveys, a pooled secondary analysis, a non-randomised on-farm comparison and a fixed-order sequence. We synthesised them narratively instead of excluding them, and relaxed the comparator requirement for these six only. None was pooled, and every pooled study compared an intervention with a control diet or practice within the same trial. The protocol also excluded interventions without an isolated dietary component, but we included six grazing and forage management studies, because forage supply and quality are the feed in grazing systems. T In the main analysis they are pooled together with all the other measured-methane studies, and they also form their own intervention category in the analysis by intervention type (Table 8). In an exploratory sensitivity analysis we removed them from the overall pool to see whether they changed the results. Studies whose methane was predicted or calculated from intake or rumen models (five studies) were included where they reported a product-scaled outcome or a

methane yield. They were left out of the main analysis, which uses measured methane only. They were added to the pool in a sensitivity analysis to test whether the pooled estimates depended on how methane was obtained. Measurement method (measured or predicted) was also tested as a moderator. . The protocol's primary outcomes (yield-scaled emission, product-scaled emission, emission per unit of production energy and emission per unit of farm output) remain primary, with yield-scaled emission taken as g CH_4 per kg dry matter intake. Absolute daily emission is a secondary outcome because many trials report that. The protocol planned to analyse interventions separately, and Table 8 gives that analysis. The overall estimates pooled across interventions were added as exploratory and are not read as the effect of any single intervention, because heterogeneity was very high. The protocol planned to calculate Hedges' g, but we used the log response ratio as the primary effect size, because all outcomes are ratio-scale quantities and variability was often unstated. Hedges' g was run as a sensitivity analysis and gave the same direction. The planned analysis of intervention duration was run as an exploratory meta-regression. National income classification, species-specific analyses and dose-response analyses were added as moderators, and the rules for averaging treatment arms and handling shared controls, which the protocol did not specify, are now stated in the Methods. The overall critical appraisal rating excludes sample size or power calculation, a reporting item, and does not count unreported attrition as a weakness. The planned risk-of-bias sensitivity analyses were run, excluding Low-confidence studies and restricting to High-confidence studies. Animal numbers were assumed for four studies and variability reported without a stated type was read as a standard error. In the main analysis, animals in crossover trials were treated as independent between periods, which ignores within-animal correlation. Each of these assumptions was tested in a sensitivity analysis. i Finally, because three outcomes were tested separately on overlapping sets of studies, which raises the chance of a false-positive result, we added a Bonferroni correction (each P value multiplied by three). The protocol did not specify any adjustment for multiple outcomes. The two primary outcomes analysed were product-scaled emission and methane yield, and daily emission was secondary.

The review followed a protocol dated 30 June 2026 (Saran et al., 2026). _Reporting follows the ROSES (RepOrting standards for Systematic Evidence Syntheses) standards for systematic reviews (Haddaway et al., 2018), with a modified PRISMA-style flow diagram (Figure 2). The completed ROSES checklist is provided as Supplementary File S1. Departures from the protocol are listed in the section "Deviations from the protocol" at the start of this Methods section.

Eligibility criteria

Eligibility was defined using the PICOS framework (Table 1).

Table 1. Eligibility criteria (PICOS)

Element	Inclusion	Exclusion
Population	Managed ruminant livestock: small ruminants (sheep, goats), dairy cattle, beef cattle (grazing or feedlot) and large ruminants (buffaloes)	Non-ruminant herbivores; monogastric species (e.g. swine, poultry); wild or unmanaged ruminants
Intervention	Feed and nutrition-related livestock interventions that improve feed quality or nutrient balance, or alter forage availability or quality. Category A (dietary additives): synthetic chemical inhibitors, alternative electron sinks, natural bioactive compounds (tannins, local leaves and peels). Category B (nutritional manipulations): lipid supplementation, concentrate-to-forage ratio adjustment, improved forages and residues, nutrient supplementation (protein, energy, minerals), feed processing (pelleting, fermentation, chopping), and grazing management including timing of paddock allocation	Genetic or breeding selection; veterinary health or vaccination treatments; downstream manure management

Comparator	A control or reference diet, practice or farm type without the intervention. Concurrent controls were expected; studies without one (fixed-order sequences, surveys, life-cycle assessments) were kept for narrative synthesis only	None
Outcome	Emissions relative to productivity or energy output: product-scaled emission (e.g. g CH4 per kg milk or per kg live-weight gain), yield-scaled emission (g CH4 per kg dry matter intake), emission per unit of production energy (per MJ or per kg protein) and emission per unit of farm output (life-cycle assessments). Absolute daily emission was added as a secondary outcome	Studies reporting only rumen fermentation estimates, breath or spot concentrations, or faecal (manure) emissions, with no product-scaled emission or methane yield per unit of intake; metabolic or performance outcomes without CH4 quantification
Study design	Primary experiments with control groups: randomised controlled trials, randomised complete block designs, Latin square designs, crossover designs; for narrative synthesis, on-farm comparisons, surveys and life-cycle assessments	Reviews, conceptual articles and perspective pieces; simulation or predictive modelling without primary data

Identification of studies

No new bibliographic searches were run for this review. The studies came from the systematic searches and coding of the evidence and gap map on agricultural climate mitigation (Saran et al., 2026), which was complete before this review began. We filtered the map by cross-tabulating intervention categories against target GHGs. This gave a cluster of 42 studies of Feed and Nutrition Strategies in ruminants. Each study in the cluster was cross-checked against the eligibility criteria in Table 1, and 33 met them. The nine studies that did not meet them are listed with reasons in Table 4. The 42 studies had already been identified and coded during the map, and they set the fixed boundary for extraction and synthesis.

Study selection

Every full text was assessed against Table 1 for population, intervention, comparator, outcome and study design, and the reason for each exclusion was recorded. Borderline cases were settled by the review team. Where the application of the criteria departed from the protocol, these departures are listed as post hoc deviations in the section “Deviations from the protocol” at the start of this Methods section.

Outcomes and effect measures

The primary outcomes were emission relative to productivity, feed intake or energy output. This covers product-scaled emission (for example g CH4 per kg of milk, per kg of live-weight gain or per kg of carcass), yield-scaled emission (methane yield, g CH4 per kg of dry matter intake, with Ym as a share of gross energy intake), emission per unit of production energy (per megajoule or per kg of protein) and emission per unit of farm output from life-cycle assessments. Absolute daily emission was also extracted as a secondary outcome, because most trials report it. Each outcome was analysed separately.

Data extraction and management

Data were extracted into a standardised workbook built for this review by two independent reviewers (Table 2).

Table 2. Data extracted from each study

Domain	Items
Study characteristics	Study ID; first author; year; journal; country; World Bank FY2026 income classification; experimental design; trial duration; number of treatment periods;

	washout or adaptation period
Animal characteristics	Ruminant sub-system; breed or genotype; age or parity; physiological status; number of animals (total and per group); number of treatment groups; baseline body weight (treatment and control, with type of variability); baseline milk yield for dairy
Diet and intervention	Intervention category and sub-category; specific additive or strategy; dose and dose levels; method of delivery; basal diet by arm (feed description, dry matter intake, concentrate:forage ratio, crude protein, NDF, ether extract, gross energy)
Methane outcomes	Measurement method (respiration chamber, sulfur hexafluoride (SF6) tracer, GreenFeed, ventilated hood, sniffers or spot sampling, predictive equation); metric and unit reported; baseline and analysis sample size per arm; mean and variability (SD or SE) per arm; statistical test; additional performance metrics (milk yield, average daily gain, body weight change, feed conversion ratio, rumen pH, VFA profile)

Critical appraisal

Each included study with an experimental design was critically appraised with the tool described in the review by Malhotra et al. (2025). That tool has been peer-reviewed, piloted and applied in earlier Campbell Collaboration syntheses, and we adopted it without substantive modification. It rates six domains: intervention description, evaluation questions, study design, outcome definition, sample size or power calculation, and attrition (Table 3). Ratings are expressed as confidence in a study's findings, so High confidence corresponds to low concern about risk of bias.

Table 3. Critical appraisal tool

Domain	High confidence	Medium confidence	Low confidence
Intervention	Full, clear description of the main components and how they are delivered	Partial description	Little or no description
Evaluation questions	Full, clear statement	Partial statement	Little or no statement
Study design	Randomised study	Non-randomised study (quasi-experiment)	Single time-point before-and-after
Outcomes	Full, clear definition, using validated instruments where available	Partial definition or validated instruments used without adequate source references	Little or no definition
Sample size	Power calculation reported and sample size meets it	Power calculation mentioned and sample size meets it	No mention of a power calculation
Attrition	Total attrition below 20% and differential attrition below 10 percentage points	Total attrition above 20% or differential attrition above 10 percentage points	Total attrition above 20% and differential attrition above 10 percentage points
Overall	High on every domain	No lower than Medium on any domain	Low on at least one domain

Domain ratings were combined into one overall rating per study using the weakest-link principle shown in the last row of Table 3. Domain ratings were combined into one overall confidence rating per study using the weakest-link principle shown in the last row of Table 3, applied to the domains other than sample size or power calculation. Sample size or power calculation is a reporting-quality item: it was recorded for every study but did not lower the overall rating, because power calculations were uncommon in the trials reviewed (none of the 29 reported one) and their absence does not indicate systematic error. Attrition that was not reported was recorded as "not reported" and was not counted as a weakness. A single serious weakness, such as missing randomisation or high differential attrition, is therefore not offset by strong performance elsewhere. This is consistent with Campbell Collaboration and Cochrane practice. Domain-level and overall ratings are reported for every study, so readers can see where a Medium or Low rating comes from.

Data synthesis

Narrative synthesis. A descriptive synthesis mapped the characteristics of the included studies, including the geographic distribution of trials, the additives and strategies tested, and the baseline diets across ruminant systems. Cross-tabulations of intervention category by target GHG, intervention category by animal species, and geographic region by publication period showed where evidence is concentrated, and how it varies by biology and over time. Studies that could not be included in the meta-analysis, for example because they reported no variability data or were not controlled comparisons, were not left out of the synthesis: their quantitative findings were extracted as percentage differences between intervention and control groups where possible, grouped by study type, and presented with their critical appraisal ratings (Table 11).

Meta-analysis. Quantitative synthesis was run for outcomes reported by at least three independent studies. The effect measure was the log response ratio (lnRR) of the intervention arm to the control arm. It expresses proportional change and converts to a percentage change as $(\exp(\text{lnRR}) - 1) \times 100$. Its sampling variance was calculated from the reported means, variability and sample sizes. Standard errors were converted to standard deviations by multiplying by the square root of the group size, a pooled standard error reported once for a table was applied to every arm, and variability reported without a stated type was read as a standard error. Studies without a sample size or variability could not be weighted and were described narratively. In one study (Meo-Filho et al., 2022) the number of animals per system was not reported, so we assumed 12 (60 steers across five systems). Animal numbers were also not reported in three further studies and were taken from the study design or tables (Pérez-Márquez et al., 2025b, four animals per diet from a table total of 16; Zhang et al., 2019 and 2021, 20 per group from 60 lambs in three groups). A sensitivity analysis excluded all four studies.

Each study contributed one effect size per outcome. Where a study had several intervention arms compared with one control (an arm is one intervention or control group within a study), the lnRR values for each comparison were averaged. Experiments in a paper that used different animals were treated as separate studies. The animal (or the paddock, in grazing trials) was the unit of analysis, and the within-animal correlation in crossover designs was ignored, which makes variances conservative. Effects were pooled with random-effects models fitted by restricted maximum likelihood (REML), with the Hartung-Knapp adjustment for confidence intervals, and 95% prediction intervals are reported. Between-study heterogeneity was quantified with τ^2 and I^2.

Moderators examined were intervention type (additive, nutritional manipulation, or grazing and forage management), animal sub-system, methane measurement method (measured, or predicted, estimated or calculated) and national income classification. A subgroup analysis required at least three studies per subgroup. Intervention duration was prespecified but not analysed because it was not reported consistently, and critical appraisal was analysed. l. Sensitivity analyses excluded studies whose methane was predicted, estimated or calculated, and removed each study in turn (leave-one-out). One study (Alves et al., 2017) was held out of all pooled analyses because its tables contradict its text on the direction of the methane effect, pending a reply from the authors. Analyses were run in Python 3 (NumPy, SciPy, pandas), with the estimators implemented from published formulas. The extracted data and the analysis script are provided as Supplementary file.

Exploratory analyses. Two analyses were added after the data were seen and were not in the protocol. First, outcomes were pooled by species (sheep, goats, dairy cattle, beef cattle, buffaloes and other cattle) wherever at least three effect sizes were available. Second, a dose-response analysis used the four studies that varied the share of a test ingredient or of concentrate in the diet dry matter at two or more levels (Barbosa et al., 2018; Nampoothiri et al., 2018; and the two studies by Pérez-Márquez et al., 2025 on Tithonia and Samanea tubulosa). Within each study, log response ratios were regressed on the dose in percentage points of diet dry matter, with the covariance among arms that shared a control, and the slopes per 10 percentage points were pooled with random effects. These analyses used measured methane only.

Publication bias. Publication and selective-reporting bias were assessed with funnel plots and Egger's linear regression test for outcomes with at least ten studies. Below that number the tests have too little power to be informative, so asymmetry was not tested.

Results

Study selection

The evidence and gap map identified 42 studies, of which 33 met the eligibility criteria and were included (Figure 2). The other nine did not meet them and were excluded. Seven of the nine exclusions were because the study reported no product-scaled emission or methane yield per unit of intake: three estimated methane from rumen fermentation products, two reported breath or spot concentrations, one reported only methane energy per day with values that cannot be physically correct, and one measured faecal rather than enteric emission. Two studies compared breeds or genetic lines (Table 4). Of the 33 included studies, quantitative outcome data (means, variability and sample sizes by study arm) were extracted for 29. The other four (two field surveys, a life-cycle assessment and a pooled secondary analysis) contribute to the narrative synthesis only.

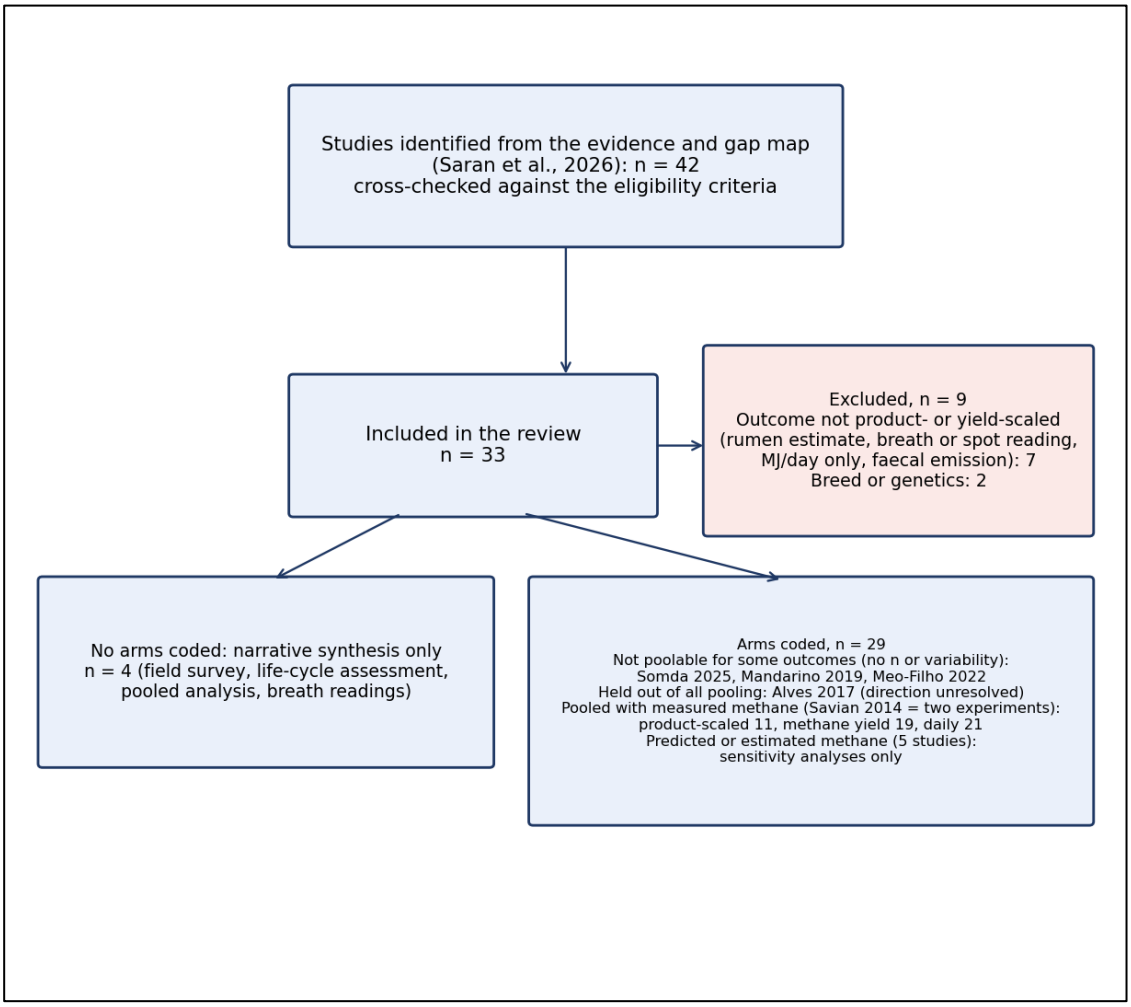


Figure 2. Modified PRISMA-style flow diagram of the studies identified from the evidence and gap map. A study arm is one intervention or control group within a study quantitative outcome data extracted" means that, variability and sample sizes could be taken from the paper.

Table 4. Studies excluded after full-text assessment. Excluded studies are identified by first author and year; their full references are in the evidence and gap map (Saran et al., 2026).

Study	Reason for exclusion
Ampapon et al., 2022	Methane estimated from rumen volatile fatty acids (mmol/100 ml), not an emission
Attri et al., 2020	Breath methane concentration at one time point (ppm), no emission rate
Maciel et al., 2019	Breed comparison (Nellore vs Angus × Nellore), a genetic intervention
Méo-Filho et al., 2020	Comparison of genetic lines of Canchim cattle
Osita et al., 2019	Methane predicted from faecal composition and reported only as MJ/day, with implausibly high values
Polyorach et al., 2016	Methane estimated from rumen volatile fatty acids, not an emission
Prachumchai et al., 2025	Methane estimated from rumen volatile fatty acids, not an emission
Sarkwa et al., 2025	Spot methane concentration (ppm) from a handheld detector, with unmatched diets fed in sequence
Savian et al., 2019	Methane and nitrous oxide from faeces, not enteric methane

Characteristics of included studies

The 33 included studies were published between 2010 and 2025, and 25 appeared from 2020 onward. They came from 11 countries: Brazil (14), China (4), India and Kenya (3 each), Colombia and Ethiopia (2 each), and Argentina, Bangladesh, Burkina Faso, Syria and Thailand (1 each). Twenty-two were in upper-middle-income countries, seven in lower-middle-income countries and four in low-income countries. Fourteen studies used small ruminants (11 sheep, 3 goats), nine used dairy cattle, five beef cattle, two buffaloes and three other cattle (calves and bulls). By intervention type, 15 tested nutritional manipulations (such as ration ratio, forage species or supplements), nine tested additives, six tested grazing or forage management, and three combined an additive with a nutritional change. Designs were 12 randomised controlled trials, seven randomised complete block designs, four Latin squares, four crossovers and six other designs (a fixed-order sequence, an on-farm package comparison, two field surveys, a life-cycle assessment and a pooled analysis). Methane was measured with the SF6 tracer technique in 15 studies, in respiration chambers in eight and with GreenFeed in one. Five studies calculated methane with equations, and four used other approaches (a laser detector in two, a face mask in one, and none in one) (Table 5).

Table 5. Characteristics of the included studies

Study	Country	Animals	Intervention	Design	Methane method
Akash et al., 2024	India	Crossbred calves	Karanj and mahua oil cake in concentrate	Randomised trial	Chamber

Al-Mamun et al., 2021	Bangladesh	Sheep	Pineapple waste, garlic leaves, moringa leaves or their combination (10 g DM/day)	Randomised trial	Calculated
Alves et al., 2017	Brazil	Dairy cows	Black wattle tannin extract (120 g/day)	Crossover	SF6 tracker
Amaral Júnior et al., 2022	Brazil	Buffalo	Palm kernel cake (0.25 to 1.0% of body weight)	Randomised trial	SF6 tracker
Arowolo et al., 2020	China	Goats	Forage chop length (20 vs 100 mm)	Crossover	Chamber
Barbosa et al., 2018	Brazil	Goats	Forage-to-concentrate ratio (100:0 to 20:80)	Randomised trial	SF6 tracker
Batalha et al., 2022	Brazil	Dairy cows	Timing of paddock allocation	Randomised blocks	SF6 tracker
Bekele et al., 2025	Ethiopia	Sheep	Browse leaves replacing half the concentrate	Randomised blocks	Laser detector and model
Costa et al., 2020	Brazil	Sheep	Zinc sulfate; propylene glycol	Randomised trial	SF6 tracker
Dong et al., 2022	China	Dairy cows	NDF-to-NFC ratio (1.19 to 1.68)	Randomised blocks	SF6 tracker
Hijazi et al., 2014	Syria	Sheep	Sheep-keeping system	Field survey	Calculated (IPCC Tier 2))
Korir et al., 2022	Kenya	Dairy cows	Desmodium hay; dairy concentrate	Latin square	Chamber
Korir et al., 2023	Kenya	Steers	Napier, Rhodes or Brachiaria grass	Randomised trial	Chamber
Koscheck et al., 2020	Brazil	Bulls on pasture	Supplement level (0.1 to 0.6% of body weight) by sward height	Randomised trial	SF6 tracker
Mandarino et al., 2019	Brazil	Beef cattle	Good-practice package with recovered pasture and supplementation	On-farm, non-randomised	SF6 tracker
Mavisoy et al., 2025	Colombia	Dairy cows	Silvopastoral tree cover	Life-cycle assessment	Calculated
Meister et al., 2021	Brazil	Goats	Grazing intensity	Randomised trial	SF6 tracker
Mekuriaw et al., 2020	Ethiopia	Dairy cows	Treated teff straw, Napier or Brachiaria hay	Latin square	Calculated from intake
Meo-Filho et	Brazil	Steers on	Five pasture production	Randomised	SF6 tracker

al., 2022		pasture	systems	blocks	
Molina-Botero et al., 2023	Colombia	Dairy cows	Cassava leaves and root replacing 30% of concentrate	Crossover	Chamber
Mwangi et al., 2024	Kenya	Lambs	Calliandra leaves (40% of diet) with or without PEG	Randomised trial	Chamber
Nampoothiri et al., 2018	India	Buffalo calves	Concentrate share (20 to 60%)	Randomised trial	SF6 tracker
Odai et al., 2010	Thailand	Dairy cows	Lactating vs dry cows (pooled analysis)	Pooled secondary analysis	Face mask
Ortiz-Chura et al., 2021	Argentina	Calves	Calcium nitrate (1.5% of dry matter)	Randomised blocks	SF6 tracker
Pena-Bermudez et al., 2022	Brazil	Steers	Yerba mate extract (0.5 to 2%)	Latin square	SF6 tracker
Pérez-Márquez et al., 2025a	Brazil	Sheep	Tithonia hay (9 to 45%)	Crossover	Chamber
Pérez-Márquez et al., 2025b	Brazil	Lambs	Samanea tubulosa fruit (up to 24%)	Latin square	Chamber
Pinto et al., 2020	India	Dairy cows	Rural-urban gradient	Field survey	Laser detector
Savian et al., 2014	Brazil	Lambs and ewes	Stocking method by herbage allowance	Randomised blocks	SF6 tracker
Savian et al., 2021	Brazil	Lambs	Rotatinuous vs rotational stocking	Randomised blocks	SF6 tracker
Somda et al., 2025	Burkina Faso	Zebu bulls	Peanut and cowpea haulms replacing hay	Fixed-order, control last	GreenFeed
Zhang et al., 2019	China	Lambs	Nitroethanol; monensin	Randomised trial	Calculated (VFA and intake)
Zhang et al., 2021	China	Lambs	Nitroethanol; monensin	Randomised trial	Calculated from intake

Methane methods. SF6 tracer: sulfur hexafluoride (SF6) tracer gas technique, in which a capsule in the rumen releases SF6 at a known rate and the ratio of methane to SF6 in air collected near the animal's nose gives daily methane. Chamber: open-circuit respiration chamber, in which all air leaving a sealed chamber is measured. GreenFeed: automated unit that measures breath when the animal visits for feed. Face mask and laser detector: breath measurements by mask or handheld laser. Calculated: methane estimated from feed intake, rumen fermentation or farm data with equations. GreenFeed: automated unit that measures breath when the animal visits for feed. Face mask and laser detector: breath measurements by mask or handheld laser. Calculated: methane estimated from feed intake, rumen fermentation or farm data with equations. None (soil N2O): no methane was measured.

Critical Appraisal

Twenty-nine studies with an experimental design were critically appraised (Table 6). With sample size or power calculation treated as a reporting item that does not lower the overall rating, 12 studies were rated High confidence, 12 Medium and 5 Low. The five rated Low were Mandarino et al. (2019), a non-randomised farm comparison, and Mekuriaw et al. (2020) and Zhang et al. (2019, 2021), whose methane was calculated from intake or rumen models. No study reported a power calculation. Most studies described the intervention and the evaluation question fully and used a randomised design. Outcome definitions were fully described in 18 studies, partly in eight and poorly in three, mainly the studies whose methane was calculated. Attrition was not reported in 25 studies. The four non-experimental studies were not appraised.

Table 6. Critical appraisal ratings across the 29 appraised studies

Domain	High	Medium	Low
Intervention	24	4	1
Evaluation questions	28	1	0
Study design	24	4	1
Outcomes	15	9	5
Sample size or power calculation	0	0	29
Attrition	2	2	25
Overall	13	9	7

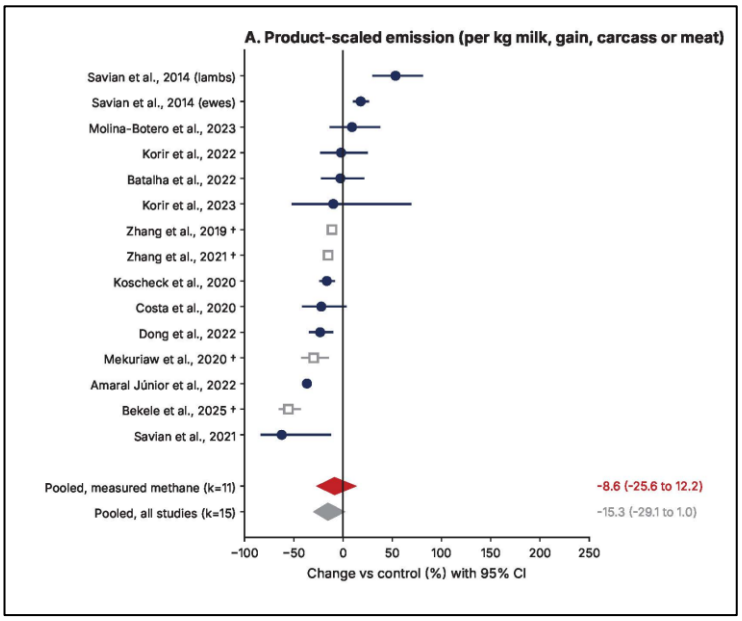
Effects of the interventions

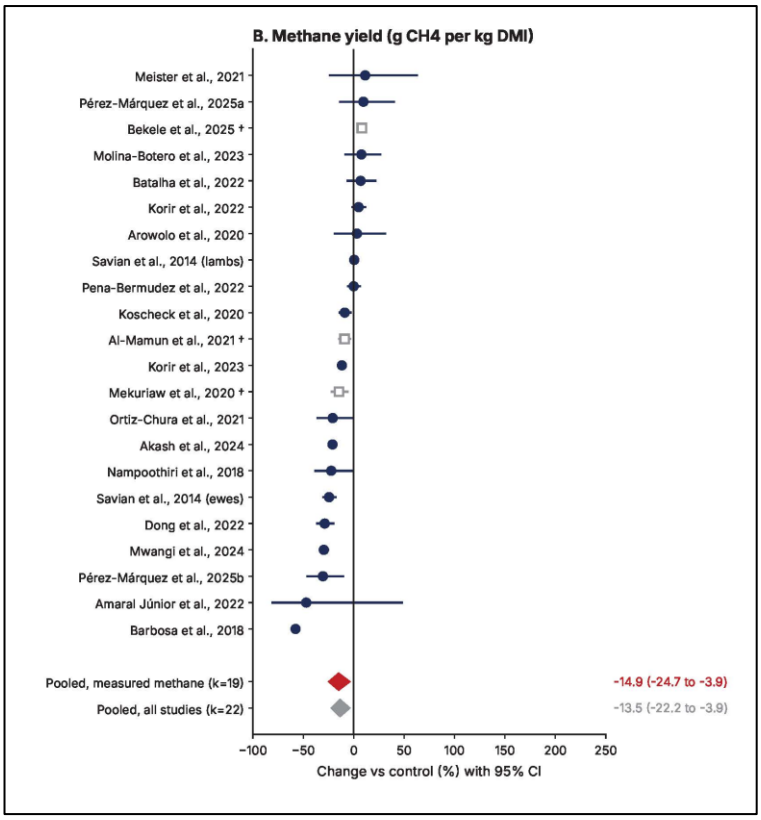
Table 7 gives exploratory estimates pooled across all interventions and Figure 3 the study-level effects. Because heterogeneity was very high for every outcome (I^2 90% to 97%), these are averages across very different interventions and should not be read as the effect of any single intervention. Estimates by intervention type, as planned in the protocol, are in Table 8. Where methane was measured, the estimated difference in emission per unit of product was −8.6% (95% CI −25.6% to +12.2%; 11 effect sizes from 10 studies). Because the interval includes no difference, this result is inconclusive; adding the four studies with estimated or calculated methane gave −15.3% (95% CI −29.1% to +1.0%), which is also inconclusive. Methane per kg of dry matter intake was 14.9% lower (95% CI −24.7% to −3.9%; 19 effect sizes from 18 studies; Bonferroni-adjusted P = 0.036), and daily emission was 10.9% lower (95% CI −19.4% to −1.5%; 21 effect sizes from 20 studies), but the daily result was no longer statistically significant after correction for the three primary outcomes (adjusted P = 0.079). The methane yield and daily estimates changed little when estimated methane was added (−13.5% and −8.4%). The 95% prediction intervals ran from large decreases to large increases (for example −49% to +41% for methane yield). Removing each study in turn moved the pooled estimates only within −13.5% to −3.6% (product-scaled), −16.1% to −11.1% (methane yield) and −11.9% to −7.0% (daily). Egger's test showed no sign of funnel asymmetry (P = 0.23, 0.61 and 0.41), although with this much heterogeneity the test is weak.

Table 7. Pooled effects of the interventions on enteric methane (log response ratio, random effects). Counts are effect sizes, and Savian et al. (2014) contributes two (lambs and ewes) P values are unadjusted; Bonferroni-adjusted P values for the three primary outcomes (measured methane) are 1.00, 0.036 and 0.079

Outcome	Analysis	Effect sizes	Pooled change, % (95% CI)	95% prediction interval, %	I^2, %	P
Product-scaled	Measured methane	11	−8.6 (−25.6 to	−52 to 72	97	0.351

emission			12.2)			
Product-scaled emission	All studies, incl. predicted or estimated	15	−15.3 (−29.1 to 1.0)	−55 to 61	96	0.063
Methane yield (g/kg DMI)	Measured methane	19	−14.9 (−24.7 to −3.9)	−49 to 41	95	0.012
Methane yield (g/kg DMI)	All studies, incl. predicted or estimated	22	−13.5 (−22.2 to −3.9)	−46 to 38	96	0.009
Absolute daily emission	Measured methane	21	−10.9 (−19.4 to −1.5)	−43 to 38	90	0.026
Absolute daily emission	All studies, incl. predicted or estimated	26	−8.4 (−15.8 to −0.4)	−39 to 38	95	0.041





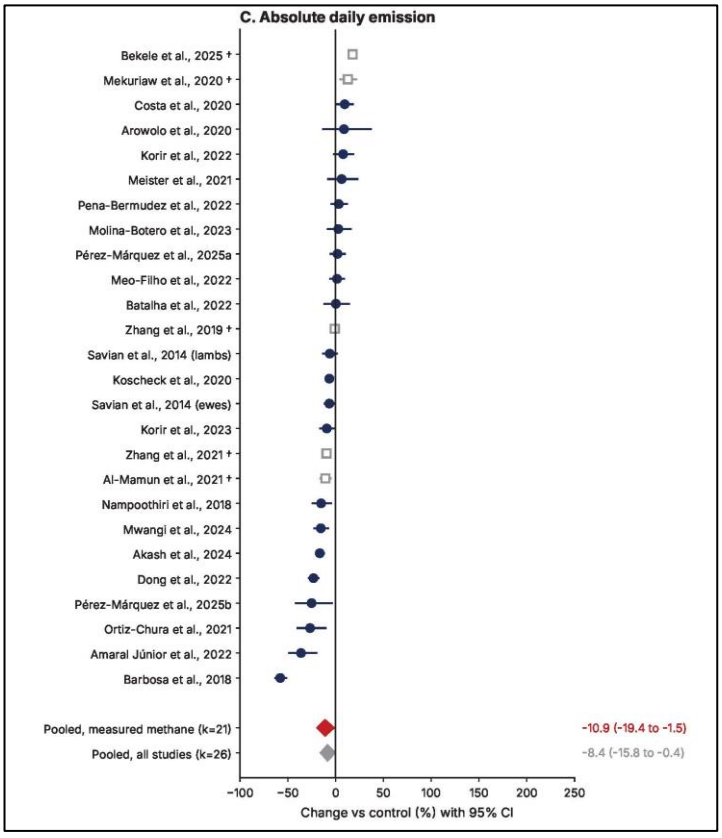


Figure 3. *Forest plots of study-level effects on (A) product-scaled emission, (B) methane yield per kg dry matter intake and (C) absolute daily emission.*

*Note:*_Each marker is one study's change in methane relative to its control, with its 95% confidence interval as the horizontal line; values to the left of zero mean lower methane with the intervention. Filled circles are studies in which methane was measured directly (SF6 tracer, respiration chamber, GreenFeed, laser detector or face mask) and are included in the main pooled estimate. Open squares marked † are studies in which methane was predicted, estimated or calculated from equations; they are

included only in the sensitivity analysis. The red diamond is the pooled estimate for measured methane and the grey diamond the pooled estimate for all studies, with the width of each diamond showing its 95% confidence interval. Alves et al. (2017) is held out of all pooled estimates because the direction of its effect is unresolved. Axes are truncated at −100% and +250%.

Intervention type did not explain the heterogeneity (between-group P = 0.38 for product-scaled, 0.37 for methane yield and 0.20 for daily emission; Table 8). Nutritional manipulations had the largest point estimates (−16.8%, −19.5% and −18.0%), additives were 18.3% (methane yield) and 9.0% (daily) lowere, and grazing and forage management was close to zero (+3.3%, −4.7% and −2.7%). Every subgroup interval included no change. Animal sub-system (P = 0.59, 0.67 and 0.94), measurement method (SF6 vs chamber; P = 0.29, 0.40 and 0.30) and, for methane yield and daily emission, income group (P = 0.82 and 0.88) did not explain the heterogeneity either.

Table 8. Pooled change (%, 95% CI) by intervention type, measured methane only

Intervention type	Product-scaled	Methane yield	Daily emission
Additives (A)	k=1, not pooled	−18.3 (−36.6 to 5.2), k=4	−9.0 (−25.4 to 10.9), k=5
Nutritional manipulations (B)	−16.8 (−44.2 to 24.0), k=4	−19.5 (−38.5 to 5.5), k=9	−18.0 (−35.5 to 4.2), k=9
Grazing and forage management	3.3 (−53.5 to 129.4), k=4	−4.7 (−28.9 to 27.8), k=4	−2.7 (−8.9 to 3.9), k=5
Both A and B	k=2, not pooled	k=2, not pooled	k=2, not pooled

Exploratory analyses

Pooling by species (Table 9) showed no difference between species groups (between-group P = 0.89 for product-scaled, 0.33 for methane yield and 0.47 for daily emission). For methane yield the point estimates were −16.7% in sheep, −22.7% in goats (very imprecise), −8.2% in dairy cattle and −1.5% in beef cattle. For daily emissions, they were −5.4% in sheep, −21.5% in goats, −8.6% in dairy cattle and +0.3% in beef cattle. Every interval included no change. Buffaloes and the other cattle (calves and bulls) had too few effect sizes to pool.

Table 9. Pooled change (%, 95% CI) by species, measured methane only

Species	Product-scaled	Methane yield	Daily emission
Sheep	−4.9 (−60.1 to 126.5), k=4	−16.7 (−35.5 to 7.7), k=5	−5.4 (−16.3 to 6.9), k=6
Goats	no effect sizes	−22.7 (−80.3 to 203.1), k=3	−21.5 (−79.7 to 202.8), k=3
Dairy cattle	−8.3 (−32.7 to 25.0), k=4	−8.2 (−32.5 to 24.9), k=4	−8.6 (−26.3 to 13.5), k=4
Beef cattle	k=2, not pooled	−1.5 (−17.4 to 17.5), k=3	0.3 (−9.9 to 11.6), k=4
Buffaloes	k=1, not pooled	k=2, not pooled	k=2, not pooled
Other cattle (calves, bulls)	no effect sizes	k=2, not pooled	k=2, not pooled

Four studies varied the share of a test ingredient or of concentrate in the diet at two or more levels (goats given more concentrate, buffalo calves given more concentrate, sheep given Tithonia hay, and lambs given Samanea tubulosa fruit). Per 10 percentage points more of that ingredient in the diet dry matter, methane per kg of dry matter intake was estimated at -10.0% ((95% CI −24.2% to +6.8%, I^2 90%, P = 0.14) and daily methane by 8.3% (95% CI −20.3% to +5.6%, I^2 95%, P = 0.15). Both interval include no change, so the dose-response is inconclusive.

The slope for methane per kg of dry matter intake was negative in three studies (−13.5% for concentrate in goats, −9.0% for concentrate in buffalo calves, −22.7% for *Samanea tubulosa*) and flat in the Tithonia study (+2.1%). These estimates mix different ingredients, so they describe an average slope, not a single dose-response curve. For *Samanea tubulosa* we used the labelled doses (6%, 12% and 24% of dry matter), although the ingredient table implies somewhat higher shares.

Sensitivity analyses

The results were tested in nine sensitivity analyses (Table 10). Excluding the seven studies rated Low confidence did not change the estimates for product-scaled emission or methane yield, because none of them was in those measured-methane analyses. For daily emission, it removed Meo-Filho et al. (2022) and gave −11.5% (95% CI −20.3% to −1.7%; 19 studies), close to the primary estimate. Restricting the analysis to the 13 studies rated High confidence gave similar estimates for methane yield (−15.2%, 95% CI −28.0% to −0.2%; 12 studies) and daily emission (−10.5%, −22.1% to +2.8%), but the product-scaled estimate changed direction (+3.7%, −26.1% to +45.6%; 4 studies). Reading unstated variability as a standard deviation, assuming a within-animal correlation of 0.5 in crossover trials, and using Hedges' g left the conclusions unchanged. Excluding studies with assumed animal numbers gave similar estimates for methane yield (−14.1%) and daily emission (−10.9%). Excluding groups of fewer than five animals made the product-scaled estimate larger (−19.4%, 95% CI −32.1% to −4.4%; 7 studies), which shows that this result depends on which studies are included.

Table 10. Sensitivity analyses: pooled change (%, 95% CI) and number of studies, measured methane only. The four studies rated Low confidence were not in the measured-methane analyses, so excluding them gives the primary result.

Analysis	Product-scaled emission	Methane yield (g/kg DMI)	Daily emission
Primary analysis	−8.6 (−25.6 to 12.2), n=10	−14.9 (−24.7 to −3.9), n=18	−10.9 (−19.4 to −1.5), n=20
Excluding studies rated Low confidence	−8.6 (−25.6 to 12.2), n=10	−14.9 (−24.7 to −3.9), n=18	−10.9 (−19.4 to −1.5), n=20
Studies rated High confidence only	3.7 (−26.1 to 45.6), n=4	−15.2 (−28.0 to −0.2), n=12	−10.5 (−22.1 to 2.8), n=13
Unstated variability read as SD	−8.6 (−25.6 to 12.2), n=10	−14.9 (−24.7 to −3.9), n=18	−10.9 (−19.4 to −1.5), n=20
Excluding studies with assumed animal numbers	−8.6 (−25.6 to 12.2), n=10	−14.1 (−24.3 to −2.5), n=17	−10.9 (−20.1 to −0.6), n=18
Within-animal correlation 0.5 (crossover trials)	−8.5 (−25.3 to 12.1), n=10	−14.7 (−24.5 to −3.8), n=18	−10.8 (−19.3 to −1.4), n=20
Excluding groups of fewer than 5 animals	−19.4 (−32.1 to −4.4), n=7	−15.2 (−27.9 to −0.1), n=14	−11.3 (−22.3 to 1.3), n=16
Hedges' g (standardised units)	−0.64 (−2.52 to 1.24), n=10	−1.11 (−2.02 to −0.19), n=18	−0.69 (−1.24 to −0.14), n=20

Studies not shown in the forest plots

Seven included studies appear in none of the forest plots, and an eighth (Meo-Filho et al., 2022) appears only in the plot of daily emission. Their results are summarised here.

Alves et al. (2017) was held out of all pooling because its tables contradict its text on the direction of the effect. Twelve Holstein cows grazed millet pasture and received a concentrate with or without 120 g/day of black wattle (*Acacia mearnsii*) tannin extract in a crossover design. The text reports that the extract lowered daily methane by about 32% and methane per kg of milk by about 31%, but the treatment labels in the results table are reversed relative to the text, so the printed values show the opposite direction. Clarification from the authors is pending. The study was rated Low confidence because its results table contradicts its text.

Somda et al. (2025) fed zebu bulls peanut or cowpea haulms in place of hay in a fixed-order sequence, with the hay control fed last. The paper reports no variability. Daily methane was 9% to 24% higher on the haulm diets than on hay, and methane per kg of intake ranged from 6% lower to 18% higher. The study was rated Low confidence because its fixed-order design confounds diet with period and no variability is reported.

Mandarino et al. (2019) compared recovered pasture within a good-practice package that included supplementation against degraded pasture on commercial ranches, without randomisation, animal numbers or variability. The study was rated Low confidence. Methane per kg of weight gain was 54% lower in the dry season and 26% lower in the rainy season, while daily methane was 28% lower in the dry season and 16% higher in the rainy season. In Meo-Filho et al. (2022), methane per kg of carcass was 30% to 50% lower in the four improved pasture systems than in the extensive system, with no variability given for the ratio, and daily methane differed by −9% to +13%. The study was rated Low confidence.

The remaining four studies did not test a controlled feed contrast. Hijazi et al. (2014) compared three sheep-keeping systems on 64 Syrian farms and estimated enteric methane with IPCC Tier 2 equations (26.0, 22.5 and 13.5 kg per sheep per year for extensive, semi-intensive and intensive systems); there was no control group. Mavisoy et al. (2025) calculated farm-level emissions for 30 dairy farms grouped by silvopastoral tree cover, with enteric methane accounting for about 69% of farm emissions. Odai et al. (2010) found daily methane of 262.7 L in lactating cows and 153.0 L in dry cows, and 25.7 and 28.7 L per kg of intake. Pinto et al. (2020) reported higher breath methane concentration and milk yield in urban than in rural dairy cows. These were rated Low confidence.

Table 11. Studies not included in the pooled analyses: design, critical appraisal rating and main findings

Study	Design	Critical appraisal	Main quantitative finding	Reason not pooled
Alves et al., 2017	Crossover	Low	Text: daily methane about 32% lower and methane per kg of milk about 31% lower with tannin extract; the results table shows the opposite direction	Direction of effect unresolved
Somda et al., 2025	Fixed-order, control last	Low	Daily methane 9% to 24% higher; methane per kg of intake 6% lower to 18% higher	No variability reported
Mandarino et al., 2019	On-farm, non-randomised	Low	Methane per kg of weight gain 54% lower (dry season) and 26% lower (rainy season); daily methane 28% lower and 16% higher	No animal numbers or variability
Meo-Filho et	Randomised	Low	Methane per kg of carcass 30% to 50% lower; daily methane −9% to	No variability for the per-product

al., 2022	blocks		+13% (included in the daily emission analysis)	ratio
Hijazi et al., 2014	Field survey	Low	Enteric methane estimated with IPCC Tier 2 by sheep-keeping system (26.0, 22.5, 13.5 kg/sheep/yr); not measured	No methane outcome
Mavisoy et al., 2025	Life-cycle assessment	Low	Enteric methane about 69% of farm emissions on 30 dairy farms	No comparison of feed strategies
Odai et al., 2010	Pooled secondary analysis	Low	Daily methane 262.7 L (lactating) and 153.0 L (dry); 25.7 and 28.7 L per kg of intake	No feed intervention
Pinto et al., 2020	Field survey	Low	Higher breath methane concentration and milk yield in urban than rural cows	Concentration, not emission

Discussion

We included 33 studies evaluating feed and nutrition strategies to reduce methane emissions from sheep, goats, dairy cattle, beef cattle, and buffaloes, with most studies conducted in low- and middle-income countries. Methane emissions per unit of feed intake were lower in pooled analyses (−14.9%), a result that remained statistically significant after correction for multiple outcomes. However, the result was inconclusive when methane emissions were expressed relative to animal productivity (−8.6%, 95% CI −25.6% to 12.2%). Estimates based on calculated or modelled methane values suggested a larger reduction in emissions per unit of product (−15.3%), but these estimates are dependent on intake and rumen models and were therefore not considered reliable evidence of effects on production efficiency.

The difference between methane emissions per day and per unit of animal product is important. Reducing daily methane emissions does not necessarily reduce the amount of methane emitted per litre of milk or kilogram of meat produced. For example, in a Latin-square trial of dairy cows, legume hay reduced daily methane emissions by 26% but increased methane emissions per kilogram of milk by 17%, largely because milk yield declined (Korir et al., 2022). In contrast, a dairy concentrate increased daily methane emissions by 11% but reduced methane emissions per kilogram of milk by 31%, although this estimate was uncertain. These findings highlight the importance of assessing methane emissions in relation to animal productivity rather than considering reductions in daily emissions alone.

Nutritional interventions had the largest point estimates for lower methane emissions (approximately 17–20%) and feed additives had smaller point estimates (approximately 9–18%), but every confidence interval included no difference, so these results are inconclusive. Grazing and forage-management interventions showed little evidence of an effect. However, these comparisons were based on relatively few studies and substantial heterogeneity, and there was no clear evidence that intervention type, animal species, methane measurement method, or country income group explained the variation in results. Exploratory analyses suggested a possible reduction in methane emissions with increasing inclusion of test ingredients or concentrates in the diet, but the evidence was imprecise. Individual studies of locally available tree leaves and fruits also reported relatively large reductions in methane emissions, including Calliandra leaves and *Samanea tubulosa* fruit. However, these findings were based on small numbers of animals and should be considered promising leads for further research rather than evidence for immediate recommendation.

Overall, the evidence is inconclusive on whether feed and nutrition strategies reduce methane emissions from ruminants in these settings. Methane per unit of feed intake was lower in pooled analyses, but reductions in methane per day or per unit of feed do not necessarily translate into lower emissions per unit of animal product**.** Future research should therefore prioritise productivity-adjusted methane

outcomes, use robust and directly measured emission estimates, and evaluate interventions at a scale and under production conditions that are relevant to low- and middle-income countries.

Comparison with previous reviews

Our findings are broadly consistent with previous reviews, although the reductions observed in this review were generally smaller than the largest effects reported in global meta-analyses. This is expected because the studies included in our review mainly evaluated feed changes, additives, and grazing or forage-management strategies, rather than some of the more effective methane-reducing technologies reported elsewhere.

The 14.9% reduction in methane per unit of feed intake was similar to the reductions reported by Purba and Sangsawad (2025) for nitrate (16.0%), oils (14.7%), and phytochemicals (13.5%), and somewhat greater than their estimate for ionophores (10.2%). In contrast, larger reductions reported for strategies such as macroalgae (51.0%) and 3-nitrooxypropanol (30.6%) were not represented in the studies included in our review. Similarly, the estimated 10.9% reduction in daily methane emissions was smaller than the approximately 21% reduction reported for the five most effective strategies in Arndt et al. (2022), which included methane inhibitors that were not evaluated in our measured-methane studies. Evidence from tropical tree foliage and pods has also reported reductions of around 10–25% in methane yield in cattle (Ku-Vera et al., 2020). The larger reductions observed in the individual Calliandra and *Samanea tubulosa* studies in our review are therefore promising but should be interpreted cautiously because each was based on a single small study.

These comparisons should be interpreted with caution. Previous reviews often estimate the effects of specific interventions, whereas our pooled estimates combine different types of feed and nutrition strategies. In addition, the very high heterogeneity across studies means that the pooled estimates should not be interpreted as the expected effect of any particular intervention. For methane emissions per unit of animal product, our estimate was also uncertain (−8.6%, 95% CI −25.6% to 12.2%) and cannot be directly compared with estimates for specific strategies such as increased feeding level, less mature grass, or lower forage-to-concentrate ratios reported by Arndt et al. (2022).

Overall, the findings from studies conducted in low- and middle-income countries are consistent with the direction of effects reported in the wider global literature, but the evidence generally points to **modest reductions with considerable uncertainty**. This reinforces the importance of evaluating methane outcomes alongside animal productivity and generating more robust evidence from production systems in low- and middle-income countries.

Evidence from studies not included in the pooled analyses

The seven studies that could not be included in the meta-analysis provide useful additional context but do not materially change the overall findings. Some suggest potentially larger reductions than those observed in the pooled analyses. For example, Alves et al. (2017) (rated Low confidence) reported a substantial reduction in daily methane emissions following the use of a tannin extract. However, uncertainty about the reported data means that this finding should be interpreted cautiously.

The studies of intensified pasture systems provide an important illustration of why methane emissions should be considered in relation to productivity. Mandarino et al. (2019) (rated Low confidence) and Meo-Filho et al. (2022) (rated Low confidence) reported reductions in methane emissions per kilogram of weight gain or carcass, while daily methane emissions did not consistently decrease. This suggests that improvements in animal growth or production can reduce the amount of methane associated with each unit of product even when total daily emissions remain similar.

The remaining observational studies provide information on factors that may influence methane emissions but do not directly evaluate interventions. For example, Mavisoy et al. (2025) found that enteric methane was a major component of farm-level emissions in Colombian dairy systems, highlighting the potential importance of feed and nutrition strategies. Odai et al. (2010) showed that methane emissions differed between lactating and dry cows, emphasising the need to account for physiological and production differences when comparing feed interventions. Other studies reported outcomes that were

not directly comparable with emission rates, such as breath methane concentrations or methane calculated from farm survey data with equations.

Taken together, these studies support the main conclusion of this review: feed and nutrition strategies may reduce methane emissions, but their effects need to be assessed in the context of animal productivity, production systems, and the specific outcome used to measure emissions.

Quality and completeness of the evidence

The evidence base is small and weak in design detail. Most trial arms had 3 to 12 animals (median 5), the largest had 20, and none reported a power calculation, which was recorded as a reporting-quality item. After excluding it from the overall rating, 13 of the 29 appraised studies were rated High confidence, 9 Medium and 7 Low. Attrition was not reported in 25 of 29. Only 17 of the 33 studies reported methane per unit of product, and four more recorded weight gain or milk yield but did not divide methane by it. Studies came mainly from Brazil (14 of 33), and six were from sub-Saharan Africa. No included study tested 3-nitrooxypropanol or macroalgae, the strategies that attract most attention elsewhere (Duin et al., 2016), so this review says nothing about them in LMIC systems. Reporting was often inconsistent: more than 80 queries about units, labels, missing statistics and contradictions between text and tables were logged, and one study (Alves et al., 2017) was held out because its tables contradict its text on the direction of the effect. Five studies calculated methane from intake or rumen models, and for those the emission result carries no information beyond the diet.

Limitations of the review

Only English-language literature was included in the map's searches, because capacity and resources to translate other languages were limited, so relevant studies published in other languages may be missing. Some statistical adjustments were required because studies reported variability in different ways. Standard errors were converted to standard deviations where necessary. For crossover trials, within-animal correlations were not available and were therefore not incorporated into the analysis. This approach is expected to produce wider confidence intervals and therefore more conservative estimates of precision. Where studies included more than one intervention group with a common control group, intervention groups were combined within the study to avoid giving that study disproportionate weight in the analysis. As a result, the dose–response relationship could only be explored in four studies and should be considered preliminary. Because the review combined interventions that may reduce methane through different mechanisms, the pooled estimate represents an average effect across different strategies and should not be interpreted as the expected effect of any individual intervention. The wide prediction intervals, such as −49% to +41% for methane yield, further indicate substantial variation in effects between studies.

Implications for practice and policy

The available evidence does not support recommending a single feed or nutrition strategy as a reliable approach for reducing enteric methane emissions across livestock production systems in low- and middle-income countries. On average, the interventions reduced methane emissions by approximately 15% per unit of dry matter intake and 11% per day. However, the evidence for reductions in methane emissions per unit of animal product was smaller and uncertain. This distinction is important because an intervention may reduce daily methane emissions while also reducing milk yield or weight gain, resulting in little or no improvement in the emissions associated with each unit of product. On average, the interventions reduced methane emissions by approximately 15% per unit of dry matter intake and 11% per day. However, the evidence for reductions in methane emissions per unit of animal product was smaller and uncertain. This distinction is important because an intervention may reduce daily methane emissions while also reducing milk yield or weight gain, resulting in little or no improvement in the emissions associated with each unit of product.

For this reason, programmes, policies and carbon-accounting approaches that assess the climate benefits of feed interventions should consider methane emissions in relation to animal productivity. Daily methane emissions or methane per kilogram of dry matter intake alone may provide an incomplete

picture of mitigation potential. Assessments should, where possible, include methane emissions per unit of milk, meat or weight gain, together with measures of feed intake and animal performance. This would help ensure that methane reductions are not achieved at the expense of productivity and would provide a more meaningful measure of the efficiency of livestock production.

The findings also suggest potential for interventions based on locally available feed resources, including tree leaves, fruits and other forage resources, as well as changes in the proportion of concentrate in the diet. These approaches may be particularly relevant in low- and middle-income countries because they can potentially build on existing feeding practices and locally available resources. However, the evidence for some of these interventions comes from small individual trials, and relatively large effects observed in such studies should not be interpreted as evidence that the interventions are ready for widespread implementation. Their effects on methane, animal productivity, feed availability, cost, animal health and feasibility need to be evaluated under routine farming conditions.

More broadly, policies aimed at reducing livestock methane should recognise the diversity of production systems in low- and middle-income countries. An intervention that is effective in a controlled feeding trial may not have the same effect when applied under different climatic, nutritional, management or market conditions. Implementation decisions should therefore consider both the magnitude of the methane reduction and whether the intervention is affordable, accessible and practical for farmers. Larger on-farm studies are needed before promising feed strategies are incorporated into large-scale mitigation programmes or used to generate carbon credits.

Implications for research

Future research should improve both the quality and comparability of evidence on feed-based methane mitigation. Trials should report methane emissions using multiple complementary outcomes, including daily methane emissions, methane per kilogram of dry matter intake and, most importantly, methane emissions per unit of animal product such as milk, meat or weight gain. Animal productivity and feed intake should be reported for every intervention arm so that reductions in methane can be interpreted alongside changes in production.Future research should improve both the quality and comparability of evidence on feed-based methane mitigation. Trials should report methane emissions using multiple complementary outcomes, including daily methane emissions, methane per kilogram of dry matter intake and, most importantly, methane emissions per unit of animal product such as milk, meat or weight gain. Animal productivity and feed intake should be reported for every intervention arm so that reductions in methane can be interpreted alongside changes in production.

Studies should also provide sufficient information to allow their results to be included in future evidence syntheses. This should include the number of animals in each study arm, group means, measures of variability, and clear descriptions of the intervention and control diets. Sample-size calculations should be reported to indicate whether studies were adequately powered to detect meaningful differences. Where methane is measured directly, authors should clearly describe the measurement method and report relevant calibration, recovery or quality-control procedures. Direct measurement approaches, including respiration chambers, GreenFeed and SF6, should be appropriately validated and consistently reported.

Crossover trials require particular attention to the statistical information needed for meta-analysis. Authors should report the within-animal correlation or provide sufficient raw data to allow this correlation to be estimated. This would improve the precision of pooled estimates and avoid the need to make assumptions about correlations that are not reported.

Future trials should also be sufficiently long to determine whether reductions in methane are sustained over time rather than reflecting short-term responses to a dietary change. Greater emphasis should be placed on well-designed studies conducted under real-world farm conditions in low- and middle-income countries. These studies should evaluate both locally available feed resources and more established methane-reducing technologies, including stronger methane inhibitors, within the production systems in which they could realistically be implemented.

Finally, greater consistency in reporting is needed. Studies should use standard units, clearly distinguish measured from modelled or calculated methane outcomes, and provide accurate and unambiguous treatment labels. In this review, several studies contained reporting or labelling problems that could not be resolved from the published information. Improving reporting quality would make the evidence more usable for systematic reviews, policy decisions and future carbon-accounting approaches.

Conclusions

The evidence that feed and nutrition strategies reduce enteric methane emissions from ruminants in low- and middle-income countries is inconclusive. Methane per kilogram of dry matter intake was approximately 15% lower in pooled analyses, but the approximately 11% difference per day was not statistically significant after correction for multiple outcomes, the approximately 9% difference per unit of animal product was inconclusive, and effects varied substantially between studies. No clear evidence indicated that intervention type, animal species or methane measurement method explained this variation.

The evidence base also has important limitations. Many studies were small, did not report sample-size calculations or measures of variability, and some relied on calculated rather than directly measured methane emissions. These limitations reduce confidence in the magnitude and consistency of the observed effects. Importantly, the findings demonstrate that reductions in daily methane emissions should not automatically be interpreted as improvements in the emissions efficiency of livestock production.

For practice and policy, feed-based mitigation strategies should therefore be assessed using methane emissions relative to animal output, alongside effects on productivity and feasibility under local conditions. For research, priority should be given to larger, well-designed on-farm trials in low- and middle-income countries that directly measure methane, report productivity-adjusted outcomes, and evaluate both promising local feed resources and more effective methane-reducing interventions. This evidence will be important for identifying strategies that can reduce methane emissions while maintaining or improving livestock productivity.

Declarations

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Data availability: The extracted data (SR_Extraction_Workbook.xlsx), the analysis script (meta_analysis.py) and the completed ROSES checklist are provided as Supplementary Files S1 to S3.

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