Existing and near-to-market methane reducing feed additives and technologies

Miller, G A; Eory, Vera; Duthie, C-A; Newbold, JR

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Existing and near-to-market methane reducing feed additives and technologies: Evidence of Efficacy, Regulatory Pathways to Market and Mechanisms to Incentivise Adoption

Gemma Miller, Vera Eory, Carol-Anne Duthie and John Newbold

Executive Summary

Background:

Climate change is the defining issue of our time. In response, the UK Government has set an ambitious target to achieve net-zero greenhouse gas (GHG) emissions by 2050 (Climate Change Act, 2008). There is now growing urgency for all sectors to reduce their GHG emissions to reach this target. Methane in particular has a high profile in political and public discourse. In 2020, agriculture accounted for 11% of total UK GHG emissions, with 50% of that attributed to enteric methane (BEIS, 2022). Methane is a powerful (global warming potential over 20 years for non-fossil fuel sources = 80.8), but short-lived gas (10-20 years), thus a focussed reduction of methane is considered one of the most important strategies to limit global warming to 1.5°C.

In response to the growing global importance of methane, the development of robust mitigation strategies is attracting significant attention. In particular, plant-based and synthetic feed additives have been a key focus of recent research for their potential to reduce methane emissions by inhibiting methane production in the rumen and/or increasing the efficiency of feed conversion. A further area of research attracting significant attention is the development and use of technologies to capture enteric methane shortly after its emission and convert (oxidise) methane to carbon dioxide and water.

There are strong political and commercial incentives to bring products to market that have both productivity and environmental benefits, but it is imperative that they are supported by a robust evidence base and are presented to the market in forms that can be easily adopted by farmers and that are acceptable to consumers.

Project aims and objectives:

The aim of this work was to (i) review the scientific evidence for a defined range of close-to-market products (five feed supplements and one technology) in relation to the diverse farm circumstances in which they may be used; (ii) evaluate the evidential requirements of relevant regulatory processes and assess the position of these products on their path to regulatory approval; and (iii) consider the role of evidence in the various public and private mechanisms that are emerging to incentivise use of these products on farm.

Key findings:

1. **Rapid Evidence Assessment**

A rapid evidence approach focussed on the quality and extent of evidence for the efficacy of on or near-to-market feed additives (n=5) and technologies (n=1) used to reduce enteric methane emissions.

Feed additives	Technologies
Asparagopsis (species of red seaweed)	ZELP
Bovaer	
SilvAir	
Agolin Ruminant	
Mootral	

Key points for each product are outlined below:

Asparagopsis: a genus of two species of red seaweed (*A. taxiformis* and *A. armata*) widely found in tropical to warm marine waters. It contains halogenated methane analogues, the most abundant of which is bromoform (CHBr3), which directly inhibits methane production. Use of *Asparagopsis* to inhibit methane is patented by FutureFeed Pty Ltd (Newstead, Australia), who deliver supply chain access to *Asparagopsis* growers and feed suppliers through licence agreements. There is evidence in the published literature supporting *Asparagopsis* as a methane inhibitor (four *in-vivo* studies using *A. taxiformis;* one *in-vivo* using *A. armata*) showing reductions in methane production (gCH_4/day) of 34.5-64.6%. Further evidence is required to understand variation in efficacy and to give confidence in its efficacy across species, production systems and diet types. Bioaccumulation in seaweed of potentially toxic elements (lead, arsenic, iodine) is of concern for animal health. *Asparagopsis* may be viable in the future when a sufficient quantity of consistent product can be supplied (e.g., through efficient production in controlled tank environments) and safety has been confirmed.

Bovaer: is DSM's trademark name for 3-nitrooxypropanol (3-NOP), a small synthetic molecule which inhibits the final step in the biochemistry of methane synthesis. There is extensive evidence for the efficacy of 3-NOP as a methane inhibitor (33 published *in vivo* studies across beef, dairy and sheep) showing reductions in methane production of 24.8-33.2%. Bovaer is the only additive authorised as a zootechnical Feed Additive for methane mitigation (in lactating ruminants) in the EU, with approval for Great Britain (GB) pending and a dossier for growing ruminants in preparation. A manufacturing line is being installed at an existing DSM facility in Scotland.

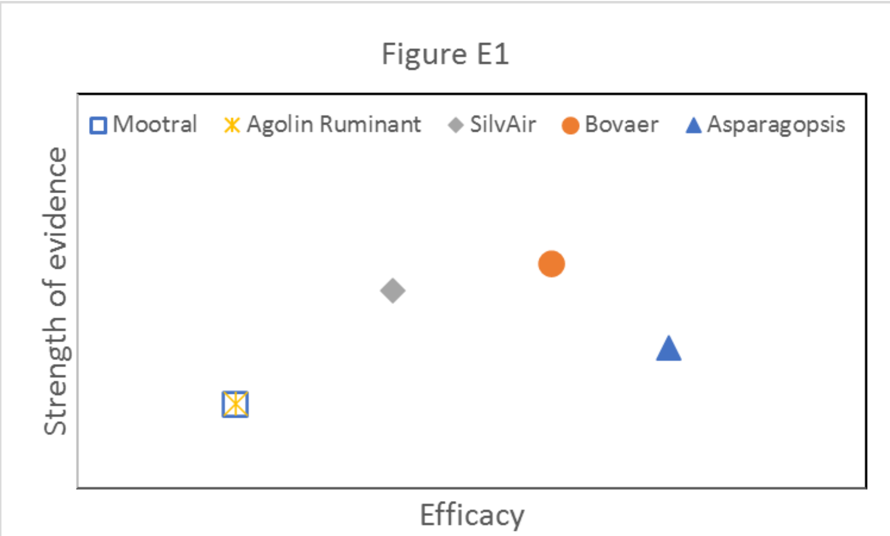
SilvAir: SilvAir is Cargill's trademark name for the inorganic salt calcium nitrate. Calcium nitrate is a Feed Material (a source of calcium and an alternative to urea as a source of non-protein nitrogen). There is extensive evidence for the efficacy of nitrate (specifically calcium nitrate) as a methane inhibitor (35 peer reviewed publications across dairy, beef and sheep) showing reductions in methane production of 10.9-22.1%. With carefully controlled administration (to avoid potential impacts of toxicity) this could be a viable option, although there may be issues with consumer acceptability. More information is required about the net GHG effects of the product.

Agolin Ruminant: Agolin Ruminant is a proprietary blend of essential oils, with the main active components being coriander seed oil, eugenol, geranyl acetate, and geraniol. These ingredients are currently approved as sensory Feed Additives in the EU and UK. Evidence on efficacy is limited to 3 short-term *in vivo* studies (beef and dairy) showing reductions in methane production of 9.1-9.8%. One study showed that the response of enteric methane to Agolin took several weeks to develop, perhaps reflecting slow changes to the rumen microbiome. More studies are required to verify the efficacy of Agolin Ruminant after longer-term adaptation periods.

Mootral: Mootral Ruminant is a pelleted feed containing a proprietary blend of garlic powder and citrus extract. Garlic contains several bioactive compounds, including alliin, diallyl sulfides, and allicin which have anti-microbial properties, and citrus extract contains flavonoids which may have methane reducing properties. Evidence on efficacy is limited to five published in vivo studies (beef, dairy and sheep) demonstrating reductions in methane production of 8.2-22.9%. The current claims of up to 38% reduction on efficacy are not adequately supported for any species or production system.

ZELP: ZELP is a wearable technology designed for cattle. The device fits to the animal's head with a "mask" sitting above the nostrils. The mask contains methane oxidising technology, converting methane to carbon dioxide, which has a lower GWP, as it is eructated from the animal. The device also contains sensors collecting data (activity, temperature, and rumination) which ZELP claims can detect heat, indicate animal production efficiency and welfare using machine learning algorithms. Currently there is insufficient evidence to encourage uptake of this technology, with no peer reviewed publications verifying its efficacy as a method for oxidising enteric methane emissions at the point of emission.. Concerns around the welfare impacts of wearing the device also need to be addressed.

Figure E1 below is a simple diagram showing the relative efficacy and strength of evidence supporting each feed additive



2. Regulatory Pathways and Requirements for Evidence

Methane mitigating feed supplements either are, or contain ingredients which are, classified as Feed Materials (e.g., nitrate, garlic, seaweed) or Feed Additives (3-NOP, essential oils).

Authorisation as a zootechnical Feed Additive to mitigate methane requires data from a minimum of three *in vivo* experiments. In principle, marketing claims for Feed Materials can be made with a lower level of proof.

In future, we think it likely that most emerging methane mitigating feed supplements will be regulated as Feed Additives (this may apply to *Asparagopsis*). Whether the current authorisation process for Feed Additives (inherited from EU law) best balances the risk of 'greenwashing' (allowing ineffective products to be placed on the market) with the risk of disincentivising product development (thereby foregoing real opportunities to reduce methane emissions) is debateable.

The regulatory framework relevant to Zelp, as a wearable device, is unclear.

3. Mechanisms to incentivise adoption

Until recently policy actions to reduce GHG emissions from agriculture have been based on voluntary actions and low-level subsidies for a limited set of farm practices. However, industry is becoming very active in this field, with various initiatives from food processors and retailers, either to improve their corporate social responsibility or even linking to financial rewards via the voluntary carbon markets.

The adoption of farm practices in general, and feed supplements in particular, can be incentivised via different interventions or schemes, either in government- or industry-led forms, and by voluntary or regulatory approaches. This study assessed four broad types of interventions: voluntary standards, product labelling, voluntary carbon markets and fiscal incentives. Regardless of the intervention chosen, the key characteristics of success are common: low cost, targeted environmental effect (with no "leakage" or rebound effect), equitability, flexibility, and enforceability. Similarly, many of the design, monitoring and verification aspects are shared between potential schemes. These include the need for trust, transparency, and scientific robustness in the schemes, but also practical aspects like verification that the targeted animals receive the supplement.

While every solution for incentivising adoption of feed supplements has its advantages and disadvantages, generally there is only limited increase in adoption with voluntary policies, unless a high compensation is available. Mandatory participation provides much wider effect but industry-wide buy-in needs to be built up in order to achieve high compliance. Voluntary schemes might also suffer of an erosion of trust unless they are built on transparent practical and scientific principles and are verified by third party organisations.

In the UK a plethora of agri-environmental instruments exists which could be extended to include methane-reducing feed supplements, in all four types of the instruments assessed in this report. Retailers and food processors could include the requirement to use feed supplements into their existing supplier sustainability criteria as part of their voluntary standard. Similarly, existing environmental labels could be used to inform consumers on the lower GHG emissions achieved by the use of feed supplements, for example through the Carbon Trust certification scheme. Regarding voluntary carbon markets, some certification bodies have already developed methodologies for feed additives, and the financial resources available through voluntary markets started to reach the industry. Finally, enteric methane emissions have not been featured yet in the plans for the new agricultural support scheme in England and Wales, so there is a clear opportunity there for fiscal intervention.

1. Introduction

Climate change is the defining issue of our time. In response, the UK Government has set an ambitious target to achieve net-zero greenhouse gas (GHG) emissions by 2050 (Climate Change Act, 2008). There is now growing urgency for all sectors to reduce their GHG emissions to reach this target. Methane emissions have a high profile in political and public discourse – as demonstrated by more than 100 countries (including the UK) signing the Global Methane Pledge at COP26 in 2021, from consumers to food producers. Those signatories to the pledge agree to collectively reduce global methane emissions by 30% or more from 2020 to 2030 (https://www.globalmethanepledge.org/ accessed November 2022). In 2020, agriculture accounted for 11% of total UK GHG emissions, with 50% of that attributed to enteric methane (BEIS, 2022). The latest IPCC report (2021) indicated that methane is responsible for up to 50% of global temperature rise since pre-industrial times. Methane is a powerful (global warming potential (GWP) over 20 years for non-fossil fuel sources = 80.8), but short-lived gas (10-20 years), thus a focussed reduction of methane is considered one of the most important strategies to limit global warming to 1.5°C.

Feed supplements have been a focus of recent research for their potential to reduce the emissions intensity arising from the livestock industry by inhibiting methane production in the rumen and/or increasing the efficiency of feed conversion. Alongside dietary manipulation, technologies such as methane neutralising animal mounted devices are now being developed to destroy enteric methane shortly after its emission and before it has an impact on the atmosphere. The scope of this report is limited to supplements and technologies that act directly (through a variety of mechanisms) to reduce absolute methane emissions (grams per animal per day). In principle, such products could be used at an industry scale either to maintain production of current quantities of milk and meat with less methane, or to produce more milk and meat at the current level of methane emission. Discussion of this societal choice is beyond the scope of this report.

Development, introduction, and uptake of novel technologies requires that many questions are answered. These answers are the evidence that guides decisions made by a range of stakeholders in the journey from an idea to impact. At each step, the evidence must be sufficient to allow decision makers to manage risks of two errors: Type I (concluding that something is effective when it is not) and Type II (concluding that something is ineffective when in fact it is).

The generalised format for the statement of an idea is 'Do X to achieve Y', where X is the proposed intervention and Y is the required outcome. Methane-mitigating feed supplements (a list of X) must 'work', although the meaning of 'work' is nuanced and changes as the development process proceeds. For example, initially the required outcome might be the demonstration of an effect, with quantification of the effect size addressed later in the development process.

'Might it work?' is a question asked at the beginning of the development process by the owner of the idea (likely to be a company or research organisation). For methane-mitigating feed supplements, this question could be answered through *in vitro* screening experiments looking simply for the existence of an effect. While *in vitro* rumen fermentation systems are a useful research tool, they do not perfectly reflect the *in vivo* situation, so testing a candidate supplement in animals will likely be the next step. Typically, such experiments will be of short duration, using sufficient replication and a reliable method to measure methane emissions. Even one such experiment, well designed and conducted, can answer the question 'Does it work?', where 'work' is defined as the existence of an effect (i.e., can prove the principle).

Establishing the magnitude of the effect, rather than simply the existence of the effect, matters to technology owners and their customers, since it will affect the benefit to cost ratio, and in the case of methane mitigation it matters to policy makers as it affects the overall 'size of the prize'. The magnitude of the effect can be determined through individual dose-response experiments or through meta-analysis of multiple experiments (when available) that evaluate different dose rates.

General effects cannot be inferred from the results of a single experiment. For methane mitigating feed supplements, there are good reasons to hypothesise interactions between the test product and the animal to which it is offered (where 'animal' encompasses species, breed, genotype within breed and aspects of phenotype such as stage of lactation). The response to the test product may depend on diet (partly mediated through dietary effects on the rumen microbiome) and on feeding system (e.g., the response at a herd level may not be the same if the product is offered within a total mixed ration or in a compound feed offered twice a day). There could also be interactions with time. Does the test product work immediately or work through a slow adaptation of the rumen microbiome? Does the effect of the product persist, or does the response decline over time?

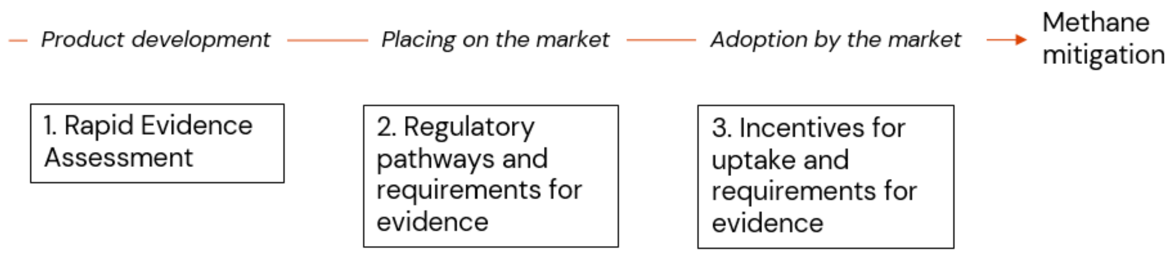
It is also important to explore potential interactions between different supplements. Depending on their mode of action, effects may be independent and additive, or additive A may interfere with the response to additive B, or the effect of both could be more than the sum of the responses to either. This question is of commercial interest to technology owners (who may also wish to benchmark against competitors) and to policy makers.

Evaluating these interactions (mapping the inference space) is a long process consuming of time and investment. Arguably, it never ends; for example, new research on well-established feed additives such as monensin or yeast cultures continues to be commissioned, conducted, and reported, even though these products have been in the market for decades, as companies seek to refresh and improve the technical propositions they make to customers and compete more effectively with their industry peers.

In this way, a 'pyramid of evidence' is built over time, as an idea is developed, placed on the market, and adopted into practice. For methane-mitigating feed supplements, multiple stakeholders have legitimate interests in constructing this pyramid as effectively and quickly as possible.

In this report (Figure 1), (i) we first review the scientific evidence for a defined range of close-to-market products (five feed supplements and one technology) in relation to the diverse farm circumstances in which they may be used.; (ii) We then evaluate the evidential requirements of relevant regulatory processes and assess the position of these products on their path to regulatory approval; and (iii) finally we consider the role of evidence in the various public and private mechanisms that are emerging to incentivise use of these products on farm.

Figure 1. Structure of report



2. Rapid Evidence Assessment

2.1 Introduction

This section presents a summary of the quality and extent of evidence for the efficacy of on or near-to-market feed additives (n=5) and technologies (n=1) used to suppress enteric methane emissions. Specifically, these products are *Asparagopsis*, Bovaer, SilvAir, Agolin Ruminant, Mootral Ruminant and the technological product ZELP. This builds directly on published work funded by DEFRA and undertaken by the authors of this report (Duthie et al., 2022).

2.2 Methodology

A rapid evidence assessment (REA) approach was used to assess the potential efficacy of the identified methane inhibiting feed supplements and technology, and any reported upstream or downstream emissions associated with product manufacture, transport, administration or waste management and utilisation. An REA is a structured approach to identifying, appraising, and summarising literature-based evidence to answer specific questions. The REAs were undertaken following the guidelines adopted by NERC (Collins et al., 2015). Specifically:

1. A literature search strategy was designed to ensure all relevant peer reviewed literature was identified. The strategy included key search words, terms, and combinations thereof for each inhibitor, and the publication databases to be searched (Scopus, Web of Knowledge, Google Scholar). The focus was on peer reviewed papers reporting methane emissions and published since 2010, with some older papers included where the authors had information recorded from previous REAs.
2. A set of criteria to critically appraise the relevancy and robustness of the identified literature. Critical evaluation of relevancy and robustness were used to judge the overall quality of each paper. Any paper judged to be irrelevant or falling below a minimum standard of robustness was excluded from the REA.
3. Synthesis of the available evidence from the screened literature. This has taken the form of short narrative summaries for each methane inhibitor, detailing efficacy, trade-offs, wider environmental impacts, suitability for

different production systems, and identification of gaps in the literature as appropriate.

In the following sections on each individual product, available data are presented as simple mean effects (% reductions) on methane production (gCH_4/d) and yield (gCH_4/kg DMI), along with mean standard errors and 95% confidence intervals. It should be noted that we have not conducted statistical meta-analyses and mean effects are not weighted according to the design and reported variation within each experiment. Wide confidence intervals may indicate heterogeneity in the response - i.e., the likelihood that the size of the response depends on factors such as basal diet, feeding system, length of feeding period, or animal breed or phenotype. These potential interactions could be identified and quantified through formal meta-analysis and meta-regression.

2.3 Results

2.3.1 Asparagopsis

Description: *Asparagopsis* is a genus of red macroalgae widely found in tropical to warm marine waters. It contains halogenated methane analogues with bioactive properties, the most abundant of which is bromoform ($CHBr_3$). Bromoform inhibits methane production by reacting with vitamin B_{12}, which inhibits the cobamide-dependent enzyme methyl-coenzyme (CoM) reductase step in methanogenesis.

Asparagopsis as a feed ingredient for livestock is patented by FutureFeed Pty Ltd (Newstead, Australia), who deliver supply chain access to *Asparagopsis* growers through licence agreements. Companies selling *Asparagopsis* as a feed additive without a licence could face legal action by FutureFeed. There are currently six licencees, three in Australia, two in the USA, and one in Sweden (Table 1), with most farming *Asparagopsis* at sea, but with two currently producing the seaweed in tanks on land. There are two *Asparagopsis* species, *A. taxiformis* and *A. armata*, that have been tested for enteric methane mitigation potential.

Table 1: Companies currently licenced (as of October 2022) to sell *Asparagopsis* as a feed ingredient for the purposes of enteric methane mitigation, the country where the *Asparagopsis* is produced, and the type of seaweed production (farmed at sea or grown in tanks on land).

Company	Country	Production
CH4 Global	Australia	Marine farming
SeaStock	Australia	Marine farming
Volta GreenTech	Sweden	Tank grown
Symbrosia	USA (Hawaii)	Marine farming
Blue Ocean Barns	USA (California)	Marine farming
Sea Forest	Australia	Marine farming and Tank grown

Claims about product efficacy: Claims on the FutureFeed website (future-feed.com, accessed 26th August 2022) state that "adding around 5g of *Asparagopsis* seaweed per kg of dry feed matter lowers methane emissions by over 80%." They do not state if this reduction is absolute (gCH_4 / day) or a reduction in yield (gCH_4 / kg feed input or product output).

Evidence base and transparency: Only four *in vivo* studies measuring the reduction in enteric methane emissions after supplementation with *A. taxiformis* (dairy: n=2, beef: n=1, sheep: n=1), and one using *A. armata* had been published in peer reviewed journals by end August 2022 (Table 2). All *in vivo* papers except one (Stefanoni et al., 2021) are detailed on the FutureFeed website. The results in Stefanoni et al. (2021) may be considered the least favourable (no reduction at 0.25% inclusion, and a 34% reduction at 0.5% inclusion).

Efficacy and rigour: Table 2 shows simple mean percentage reductions in methane emissions for *in vivo* studies on dairy, beef, and sheep. One study on dairy cows (Kinley et al., 2020) only reported data on methane yield (gCH_4/kg DMI) and not absolute methane emissions. A simple average across all studies suggests a 52.6% reduction in methane production, with all studies demonstrating a statistically significant reduction of methane emissions for at least one dosage level. One study (Roque et al. ,2021) found reductions in methane production of >80% with a dosage level of 5 g/kg feed organic matter on both high concentrate and mixed concentrate/forage diets. A further study (Li et al., 2018) found a methane reduction of >80% in sheep but at a dosage of 3% organic matter.

All *in vivo* studies were undertaken in intensive systems. Dairy studies were undertaken in free stall or tie stall barns, the sheep study was on slatted floor pens, and the beef studies were on feedlots. There are only two dairy and one beef study where high forage diets are offered (<400g concentrate per kg dry matter feed).

Table 2: Summary of *in vivo* studies testing the efficacy of *Asparagopsis* in reducing methane production (gCH_4/day) and yield (gCH_4/kg DMI)

Species	Metric	No. papers	No. data points	Mean % reduction (Standard error)	95% CI (±)	References
Dairy	gCH_4/day	2	4	-34.5 (14.9)	29.2	Roque et al. (2019); Stefanoni et al. (2021)
	gCH_4/kg DMI	2	4	-22.2 (9.7)	19.1	Roque et al. (2019); Stefanoni et al. (2021)
Beef	gCH_4/day	1	6	-64.6 (7.9)	15.4	Roque et al. (2021)
	gCH_4/kg DMI	2	9	-56.0 (9.4)	18.3	Kinley et al. (2020); Roque et al. (2021)
Sheep	gCH_4/day	1	4	-52.6 (13.9)	27.3	Li et al. (2018)
	gCH_4/kg DMI	1	4	-53.0 (13.8)	27.0	Li et al. (2018)

A recent meta-analysis of the three published studies supplementing dairy and beef cattle with *A. taxiformis* (Lean et al., 2021) indicated a "substantial reduction in methane yields" based on "very limited data". The meta-analysis found a weighted average reduction in methane yield of 5 g/kg dry matter intake. However, a large proportion (84%) of variation in methane reduction between studies was unexplained by the analysis. This may be partly due to the low number of studies in the meta-analysis.

Health and welfare implications: Duthie et al. (2022) reviewed the health and welfare implications of feeding seaweed to ruminants:

"*Seaweeds are nutrient rich foods, including iodine and heavy metals, e.g., arsenic, mercury, lead, aluminium, cadmium, rubidium, silicon, strontium and tin (Morais et al., 2020). Although these micronutrients are generally not at levels high enough to cause toxicity, bioaccumulation of arsenic, lead (Morais et al., 2020) and iodine (Makkar et al., 2016) can occur and this level will vary dependent on the type, species, and environmental conditions the seaweed was produced under (Roleda et al., 2018). Publications have concentrated on transfer of iodine from the animal to products for human consumption (particularly milk, e.g., Antaya et al., 2019). However, concentrations of minerals and heavy metals can reach levels where they become limiting – for example, iodine concentrations may reach levels where you could not feed enough seaweed to meet the methane reduction potential without causing iodine toxicity (nasal and lacrimal discharge, coughing, pneumonia, and skin irritation, Hillman and Curtis, 1979). More research into the conditions leading to high levels of trace nutrients is needed and great care must be taken that levels of minerals and heavy metals in the total ration do not breach regulatory limits or exceed recommended levels.*

In addition, a recent publication from The Netherlands (Muizelaar et al., 2021) has questioned the safety of bromoform for the animal. They examined the organs of two dairy cows slaughtered after receiving 67g A. taxiformis per day for 22 days and found inflammation of the rumen wall and loss of papillae. They also detected Bromoform in milk, but this was not consistently across the experimental period."

Practical implementation: *Asparagopsis* sources used in efficacy experiments have been simple preparations (dried and ground meal) that could be used directly on farm or incorporated into a range of feed products (including pelleted compound feeds). 'Seaweed' is an approved Feed Material so there is no direct regulatory barrier to its use. An indicative dosage level is ~100 g/head/day (estimate for a dairy cow consuming 22 kg dry matter per day), however this could be constrained by maximum limits on iodine intake, and the overriding obligation on the feed industry to supply safe feed. Use in grazing animals would be difficult as the dosage level is too high for slow-release boluses, but incorporation into a mineral lick may be possible, although intake would vary widely between animals, and associated risks of uncontrolled consumption would need to be considered (e.g., potential toxicity due to over-consumption of trace minerals and heavy metals).

Scaling up: There are two main barriers to scaling up. The first is the low number of *in vivo* studies and the large and unexplained heterogeneity in methane response. This suggests that more *in vivo* studies covering a wider variety of diets, production systems and longer time scales are needed to strengthen the evidence base. The second barrier relates to supply of a consistent product. Sweden based company Volta Greentech (https://www.voltagreentech.com) is developing land based *Asparagopsis* cultivation factories to meet the increasing global demand for *Asparagopsis*. Growing seaweed in an automated, controlled environment would ensure that the seaweed is grown at optimal conditions to maximise yield and regulate concentrations of bioactive compounds and potentially toxic nutrients. A project report on the Volta Greentech website details a (not peer reviewed) study testing the efficacy of factory grown *Asparagopsis* on a commercial beef farm in Sweden. The report claims an 81% reduction in enteric methane (g/head/day) compared to baseline emissions prior to introducing 6g *Asparagopsis* / kg of feed dry matter into the diet.

Wider environmental impacts: Duthie et al. (2022) reviewed the evidence of wider environmental impacts:

"Short-lived biogenic bromine-containing compounds, such as bromoform and bromochloromethane, emitted from seaweeds can cause ozone depletion (Wisher et al., 2014). The loss of ozone in the atmosphere leads to an increase in UVB rays reaching the Earth's surface which is harmful to human, animal, and plant health. Increased farming of seaweed, particularly red species rich in bromine-containing compounds such as A. taxiformis, could lead to increased emissions of bromocarbons. Estimates ranging from a 6 to 11 times

increases in bromocarbon emissions from Malaysian red seaweed farms have been projected with increasing production (Leedham et al., 2013). However, a paper currently in review concludes that Asparagopsis farming in Australia, at a scale sufficient to provide supplement for 50% of Australian cattle, would have an insignificant effect on atmospheric ozone (Jia et al., 2021). More research is required to gain consensus."

Asparagopsis is highly invasive, and when introduced it can spread rapidly over a wide area outcompeting native seaweed species and reducing habitat biodiversity (Navarro-Barranco et al., 2018; Mancuso et al., 2021; Silva et al., 2021). This can have an impact on ecosystem function and services. The economic impacts are not well documented, but there are costs associated with control programmes, and some impact on the local aquaculture economy may be expected (e.g., fisheries).

RAG for the sector: There is some limited evidence in the published literature to support the claim that *Asparagopsis* can reduce methane emissions by >80%. However, further evidence is required to understand variation in efficacy and to give confidence in its efficacy across species, production systems and diet types. In particular, there is a lack of evidence on high forage feeding and grazing systems. Not near scale but may be viable in the future when a consistent product can be supplied (e.g., through efficient production in controlled tank environments).

2.3.2 Bovaer

Description: Bovaer is DSM's trademark name for 3-nitrooxypropanol (3-NOP) which is a small synthetic molecule which inhibits the final step in the production of methane by microbes in the rumen. Like Asparagopsis, it does this by inhibiting the enzyme methyl-coenzyme M reductase which catalyses the production of methane by archaea (Duin et al., 2016).

Claims about product efficacy: DSM claims on their website (https://www.dsm.com/corporate/sustainability/our-purpose/minimizing-methane-from-cattle.html - accessed 9th September 2022) "just a quarter teaspoon of Bovaer® per cow per day suppresses the enzyme that triggers methane production in a cow's rumen and consistently reduces enteric methane emissions by approximately 30% for dairy cows and even higher percentages (up to 90%) for beef cows." A video on the same site mentions that there have been 42 trials, with methane reductions of up to 82%.

Evidence base and transparency: Thirty-three *in vivo* studies testing the efficacy of 3-NOP in reducing enteric methane had been published by end August 2022. All of these studies are listed on the DSM website. It is assumed that the 42 studies mentioned in the video on the website includes *in vitro* studies although this is not clear.

Efficacy and rigour: The simple averages shown in Table 3 are in general agreement with the claim that 3-NOP can reduce enteric methane emissions by around 30%. Two *in vivo* studies showed exceptionally high mitigation (Vyas et al., 2016, >80%; Alemu et al., 2021, >75%). All studies were undertaken in intensive systems (tie stall, free stall, or feedlot). There are eleven beef studies and nine dairy studies where high forage diets were offered, all of which showed significant reductions in methane production (gCH_4/day) on at least one dosage level. One beef study offered a hay only diet (Rhodes grass hay) and reported a ~30% reduction in methane production (Martinez Fernandez et al., 2018).

There have been several reviews and meta-analyses relating to the efficacy of 3-NOP as a methane mitigating feed additive. All agree that 3-NOP supplementation results in a linear decrease in methane emissions with increasing dose. A meta-analysis by Djikstra et al. (2018), which includes 11 *in vivo* studies on beef and dairy cattle found a 22% reduction in methane emissions from beef cattle, and 39% reduction from dairy cattle. However, this was affected by dose and diet chemical composition. The meta-analysis conducted by Kim et al. (2020), based on 14 publications found that dairy cattle responded more strongly to dosage level than beef cattle, and so optimum dose may vary by cattle type.

Table 3: Summary of *in vivo* studies testing the efficacy of Bovaer in reducing methane production (gCH_4/day) and yield (gCH_4/kg DMI)

Species	Metric	No. papers	No. data points	Mean % reduction (Standard error)	95% CI (±)	References
Dairy	gCH_4/day	11	22	-24.8 (2.0)	3.9	Reynolds et al. (2014); Hristov et al. 2015; Lopes et al. (2016); van Wesemael et al. (2019); Melgar et al. (2020); van Gastelan et al. (2020); Hristov et al. (2020); Meale et al. (2021); Melgar et al. (2021)
	gCH_4/kg DMI	11	21	-25.6 (2.5)	5.0	Haisan et al. (2014); Reynolds et al. (2014); Hristov et al. 2015; Lopes et al. (2016); van Wesemael et al. (2019); Melgar et al. (2020); van Gastelan et al. (2020); Hristov et al. (2020); Schilde et al. (2021); Melgar et al. (2021)
Beef	gCH_4/day	9	29	-31.9 (4.0)	8.8	Vyas et al. (2016); Martinez Fernandez et al. (2018); Vyas et al. (2018a); Vyas et al. (2018b); Kim et al. (2019); de Araujo et al. (2020); Zhang et al. (2021); Alemu et al. (2021a); Alemu et al. (2021b)
	gCH_4/kg DMI	11	34	-26.6 (4.0)	7.9	Romero Perez et al. (2014); Romero Perez et al. (2015); Vyas et al. (2016); Martinez Fernandez et al. (2018); Vyas et al. (2018a); Vyas et al. (2018b); Kim et al. (2019); de Araujo et al. (2020); Zhang et al. (2021); Alemu et al. (2021a); Alemu et al. (2021b)
Sheep	gCH_4/day	1	4	-33.2 (12.7)	24.9	Martinez Fernandez et al. (2014)
	gCH_4/kg DMI	1	4	-33.8 (6.7)	13.1	Martinez Fernandez et al. (2014)

Health and welfare implications: None identified. 3-NOP has been shown to be non-mutagenic and non-genotoxic (Thiel et al., 2019) and these data are included in the EFSA dossier for this product.

Practical implementation: The median dose in studies reported was 106 mg/kg diet DM. Therefore, the product could be supplied as a premix for incorporation into diets on farm. The daily dose is small enough that it may be practical to administer the compound as a bolus into the rumen to release 3-NOP over an extended period and therefore compatible with the grazing situation. Current view of the manufacturers is that optimum dose rates will be 60 – 100mg / kg feed for dairy cows and 100 – 200 mg / kg feed for beef cattle. The authorised range in diets for dairy animals in the EU is 53-80 mg 3-NOP / kg complete feed (EC Regulation 2022/565). At 10% 3-NOP in the product Bovaer, this equates to a permitted feeding rate of Bovaer of 0.6-0.9 g Bovaer/kg DM or, 13-20g Bovaer/day at an average dry matter intake of a dairy cow of 22kg/day.

The method of administration is critical, and they currently recommend dosing of a TMR to ensure coupling of feed intake to intake of methane inhibitor. The proposed use within a granular premix will also allow access to many beef cattle and sheep, for example by top-dressing the premix on forage or other feeds provided in a feed trough. It is likely that future presentations will include incorporation in 'lick products' (blocks and buckets) currently used to deliver energy (e.g., from molasses or fat), protein and vitamins and minerals. Other presentations, including a slow-release bolus for grazing ruminants, are known to be in development. Such future presentations will make it easier to access more extensive cattle and sheep production systems.

According to the public summary of the technical dossier submitted to EFSA, no incompatibilities with other feed materials or feed additives have been identified.

Scaling up: Bovaer is designed primarily as an ingredient of total or partial mixed rations for dairy cows. It has received authorisation in the EU as a 'zootechnical Feed Additive with a favourable effect on the environment'. Technical dossiers supporting authorisation for beef cattle and other ruminants are understood to be in preparation. With support from Scottish Enterprise, DSM are constructing a Bovaer manufacturing plant in Scotland to scale up production for the European market (announced at COP26, with full production expected in 2025).

Wider environmental impacts: Duthie et al. (2022) reviewed the evidence of wider environmental impacts:

"Alvarez-Hess et al., (2019) detail a partial life cycle assessment (LCA) of 3-NOP on GHG emissions from average beef and dairy farms in Canada and Australia (Alvarez-Hess et al., 2019). The effect of 3-NOP on GHG emissions were modelled

over their productive lifespan. The boundary of the partial LCA was defined as the farm gate, including emissions associated with on-farm activities and production and transport of major production inputs. This modelling exercise assumes that there is no change in on-farm N_2O or CO_2 emissions and base these reductions on reductions in enteric methane reduction and increases in pre-farm emissions e.g., increasing inputs depending on what portion of the herd is receiving the additive (young stock, breeding stock, lactating cows or entire herd)."

There is, however, conflicting evidence on the effect of 3-NOP on GHG emissions from manures. Nikema et al. (2019) found a significant reduction in methane emissions (9.6% reduction compared to control, $p<0.05$) from the faeces of finishing beef heifers, but not in growing heifers. Owens et al. (2020) found no reduction in GHG or ammonia emissions from stored manure from growing beef cattle, and Weber et al. (2021) found that the effect on total GHG emissions was dependant on the soil type, either resulting in no change or a significant increase. One study has found no effect on soil chemical health indicators or soil physical and hydraulic properties (Owens et al., 2021).

RAG for the sector. Bovaer is authorised as a zootechnical Feed Additive for lactating ruminants in the EU, with approval for GB pending and a dossier for growing ruminants in preparation for both the EU and GB. A slow-release presentation suitable for use with grazing animals is in development. Large scale pilot trials with dairy cows are in progress in the Netherlands (20,000 cows on 150 farms, with feed company Agrifirm and dairy company Friesland Campina), and somewhat smaller implementations in Belgium (with Danone, to reduce the carbon footprint of Actimel drinking yoghurt) and Finland (Valio) (source: N. Walker, DSM, pers. comm., 'Bovaer pilot: CO2 reduction revenue model', article in Dairy Global online magazine, 4Nov22). Bovaer was authorised for use in dairy and beef cattle (and sheep and goats) in Brazil and Chile in September 2021. Bovaer is approved in Australia (where one of the first implementations will be by the North Australian Pastoral Company, one of Australia's largest beef producers). DSM have entered into an exclusive agreement with Elanco, who will manage the approval process in the USA and then market the product. A manufacturing line is being installed at an existing DSM facility in Dalry, Scotland (work is due to commence November 2022, with Bovaer production likely from 2025) and the product will be incorporated into premixes for the feed industry at DSM's mill in Heanor, Derbyshire. There is a large body of evidence substantially supporting claims made about the efficacy of this product for dairy cows, although claims of >90% reduction in beef cows are not substantially supported.

2.3.3 SilvAir

Description: SilvAir is Cargill's trademark name for the inorganic salt calcium nitrate. Calcium nitrate is a Feed Material (a source of calcium and an alternative to urea as a source of non-protein nitrogen).

Claims about product efficacy: There is little information about the SilvAir product. The product is not promoted on the Cargill website and no claims about the efficacy of the product were available.

Evidence base and transparency: This assessment of the evidence base only includes papers that allow identification of the nitrate form used as calcium nitrate, other forms were not considered. A total of 35 papers were identified.

Efficacy and rigour: There is a substantial evidence base supporting the efficacy of calcium nitrate for methane reduction. Simple averages (Table 4) show the range of absolute methane reduction (gCH_4 / day) from 10.9±2.6 for beef cattle and 22.1 ± 2.5 for dairy cattle. Most studies were undertaken in housed or feedlot systems, except for one beef and one dairy study which are on grazing systems using the sulphur hexafluoride (SF_6) technique.

Seven beef, four dairy, and four sheep studies offered high forage diets (<400g concentrate / kg feed dry matter), with one beef and two sheep studies offered a forage only diet. The beef forage only study, and one of the sheep forage only studies did not find a significant reduction in methane emissions, although the other sheep study did find a 19% reduction in methane production (De Raphaelis-Soissan et al., 2014) it had a substantially higher dosage.

Table 4: Summary of *in vivo* studies testing the efficacy of calcium nitrate in reducing methane production (gCH_4/day) and yield (gCH_4/kg DMI)

Species	Metric	No. papers	No. data points	Mean % reduction (Standard error)	95% CI (±)	References
Dairy	gCH_4/day	11	22	-22.1 (2.5)	4.9	van Zijderveld et al. (2011); Guyader et al. (2015a,b); Veneman et al. (2015); Klop; et al. (2016); Olijhoek et al. (2016); Guyader et al. (2016); van Wyngaard et al. (2018); Meller et al. (2019); Ortiz-Chura et al. (2021); Lund et al. (2014)
	gCH_4/kg DMI	13	27	-18.3 (1.5)	2.9	van Zijderveld et al. (2011); Newbold et al. (2014); Guyader et al. (2015a); Guyader et al. (2015b); Veneman et al. (2015); Klop; et al. (2016); Olijhoek et al. (2016); Guyader et al. (2016); van Wyngaard et al. (2018); Meller et al. (2019); van Wyngaard et al. (2019); Ortiz-Chura et al. (2021)
Beef	gCH_4/day	17	26	-10.9 (2.6)	5.1	Velazco et al. (2014); Lee et al. (2015); Troy et al. (2015); Pesta et al. (2016); Lee et al. (2017); Sun et al. (2017); Popova et al. (2017); Duthie et al. (2018); Tomkins et al. (2018); Doreau et al. (2018); Granja-Salcedo et al. (2019); Alemu et al. (2019); Rebelo et al. (2019); Villar et al. (2020); Callaghan et al. (2020); Henry et al. (2020)
	gCH_4/kg DMI	18	28	-7.0 (2.4)	4.8	Hulshof et al. (2012); Velazco et al. (2014); Lee et al. (2015); Troy et al. (2015); Rooke et al. (2016); Pesta et al. (2016); Lee et al. (2017); Sun et al. (2017); Popova et al. (2017); Duthie et al. (2018); Tomkins et al. (2018); Doreau et al. (2018); Granja-Salcedo et al. (2019); Alemu et al. (2019); Rebelo et al. (2019); Villar et al. (2020); Henry et al. (2020)
Sheep	gCH_4/day	1	1	-14.6	-	Villar et al. (2020)
	gCH_4/kg DMI	1	1	-26.0	-	Villar et al. (2020)

Health and welfare implications: Duthie et al. (2022) outlined the health and welfare implications of nitrate supplementation:

"Nitrite, an intermediate product in the reduction of nitrate to ammonia can accumulate in the rumen because the rate of nitrate reduction is faster than that of nitrite reduction. The nitrite is then absorbed into the bloodstream and converts haemoglobin to met-haemoglobin (Met-Hb). Met-Hb cannot transport oxygen and thus acute symptoms of nitrate toxicity are anoxia leading to death. Subacute or chronic effects are reported to include retarded growth, lowered milk production and increased susceptibility to infection. Most studies have reported no adverse effects of feeding nitrate although individual animals display elevated (but sub-toxic) concentrations of Met-Hb. In experience from SRUC research, these elevated Met-Hb concentrations were animal-specific and persisted for at least 10 weeks."

Practical implementation: Duthie et al. (2022) outlined the practical issues with implementing the use of nitrate as a methane inhibitor:

"Importantly, there is no standard protocol for adapting animals to nitrate. Nitrate must be thoroughly mixed and diluted by other feed constituents. This is probably best achieved using total mixed rations or by inclusion of nitrate in pelleted compound feeds. The risks associated with (a) inadvertent inclusion of excess nitrate in feeds and (b) access of unadapted animals to nitrate-containing feed are high. Nitrate has been ineffective when included in intensive (high concentrate) finishing beef diets and should not be used this situation."

The form of nitrate used in studies supported by Cargill and Provimi (the latter acquired by the former in 2011) was specifically 'calcium nitrate double salt', $5Ca(NO_3)2.NH_4NO_3.10H_2O$. This was a very deliberate choice, as this form carries no risk of use to make explosives (unlike ammonium nitrate) and is subject to fewer regulations on storage and transport.

SilvAir is being developed for use in compound feeds to minimise the risk of over consumption by animals. Dosage levels are too high for slow-release rumen boluses, or mineral licks which limits its applicability for grazing systems.

Scaling up: Calcium nitrate double salt is a feed material, supplying calcium and non-protein nitrogen. Sales of the branded product SilvAir may begin (probably initially in NL and BE) in late 2022.

Wider environmental impacts: Duthie et al. (2022) outlined the environmental impacts of the use of nitrate as a methane inhibitor:

"Concerns are that nitrate be excreted in urine and potentially contribute to nitrous oxide production from manure. In studies where nitrogen excretion has been measured there is no evidence for excretion of significant quantities of nitrate or overall increases in nitrogen excretion. However, as the reduction of nitrate to ammonia is a component of both the dissimilatory and assimilatory routes of nitrate metabolism, then nitrogen gas and nitrous oxide are possible products of nitrate reduction in the rumen."

Nitrous oxide production has been rarely measured but one study in which nitrate was fed to sheep the effective methane reduction after nitrate supplementation was reduced by 18% when increases in nitrous oxide emissions were accounted for (Raphélis-Soissan et al., 2014).

RAG for the sector: There is extensive evidence for the efficacy of nitrate as a methane inhibitor. More information about the recommended dosage level and efficacy of the SilvAir product specifically are required. With carefully controlled administration this could be a viable option, although there may be issues with consumer acceptability (Duthie et al., 2022). More information is required about potential increases in nitrous oxide emissions.

2.3.4 Agolin Ruminant

Description: Agolin Ruminant is a proprietary blend of essential oils, with the main active components being coriander seed oil, eugenol, geranyl acetate, and geraniol. These ingredients are currently approved as sensory Feed Additives in the EU and UK.

Claims about product efficacy: No specific claims about methane reduction are made on the company website. However, they do state "…the product technology ensures……delivery of key benefits to ruminants. A 2020 published meta-analysis, conducted by The Spanish National Research Council (CSIC) confirms these benefits." They then link to the meta-analysis of Belanche et al. (2020), which found consistent effects of Agolin Ruminant (8.8% reduction in methane production per day), but only after "long-term treatment". This means that studies which base results on methane measurements taken without at least four weeks of adaptation to the additive have inconsistent results. Belanche et al. (2020) also state "these findings should be cautiously interpreted given the relatively low number of studies (four studies published in three papers) included in the meta-analysis which reported CH_4 emissions and the inherent differences across the measuring methods"

Certification for methane reduction in ruminants with the Carbon Trust is highlighted on the website, although the certificate expired in July 2022 (Carbon Trust certificates are of limited duration). The Agolin Ruminant product information sheet does not claim methane reduction, but that it "helps to optimise feed intake." Website accessed 5th September 2022.

Evidence base and transparency: There are three *in* vivo papers published before the end of August 2022. All publications are listed on the Agolin website.

Efficacy and rigour: There is a lack of evidence on the efficacy of Agolin Ruminant for reduction of methane production. There has been a focus on dairy animals, and the simple averages shown in Table 5 are slightly more optimistic than the 8.8% reduction in methane production suggested by the Belanche et al. (2020) meta-analysis.

All studies were undertaken under housed conditions, although three of the four studies offered high forage diets (<200g/kg concentrate). Interestingly, only one study found a significant reduction in methane production (Hart et al., 2019), but it also reported the lowest percentage reduction (6.1%). Hart et al. (2019) showed that the response of enteric methane to Agolin took several weeks to develop, perhaps reflecting slow changes to the rumen microbiome. This supports the suggestion that short-term experiments (e.g., 21 or 28d periods in Latin Square designs) may not fully reflect the response to the product.

Table 5: Summary of *in vivo* studies testing the efficacy of Agolin Ruminant in reducing methane production (gCH_4/day) and yield (gCH_4/kg DMI)

Species	Metric	No. papers	No. data points	Mean % reduction (Standard error)	95% CI (±)	References
Dairy	gCH_4/day	3	3	-9.1 (2.9)	5.6	Castro Montoya et al. (2015); Hart et al. 2019; Carrazco et al. 2020
	gCH_4/kg DMI	3	3	-16.5 (6.1)	12.0	Castro Montoya et al. (2015); Hart et al. 2019; Carrazco et al. 2020
Beef	gCH_4/day	1	1	-9.9	-	Castro Montoya et al. (2015)
	gCH_4/kg DMI	1	1	-10.5	-	Castro Montoya et al. (2015)

Health and welfare implications: None. Agolin state that feed intake may be affected when consumed at three times the recommended inclusion rate, and that accidental access by non-target animals presents no particular risk.

Practical implementation – scaling up: Agolin Ruminant is already commercially available in the UK under a different brand name. The UK distributor considers the fact that their product is a re-brand of the product to be confidential. We have no information on the security of supply of the ingredients of the product, or prospects for scaling-up should demand for the product increase.

Agolin specify that the product (supplied as a powder or liquid) “should be incorporated into premixes or concentrates prior to mixing in feed in order to ensure a homogenous distribution”. The UK distributor incorporates Agolin Ruminant into mineral supplement packs. The high dosage requirement means that it is not suitable for slow-release boluses or mineral licks, limiting its usage in grazing systems and the volatile nature of the essential oil ingredients will likely limit the range of feed products into which it can be incorporated.

Wider environmental impacts: Not known

RAG for the sector: Evidence on efficacy is very limited, more *in vivo* studies, and in particular, more studies to verify the efficacy of Agolin Ruminant after longer-term adaptation periods are required.

2.3.5 Mootral Ruminant

Description: Mootral Ruminant is a pelleted feed containing a proprietary blend of garlic powder and citrus extract. Garlic contains several bioactive compounds, including alliin, diallyl sulfides, and allicin which have anti-microbial properties, and citrus extract contains flavonoids which may have methane reducing properties.

Claims about product efficacy: It is claimed on the Mootral website (https://mootral.com/about/, accessed 2nd September 2022) that Mootral Ruminant "shows up to 38% reduction* of enteric methane emissions under real farm conditions (in vivo)." As a footnote they clarify that this is "dependant on animal breed, age, farm conditions and feed regime." It is also claimed that "Mootral Ruminant can also help increase yields, animal health and reduce the number of flies".

Evidence base and transparency: Five *in vivo* studies testing the efficacy of Mootral Ruminant had been published in peer reviewed journals by 31st August 2022 (dairy: 2, beef: 2, and sheep: 1), the results are summarised in Table 6. All published studies are highlighted on the Mootral website along with key results.

Efficacy and rigour: There is a lack of evidence on the efficacy of Mootral Ruminant for the reduction of methane production. The simple averages shown in Table 6 do not support the claims of up to 38% reduction. This value appears to have come from one study in dairy cows (Vrancken et al., 2019) conducted using the Laser Methane Detector (LMD) method. This handheld device is used to obtain point measurements of the concentration of methane in cattle breath (in ppm). Methane production (g/d) and yield (g/kg DMI) were not measured by Vrancken et al. (2019). This study is not included in Table 6 because the LMD method is not considered to be an accurate measurement of methane emission. It uses low frequency, short term (minutes) measurements, which do not take the size of the breath 'cloud' into consideration.

Three studies (one beef, one dairy, and one sheep) did find significant reductions in methane production on at least one dosage level. One further study (Roque et al. (2019) found a reduction in methane yield (production not reported). All studies (including Vrancken et al., 2019) were undertaken under housed conditions, with only one study on beef cattle offering a high forage diet (others are mixed or high concentrate).

Table 6: Summary of *in vivo* studies testing the efficacy of Mootral Ruminant in reducing methane production (gCH_4/day) and yield (gCH_4/kg DMI)

Species	Metric	No. papers	No. data points	Mean % reduction (Standard error)	95% CI (±)	References
Dairy	gCH_4/day	1	1	-22.9	-	Brand et al. (2021)
	gCH_4/kg DMI	1	1	-23.8	-	Brand et al. (2021)
Beef	gCH_4/day	1	4	-12.2 (6.2)	12.2	Bitsie et al. (2022)
	gCH_4/kg DMI	2	5	-7.0 (7.6)	16.8	Roque et al. (2019); Bitsie et al. (2022)
Sheep	gCH_4/day	1	3	-8.2 (1.1)	2.2	Ahmed et al. (2021)
	gCH_4/kg DMI	1	3	-8.7 (1.6)	3.2	Ahmed et al. (2021)

Health and welfare implications: None.

Practical implementation – scaling up: Mootral has a Verra-certified project – the 'UK CowCredit Project' - to generate verified carbon credits which can be sold as emissions off-sets. This is currently limited to a small number of dairy farms. The project aims to off-set an estimated annual average of 187,563 tonnes of carbon dioxide equivalent (tCO2e) over the initial seven-year period. We have no information on the company's ability to scale-up production should demand for Mootral increase.

Mootral Ruminant is currently only available in a pelleted feed. The volatile nature of the essential oil ingredients will likely limit the range of feed products into which it can be incorporated.

Wider environmental impacts: Not known.

RAG for the sector: Evidence on efficacy is very limited, more *in vivo* studies are required. The current claims on efficacy are not adequately supported for any species or production system.

2.3.6 ZELP

Description: ZELP is a wearable technology designed for cattle. The device fits to the animal's head with a "mask" sitting above the nostrils. The mask contains methane oxidising technology, converting methane to carbon dioxide, which has a much lower GWP (enteric methane has a GWP of 80.8, carbon dioxide has a GWP of 1), as it is eructed from the animal. The device also contains 'sensors' (which are not defined) collecting data (activity, temperature, and rumination) which ZELP claims can detect heat, indicate animal production efficiency and welfare using machine learning algorithms. The device can be used after weaning from 6-8 months and for the duration of the animal's life.

Claims about product efficacy: No claims about the efficacy of enteric methane oxidation are made on the ZELP website (accessed 29th August 2022). A press release dated July 2021 is reported to state: 'the technology has already demonstrated a 53% reduction in methane emissions' (Cargill and ZELP align to tackle methane emissions in the dairy industry (feednavigator.com)).

Evidence base and transparency: As of 25th August 2022, there were no peer reviewed publications verifying the efficacy of ZELP as a method for oxidising enteric methane emissions at the point of emission. The ZELP website states multiple *in vivo* trials have been undertaken but no citations or reports of results are provided.

Efficacy and rigour: No peer reviewed journal papers have been published. However, ZELP received EU funding through Horizon2020 and a report on the project on the funder website state "The preliminary tests show an average 26.5 % reduction in methane emissions by animals wearing the device, with a maximum reduction achieved of 32 %".

Health and welfare implications: No evidence specifically related to ZELP is currently accessible. There may be negative implications (shared with neck-borne wearable devices) for feeding and social behaviours, but also positive implications associated with increased and automated monitoring of individual animals. From the ZELP website: 'We track activity, temperature, rumination and feed to identify potential signals of disease…'.

Practical implementation – scaling up: The devices are available on a subscription-based model. They can be funded by corporations or farmers, with the funder receiving the generated carbon credits which can be sold or used for internal emissions off-setting. ZELP are currently developing VERRA and Gold Standard methodologies for carbon credit verification and hope to have these in place by mid-2023 (ZELP, pers. comm.). In return, farmers receive the activity, production efficiency and methane emission data generated by the device. ZELP claim the devices can be used continuously for up to four years with little to no maintenance requirements.

Wider environmental impacts: Not known.

RAG for the sector: Currently there is insufficient available evidence to encourage uptake of this technology. Concerns around the welfare impacts of wearing the device also need to be addressed. If evidence emerges supporting the efficacy of this technology (without impacting on behaviour and welfare) this could be used on any animal generating methane - grazed or housed.

2.4 General conclusions from the REA

The evidence base supporting efficacy of the products considered in this report vary widely, most have concentrated on housed dairy systems (reflecting the initial targeting of this market). There is a general lack of evidence supporting their use on grazing systems. There are two main reasons for this:

1. Difficulty in accurately measuring enteric methane emissions in extensive systems. Many proxy methods which can be used at grazing lack accuracy or rely on "bribing" animals with concentrate feed into measurement stations several times per day over extended periods of time.
2. Difficulty in administering additives at correct dosages to animals in grazing systems e.g., due to high dosage requirements or an inability to ensure all animals receive an adequate dose.

There is also a lack of information on the net GHG impacts across the full lifecycle of these products. This would include all emissions associated with extraction of plant-based compounds, synthesis of chemical additive, manufacture of the additive, emissions directly from the animal, and from their wastes, including increased emissions from soils after application of manures. These should be weighed against potential enteric methane emission reductions to understand if there is a real environmental benefit. The Food and Agriculture Organization of the United Nations Livestock Environmental Assessment and Performance (LEAP) Partnership published guidelines on how to assess the environmental footprint of feed additives (FAO, 2020). Equally there is a general lack of information on wider (non-GHG) related environmental impacts (e.g., impacts on soil microbial communities after deposition of wastes).

In general, feed additives are easier to use in animals housed and fed prepared diets: the big challenge is to access extensively grazed livestock, where supplementation is minimal or non-existent and where emissions intensity is likely to be high.

3. Regulatory Pathways to Market

The regulatory pathway for methane-mitigating animal feeds depends on their legal classification. The phrase 'feed supplements' is used here as a general term including Feed Materials (as defined by EC Regulation 767/2013) and Feed Additives (as defined by EC Regulation 1831/2003). Both regulations were carried forward into UK law after Brexit.

In 2011 the European Commission published a formal recommendation 'establishing guidelines for the distinction between feed materials, feed additives, biocidal products and veterinary medicinal products. This states that a substance cannot be both a feed material and a feed additive. It further states: 'a feed material can also exert an additive function… but this should not be the only intended use.' Also, 'If for reasons of animal or human health it is necessary to set a maximum content of the product in the daily ration the products qualify for classification as additive.' These recommendations are relevant to the probable future treatment of *Asparagopsis*, and perhaps nitrate, as discussed below.

3.1 Feed Materials

EC Regulation 767/2013 defines Feed Materials as: "products of vegetable or animal origin, whose principal purpose is to meet animals' nutritional needs, in their natural state, fresh or preserved, and products derived from the industrial processing thereof…".

Article 13 of EC Regulation concerns claims that suppliers may make for Feed Materials in their labelling and presentation (including advertising). They may "…draw particular attention to the presence or the absence of a substance in the feed, to a specific nutritional characteristic or process or to a specific function related to any of these". However, such claims are only valid if: "(a) the claim is objective, verifiable by the competent authorities and understandable by the user of the feed; and (b) the person responsible for the labelling provides, at the request of the competent authority, scientific substantiation of the claim, either by reference to publicly available scientific evidence or through documented company research."

This wording seems to allow for a relatively low and loosely-defined burden of proof – perhaps just one experiment conducted internally - before a supplier of a Feed Material can claim methane mitigation as a 'specific function'. No mechanism is described by which the (undefined) 'competent authorities' can identify claims, or by which third-parties can bring such claims to their attention.

EC Regulation 767/2013 mandated the creation of a 'Community Catalogue' of Feed Materials, which was created through Regulation 68/2013 (with individual feed materials listed in Part C of the Annex (updated periodically, most recently in EC Regulation 1017/2017). Use of the catalogue by feed business operators is voluntary. The feed industry (acting as the 'EU Feed Chain Task Force') provides and manages a Feed Materials Register (**https://www.feedmaterialsregister.eu/**), designed to capture new Feed Materials as they are placed on the market. The UK currently utilises the EU Feed Materials Register, although a GB Register of Feed Materials is under development.

EC law also defines 'feed intended for particular nutritional purposes' in Regulation 2020/354 (repealing Directive 2008/38). Control of methane emissions is not included in the list of 'particular nutritional purposes' provided in Part B of the Annex to Regulation 2020/354.

3.2 Feed additives

EC Regulation 1831/2003 defines feed additives as "substances, micro-organisms or preparations, other than feed material and premixtures, which are intentionally added to feed or water in order to perform, in particular, one or more of the functions mentioned in Article 5". One such function is to "favourably affect the environmental consequences of animal production" (Article 5e).

Feed Additives are further categorised by Article 6, including the category of "zootechnical additives: any additive used to affect favourably the performance of animals in good health or used to affect favourably the environment" (category d).

Detailed rules for the implementation of EC Regulation 1831/2003 are set out in EC Regulation 429/2008. In brief, applicants must submit, to the European Commission, a dossier of information. Typically, the EC invites the European Feed

Safety Authority (EFSA), via it's 'Panel on Additives and Products or Substances used in Animal Feed' (FEEDAP) to form an opinion on the safety and efficacy of the proposed feed additive. The EC (responsible for risk management) then makes its decision, informed by the opinion of EFSA (the risk assessor).

The categorisation of Feed Additives affects both the information required in the dossier (and therefore the cost) and the protection of the commercial interest of the applicant (so-called 'brand-specific approval'). For zootechnical Feed Additives (as opposed to, for example, sensory additives which "improves or changes the organoleptic properties of the feed" (category b)), efficacy, as well as safety, must be demonstrated to the satisfaction of the EC.

Specifically, for zootechnical Feed Additives designed to favourably affect the environment (which includes "reduced methane production"), EC Regulation 429/2008 states: "…evidence of efficacy for the target species can be given by three short term efficacy studies with animals showing significant beneficial effects. Studies shall take into consideration the possibility of an adaptive response to the additive." The minimum evidence requirements for EFSA approval as a zootechnical Feed Additive are summarised in Table 7.

Table 7: Minimum evidence requirements for assessment of efficacy of methane reducing feed additives for EFSA approval as a zootechnical additive.

Factor	EFSA requirements (minimum)
No. independent studies	Minimum 3 *in vivo*
Specificity	Studies in cattle can be extended to other ruminants in the same physiological state, or from fattening to breeding animals within a species
Additive inclusion	Minimum recommended level
Study length (long-term studies)	Calves, lambs and kids = 56 days, cattle, sheep, goats = 84 days (where measuring production response)
Statistical robustness	Power: 75%; statistical significance p<0.1
Statistical analysis	Statistical models accounting for all fixed and random effects
Evidence relevancy	Relevance to EU production systems
Experimental design	Justified according to additive function, use, species, and physiological state

For efficacy in methane reduction, EFSA state that "efficacy for the target species can be demonstrated by short-term studies. These studies should take into consideration the possibility of an adaptive response to the additive." Extrapolation between ruminant species in the same physiological state is also permitted in principle (e.g., from growing beef cattle to growing dairy cattle, sheep, goat, and buffalo), where they are kept for the same purpose (e.g., suckler cows and dairy cows are both kept for the purposes of reproduction). Extrapolation from fattening to breeding animals is also permitted. Minimum study requirements for applications which cover more than one category of ruminant are also defined. For applications covering all growing ruminants (calves, fattening cattle, sheep, and goats) three studies in calves and three in fattening cattle are required. For applications covering all ruminants (calves, cattle, cows, sheep and goats for fattening and dairy production) three studies in calves and three in cows are required. The physiological state of cows for these studies (e.g., dry, pregnant, or lactating) is not specified.

Since the UK's exit from the European Union, the Food Standards Agency (FSA) are recommending that applicants for approvals of feed additives in the UK follow the EFSA technical guidance for the preparation of dossiers to submit to the FSA. Applications take at least one year to complete the assessment process. Through the Northern Ireland protocol of the Bexit Agreement, the EU system of risk assessment and management continues to apply in Northern Ireland.

The FSA has five Scientific Advisory Committees (SACs) including the Committee on Toxicology (COT) and the Advisory Committee of Animal Feedingstuffs (ACAF), first established in 1999 (**https://sac.food.gov.uk/**). Following Brexit, three new Joint Expert Groups were established within the COT, including the 'Joint Expert Group on Animal Feed and Feed Additives' (**https://cot.food.gov.uk/JEGAFFA**). Agendas, notes, and minutes of JEGAFFA meetings are not currently available (website accessed 27th September 2022 states: 'coming soon'). However, the ACAF website is being updated and will include a section on how the Committee operates, as well as a section for minutes and agendas for previous JEGAFFA meetings.

Risk management (i.e., decisions on requests for authorisations) is the responsibility of respective Ministers in England, Wales and Scotland. There is a four-nation framework in place to acknowledge the UK Internal Market (UKIM) on the authorisation of regulated products.

3.3 Current regulatory status and future regulatory path of feed supplements included in this review

The current and possible future regulatory status of feed supplements covered in this review are summarised in Table 8.

	Current	**Future changes**
Asparagopsis	Allowed as Feed Material	Possible development of zootechnical Feed Additives
Bovaer 10	Authorised as zootechnical Feed Additive for 'ruminants for milk production and reproduction' in EU and N. Ireland (and selected other countries, e.g., Chile and Brazil).	Similar authorisation in GB expected by mid 2023. Authorisation for growing ruminants expected in 2024.
SilvAir	Registered Feed Material	
Agolin Ruminant	Mixture of authorised sensory Feed Additives. Not authorised as zootechnical Feed Additives that affect favourably the environment.	
Mootral	Mixture of Feed Material (garlic) and a sensory Feed Additive (citrus oil). Not authorised as zootechnical Feed Additives that affect favourably the environment.	

3.3.1 Asparagopsis

Asparagopsis, like other species of seaweed, if simply dried and ground, is a Feed Material, described in EC Regulation 1017/2017 (entry 7.1.6) as "Product obtained by drying and crushing macro-algae, in particular brown algae. This product may have been washed to reduce the iodine content." Used as a Feed Material, seaweed meal is a source of energy (energy concentration limited by high ash content and moderate digestibility), protein (generally higher in red than green or brown seaweeds) and minerals (e.g., iodine, sodium, potassium, iron, chlorine, and calcium: see Bikker et al. (2020) for review of the value of seaweed in animal nutrition).

In practice, incorporation of Asparagopsis into ruminant diets may be limited by legislation on iodine. EC Regulation 2015/861 sets upper limits for iodine at 5mg/kg complete feed and 10mg/kg complete feed for dairy and beef cattle, respectively (with the lower limit for dairy driven by concerns over transfer to milk).

Concerns over the high concentrations of halogens may stimulate a re-appraisal of the regulatory status of *Asparagopsis* in the EU (in line with the principles outlined in the EC Recommendation of 14th January 2011). This was discussed at a meeting of the Animal Nutrition section of the EC Standing Committee on Plants, Animals, Food and Feed (SCoPAFF) in February 2020. From the minutes: "…red seaweed meal of the *Asparagopsis* spp. was considered to be covered by entry 7.1.6 in the feed material Catalogue. However, a specific entry for this algae species might be envisaged in the next revision of Regulation 68/2013. Like other aquatic feed materials, this algae meal has naturally considerable levels of bromine and iodine. When incorporating red seaweed meal into the animals diets, the feed business operators should take into account its evident contribution to the supply with these elements. Considering the concerns about high contents of bromine or iodine, but also other constituents naturally present in aquatic feed materials, the Commission might envisage an assessment to be done by EFSA."

A re-appraisal may also be triggered if more intensively processed products are developed from *Asparagopsis* (e.g., to reduce iodine concentration or standardise bromoform content). Such products might be directed to seek authorisation as zootechnical additives.

3.3.2 Bovaer

Bovaer 10 (DSM Nutritional Solutions Ltd.) is a presentation of 3-nitrooxypropanol, now authorised for dairy cows in the EU and Northern Ireland (EC Regulation 2022/565, 7Apr22, added to Community Register 18May22 as additive 4c1). This followed the publication of a positive opinion by EFSA, who concluded: "… the additive has a potential to be efficacious in dairy cows to reduce enteric methane production under the proposed conditions of use. This conclusion was extrapolated to all other ruminants for milk production and reproduction" (Bampidis et al., 2021). The authorisation will expire on 28th April 2032 (the expectation is that renewal will be requested and granted).

A request for authorisation in GB (presenting the same technical information as provided to the EC) is under review by FSA: timeline for an opinion (JEGAFFA) and decision (FSA) is not known.

Requests for authorisation for growing cattle, sheep and goats in the EU and GB are under preparation by the manufacturer. These dossiers will use the same data on safety that led to authorisation for lactating ruminants, so authorisation will depend on the efficacy data presented (i.e., authorisation for growing cattle is likely to take less time than authorisation for lactating cattle).

3.3.3 SilvAir

SilvAir is brand name for a specific form of nitrate, 'calcium nitrate double salt', $5Ca(NO_3)2.NH_4NO_3.10H_2O$. This is a registered Feed Material, a source of calcium and non-protein nitrogen.

We are not aware of any plans to seek authorisation of this or any other form of nitrate as a Feed Additive.

3.3.4 Agolin Ruminant

Agolin Ruminant is a mixture of the authorised sensory Feed Additives eugenol and coriander seed oil. In contrast to zootechnical Feed Additives, sensory Feed Additives (like technological and nutritional Feed Additives) fall under a generic authorisation (rather than being holder-specific). Once authorised, any business may manufacture and market the feed additive.

On 1st July 2019 an application was made to authorise Agolin Ruminant in the EU as a zootechnical Feed Additive with a favourable effect on the environment. The applicant (formally, Agolin (Ireland) Ltd.) requested the withdrawal of this application on 7th March 2022. No such application was made for GB.

We do not know the reasons for this withdrawal or whether the applicant intends to make further submissions (in either the EU or GB).

3.3.5 Mootral

Mootral is a pelleted product containing garlic powder and citrus oil. Garlic (fresh) is a registered Feed Material (ID number 009214). The Community Register of Feed Additives lists multiple sources of citrus oil as sensory Feed Additives (category 2, functional group B). It is not known which of these is used in the product

3.3.6 ZELP

We are not aware of direct regulation of 'wearable devices' (a category that also includes various neck-mounted and leg-mounted sensors such as accelerometers). The Code of Practice for the Welfare of Cattle states "If you are marking the cattle with neck bands or chains, and tail bands or leg bands (which you use for herd management identification purposes) you should fit them carefully and adjust them as necessary to avoid causing the animals any unnecessary pain, suffering or injury. ZELP technology is not within the scope of a recent report from the Animal Welfare Committee on the welfare implications of virtual fencing systems (another 'wearable' technology).

3.4 Commentary on regulatory requirements for evidence

EC Regulation 1831/2003 was introduced partly in response to what was perceived as a 'wild west' of feed additives (generally based on flavours and appetisers) claimed to exert a range of positive effects on animal performance. Therefore, for zootechnical additives, the Regulation includes a requirement for suppliers to demonstrate efficacy, as well as safety, before products can be placed on the market.

A discussion of the origins of EC regulatory requirements for efficacy data for feed additives is beyond the scope of this project. However, those requirements are clear: three in vivo experiments with statistical significance level of $P<0.1$ (summarised in Table 7). Implicit in this is the judgement that this provides adequate protection against both Type I and Type II error. Placing products on the market with this degree of evidence is a societal choice.

After Brexit, UK authorities can change this system. Arguably, given the urgency of the climate emergency, the cost of a Type II error (denying use of an effective product), in terms of methane not mitigated, is greater than the cost of a Type I error (greenwashing). We have heard this argument used, especially by smaller companies with limited financial resources, to advocate use of a lower burden of proof (for efficacy, not safety) before products receive regulatory authorisation and are placed on the market.

UK regulatory authorities could also insist on evidence obtained in conditions (e.g., basal diets, feeding systems) relevant to UK farming, or could elect to limit approvals to more narrowly defined target animals.

4. Recommended standard of rigour required for regulatory authorisation

When considering the rigour of evidence for the efficacy of a methane reducing product for the purposes of making specific claims there are several things to take into consideration.

- It is important to look beyond hypothesis testing (p-values). Estimates of the size of the affect accompanied by confidence intervals should be presented. Confidence intervals may be quite wide due to large variation in effect.
- The method of measurement must be appropriate. Many proxy measures are associated with significant error and do not present a reliable measure of absolute emissions reductions.
- The evidence base must be representative for the physiological state, diet type and production system of the target animals of the product, e.g., evidence must show that the product is effective for each population.
- Studies should follow normal good practice in publication e.g., they should be reproducible (described in adequate detail to replicate the study), with appropriate experimental design to test the effect (no confounding factors) and be statistically sound.

Taking the above into consideration, and to obtain a high level of confidence in the evidence, we propose a framework to aid in the assessment of the evidence base in the context of authorisation of methane mitigating products (Table 9). The framework is an extension of the EFSA requirements for zootechnical Feed Additives (Table 7).

Table 9: Suggested framework for assessing rigour of the evidence base for the efficacy of methane reducing feed additives

Factor	Recommended Higher Standard
No. independent estimates	3 per species, production system, physiological state, and diet type
Additive inclusion	Minimum recommended by manufacturer
Study length	At least one study 56 days for growing / finishing animals
Experimental design	Justified according to additive function, use, species, and physiological state
Statistical robustness	Power: 80%; statistical significance: $p<0.05$
Statistical analysis	Statistical models accounting for all fixed and random effects. Effect size estimate and error/confidence interval should be given
Evidence relevancy	Relevancy to UK production systems
Methane measurement	Using appropriate methods, with at least one respiration chamber study

No. independent estimates: We do not propose a minimum number of studies here. There should be adequate independent estimates of efficacy for a specific system and animal type, e.g., one study may include multiple diet types or experiments spanning more than one physiological state.

Additive inclusion: Studies should include a dosage level which is the minimum recommended by the additive manufacturer. This is a current requirement of EFSA.

Study length: EFSA currently do not require any long-term studies for measurement of methane reduction. Longer term studies are only required for production effects. We propose that at least one study over a 56-day period should be included in the evidence base. This would provide some evidence that adaptation of the rumen microbial community to the additive does not suppress the effect, or as potentially shown in the case of Agolin Ruminant, that enhance the effect.

Experimental design: No change from EFSA guidelines. This will vary according to the additive, production system and physiological state of the animal whether studies are appropriately designed should be assessed on a case-by-case basis by the AAFAJEG committee.

Statistical robustness: Statistical power is the probability that a statistical test will find a significant effect. Power calculations should be used during the design phase of a study to ensure that enough animals are included to have a reasonable chance of detecting a real effect, and not one created by chance. EFSA requires a power of 75%, however 80% is a more commonly accepted standard. Lower power may be justifiable if a large effect is expected. Statistical significance (p-values) is most commonly set at <0.05, representing a less than 1-in-20 chance that the effect is not real. EFSA set this requirement at <0.1, which is generally considered a 'trend' rather than being 'significant'.

Statistical analysis: As for EFSA, appropriate statistical models should be used to analyse data. We also suggest that the actual effect size and associated error should be stated (note that 95% confidence intervals can be calculated from standard errors if they are not stated).

Evidence relevancy: Production system represented in the evidence base should be relevant to UK production systems. Due to the wide diversity of production systems, we suggest that this would be at the discretion of the AAFAJEG Committee.

Methane measurement: EFSA do not stipulate any requirements around the methods of methane measurement. However, there is wide variation in the accuracy, reliability, and applicability to production systems of different methods. There are several reviews detailing the pros and cons of *in vivo* methods for the measurements of enteric methane emissions and is out with the scope of this report. We refer readers to Hammond et al. (2016). In this report we have included studies which use respiration or metabolic chambers, point measurements using 'hooded' systems (e.g. head chambers or GreenFeed systems), and the sulphur hexafluoride tracer technique. There methods have been sufficiently validated and have defined levels of accuracy.

Technologies that do not affect the biology of the animal (e.g., those that capture methane after it is eructed) should be assessed in a different way (Table 10) as they are unlikely to be affected by factors such as diet composition, and the effect will not be reduced by biological adaptation (e.g., adaptation of the rumen microbial community).

Table 10: Suggested framework for assessing rigour of the evidence base for the efficacy of methane reducing technologies

Factor	Recommended Higher Standard
No. independent estimates	3 per species and production system
Study length	Short term studies are adequate
Experimental design	Justified according to technology function, and species
Statistical robustness	Power: 80%; statistical significance: $p<0.05$
Statistical analysis	Statistical models accounting for all fixed and random effects. Effect size estimate and error/confidence interval should be given
Evidence relevancy	Relevancy to UK production systems
Methane measurement*	Using appropriate methods, with at least one respiration chamber study

* Appropriate methods will depend on the type of technology

The framework for such technologies differs from the one outlined for feed additives in the following ways:

- As the biology of the animal is not being manipulated, diet type and physiological state are less likely to affect the efficacy of the technology. However, it may be affected by production system (for example, it could be imagined that wind speed in a grazing system may affect breath capture by the ZELP technology)
- As there is no biological adaptation of such devices, short-term studies are likely to be adequate, as long as the animal is appropriately trained to use/wear the device and it is not affecting animal behaviour (e.g., any impact on feed intake or grazing behaviour will affect methane production).
- Comments on appropriate methods of methane measurement made above apply here. However, some systems may not be appropriate depending on the type of technology. For example, SF_6 could not be used with the ZELP technology as there would be too much equipment mounted on the animal and the device obscures the nostrils where the SF_6 system samples breath from. This would need to be assessed on a technology-by-technology basis.

Additional to the above, we recommend that datasets used as evidence for the efficacy of methane reducing feed additives should also follow FAIR principles (https://www.go-fair.org/):

- **F**indable: A dataset should be assigned a unique and persistent identifier (e.g., a digital object identifier or DOI).
- **A**ccessible: Data (or metadata where data is no longer available) should be retrievable using the unique identifier and indexed or registered in a searchable resource (e.g., stored in a data repository). Note that this does not mean the data should be open access, but the conditions under which the data may be accessed are made clear. This means private/confidential data can still be classified as FAIR.
- **I**nteroperable: Data should be in a format that is readily interpreted by humans and machines (e.g., using common language for the subject area) and have a well-defined structure to describe the data.
- **R**eusable: Having clearly described usage rights (e.g., a Creative Commons Licence), including instructions on how the data should be cited.

The FAIR principles are relevant to studies used to secure regulatory approval and to later studies that add to the pyramid of evidence and are used to improve models of efficacy in the codes and standards that underpin carbon markets.

5. Benchmarking rigour of efficacy evidence

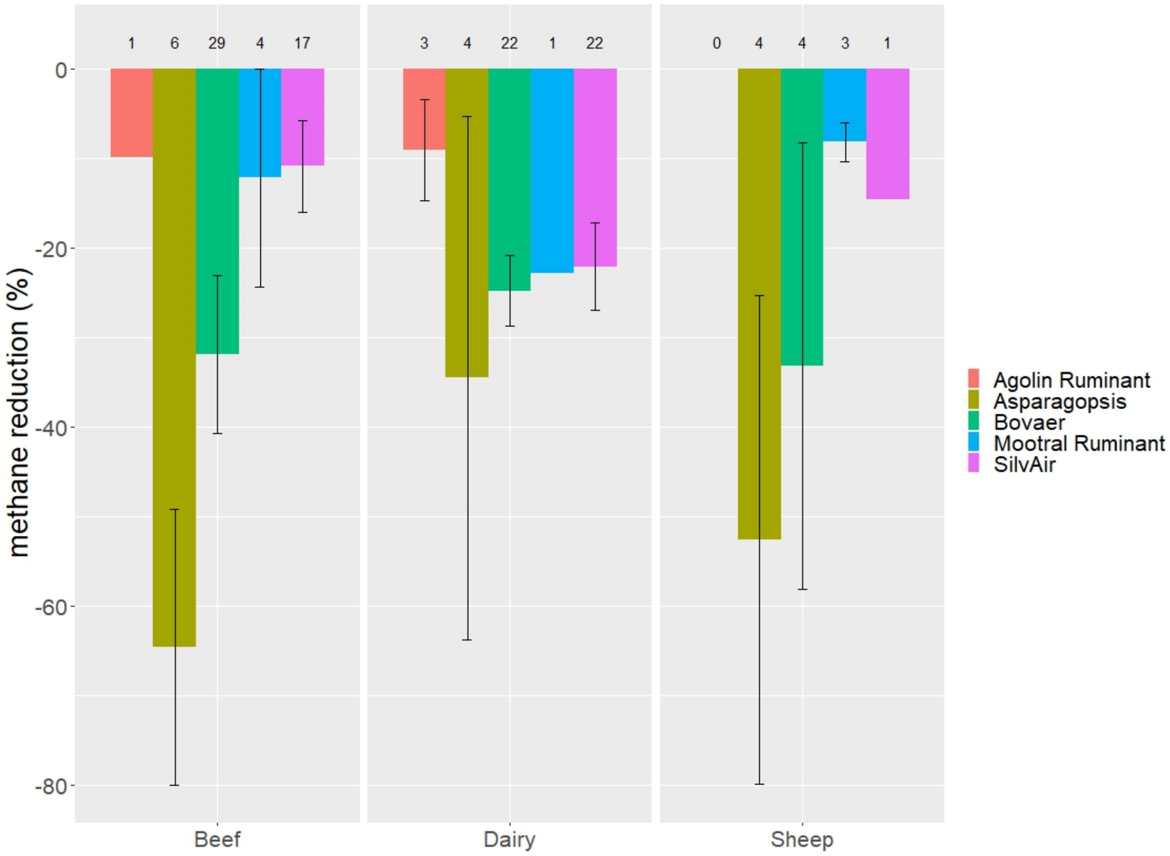
Based on the proposed framework for assessing the efficacy of feed additives outlined in Table 9 and the evidence presented in the REA we have benchmarked the evidence for each feed additive product. There is an accompanying database (.xlsx spreadsheet) which shows to what extent each feed additive meets those standards for different species, production systems, diet types and physiological states using a RAG system.

Below are a series of Figures (2-6) which show the magnitude of potential reduction in methane production (gCH_4/day) and associated confidence intervals for each additive by species (beef, dairy or sheep) (Figure 2), production system - grazing (Figure 3) or housed. Housed estimates are further split by diet type: high forage (>600g/kg feed dry matter as forage; Figure 4); mixed diet (≤600g/kg ≥400g/kg feed dry matter as forage; Figure 5); or high concentrate (<400g/kg feed dry matter as forage; Figure 6). We have focused on reductions in methane production here rather than methane yield (gCh_4 per kg dry matter intake or per kg of meat or milk output) to represent actual reductions in methane as opposed to dilution of methane production through increased performance.

The lack of evidence for sheep (for all diet types) likely reflects the low likelihood that feed additives will have a significant market penetration for sheep. Also, EFSA allows extension from cattle to other ruminants so it is reasonable to expect that companies will focus their efforts on their target markets (dairy and beef).

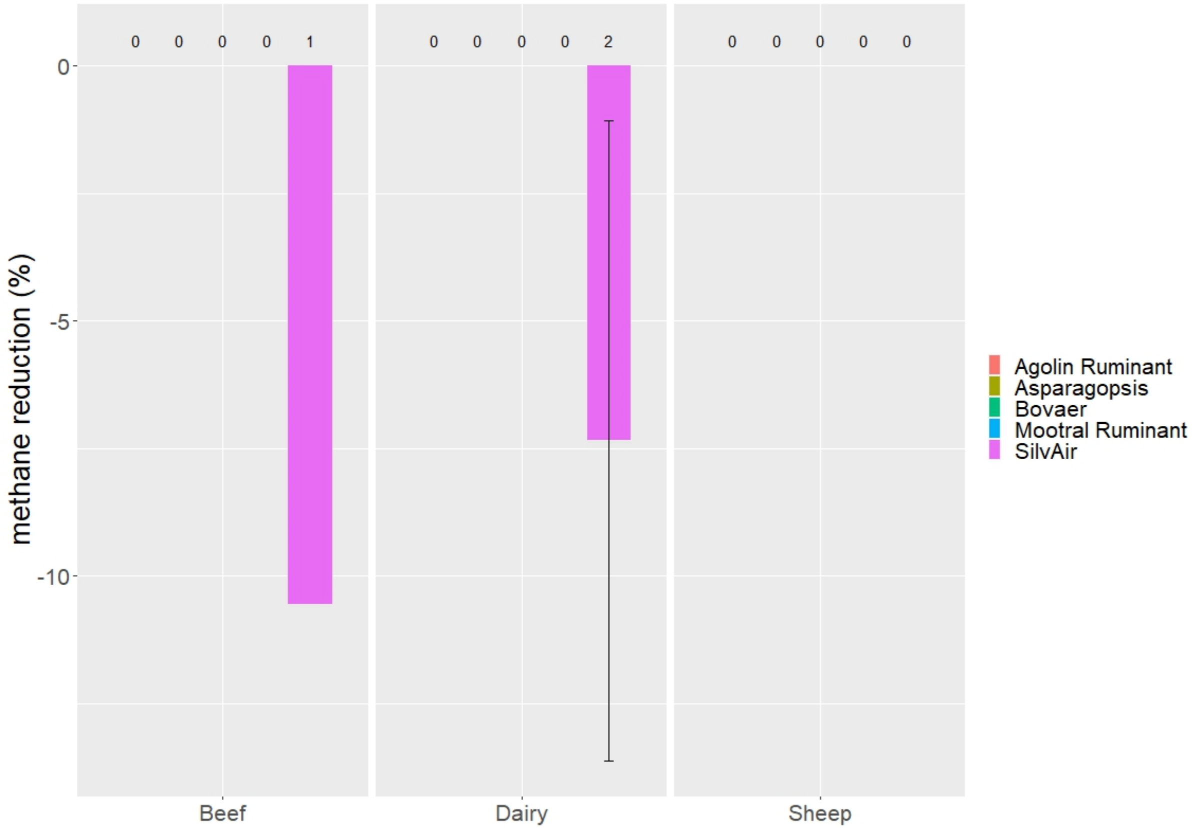
The 95% confidence intervals represent the range of values within which we can be 95% sure that the actual effect lies. In the figures below, the wider the error bars are, the less certain we are of the actual effect, indicating that more estimates are required. Where there are no error bars, this indicates that only one estimate was available (and not that we are certain of the magnitude of the effect). It should be noted that this analysis does not take the dosage level into account, which will cause variation in the response.

Figure 2: Mean percentage reductions in methane production (gCH_4/day) for each feed additive by **species**, including all estimates in the REA. Error bars represent 95% confidence intervals. Numbers above bars are the number of estimates. Where there are no error bars, only one estimate was available.



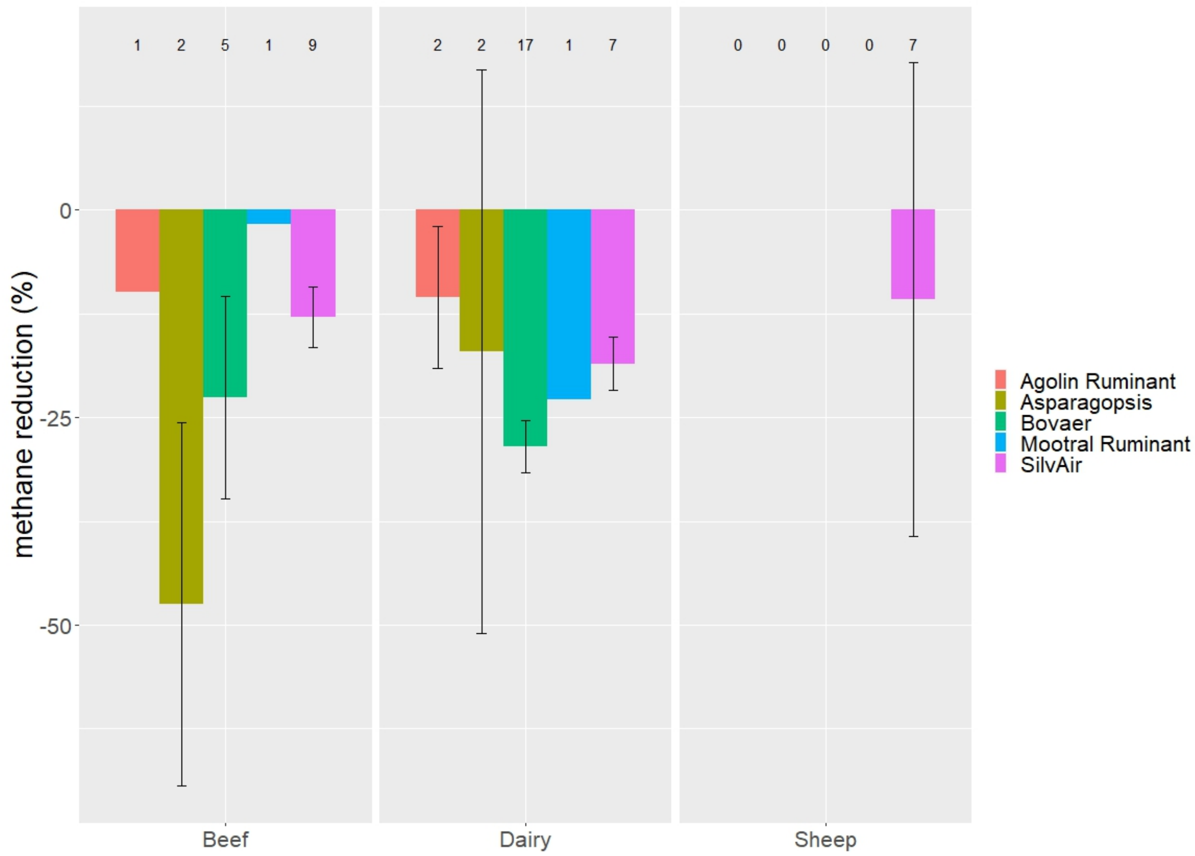
***Grazing*:** The lack of evidence for efficacy on grazing systems noted in the conclusions for the REA is starkly highlighted in Figure 3. There is only evidence available for SilvAir, and that is also sparse. Whilst most methane suppressing feed additives are more effective on forage-based diets, the lack of direct evidence for grazing systems should limit claims that can be made about products for grazing ruminants.

Figure 3: Mean percentage reductions in methane production (gCH_4/day) for each feed additive, for studies undertaken on **grazing** systems in the REA. Error bars represent 95% confidence intervals. Numbers above bars are the number of estimates. Where there are no error bars, only one estimate was available.



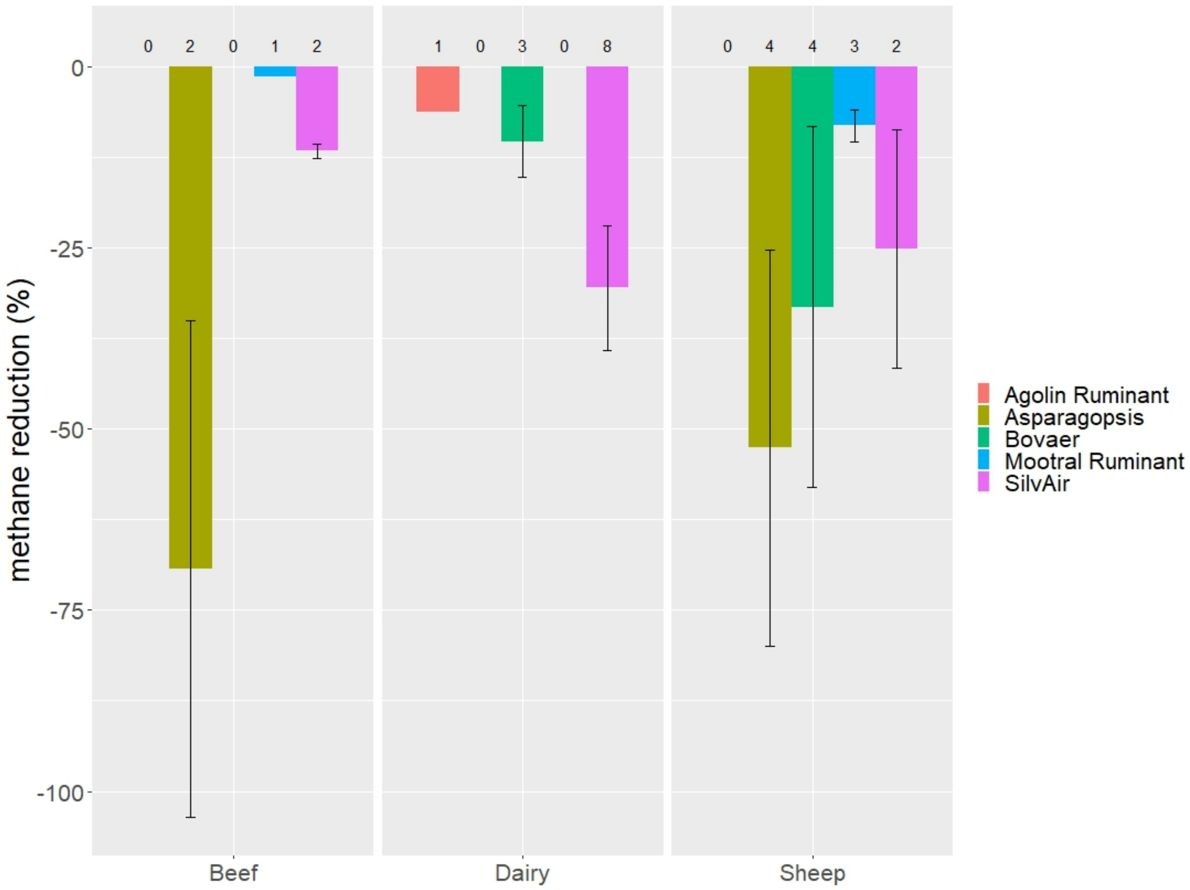
High forage diets: Bovaer and SilvAir have large numbers of estimates for dairy (and associated narrow 95% confidence intervals), SilvAir also has fairly narrow 95% confidence intervals for beef cattle. This means we could be fairly certain that these effects are real, and that the magnitude of the effect is accurately estimated. (Figure 4).

Figure 4: Mean percentage reductions in methane production (gCH_4/day) for each feed additive, for studies undertaken in **housed** systems where **high forage** diets (>600g/kg feed dry matter as forage) in the REA. Error bars represent 95% confidence intervals. Numbers above bars are the number of estimates. Where there are no error bars, only one estimate was available.



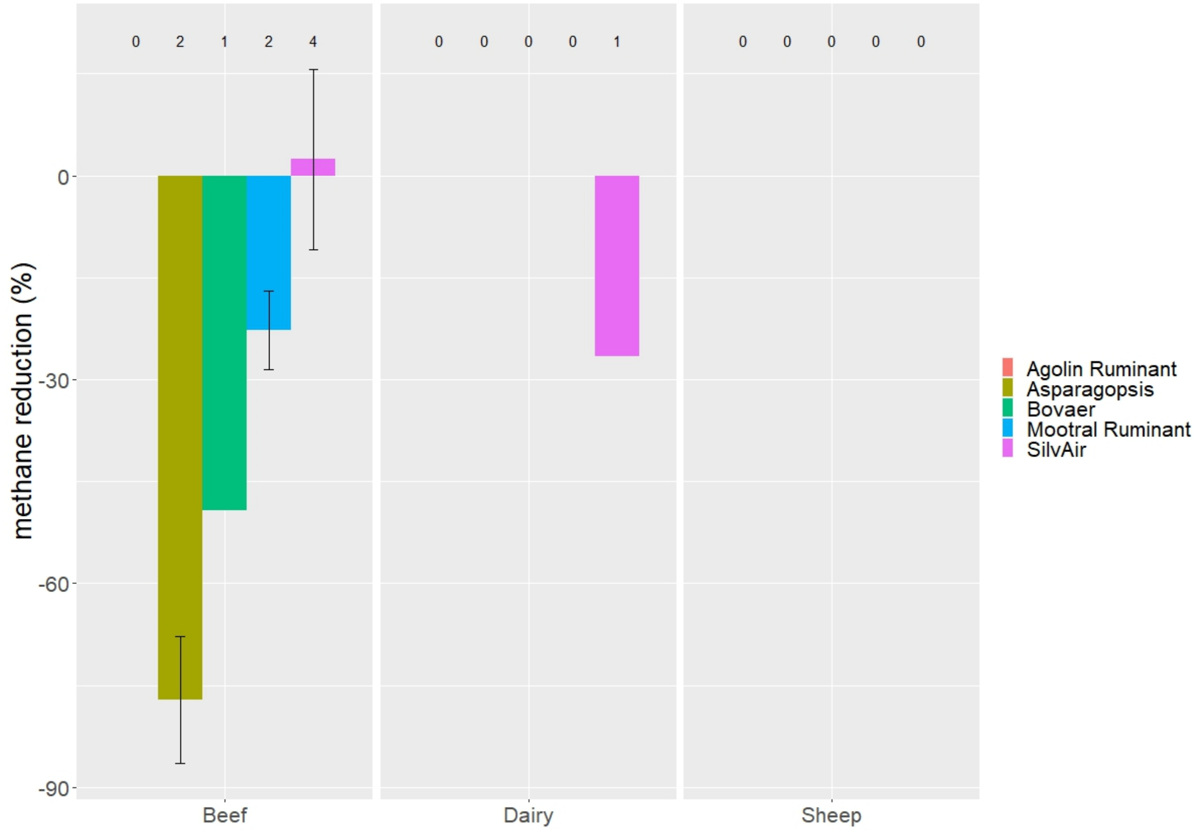
Mixed diets: The narrow 95% confidence interval for beef cattle receiving SilvAir (Figure 5) is misleading as it is generated from only two non-independent estimates. Similarly, for Mootral Ruminant, the mean in Figure 5 is derived from one study with three non-independent estimates. *Asparagopsis* has wide 95% confidence intervals for both beef and sheep (no studies on dairy cattle receiving mixed diets).

Figure 5: Mean percentage reductions in methane production (gCH_4/day) for each feed additive, for studies undertaken in **housed** systems where **mixed forage and concentrate** diets (≤600g/kg ≥400g/kg feed dry matter as forage) in the REA. Error bars represent 95% confidence intervals. Numbers above bars are the number of estimates. Where there are no error bars, only one estimate was available.



High concentrate diets are more applicable for intensive beef finishing operations than for dairy or sheep production, thus the lack of evidence for dairy and sheep (Figure 6). Despite feed additives being less effective on concentrate diets, due to concentrates being easier than forage to digest and so less fermentation (and by extension less methane production) occurring in the rumen, *Asparagopsis* and Mootral Ruminant appear to have notable effects with reasonably small 95% confidence intervals (*Asparagopsis*: -77 ± 9.3%, Mootral Ruminant: -22.7 ± 5.7%). Care must be taken when interpreting this as numbers of estimates are low (n=2 for both) and not independent (no. studies = 1 for both). SilvAir has four estimates (from two independent studies). Wide 95% confidence intervals reflect a large (22%) increase in methane production in one estimate on a lower dosage level (Lee et al., 2017). When disregarding this, the effect is close to zero (-4 ± 5%), confirming that this product is not suitable for use with high concentrate diets. Low numbers of estimates should prevent claims being made about the efficacy of these products on high concentrate diets.

Figure 6: Mean percentage reductions in methane production (gCH_4/day) for each feed additive, for studies undertaken in **housed** systems where **high concentrate** diets (<400g/kg feed dry matter as forage) in the REA. Error bars represent 95% confidence intervals. Numbers above bars are the number of estimates. Where there are no error bars, only one estimate was available.



6. Advertising – Avoiding Greenwashing

The Advertising Standards Agency (ASA) provide guidance on interpreting the UK Code of Non-broadcast Advertising and Direct & Promotional Marketing (the CAP Code) and the UK Code of Broadcast Advertising (the BCAP Code) in relation to environmental claims made about products. This advice can be found on the ASA website (https://www.asa.org.uk/resource/advertising-guidance-misleading-environmental-claims-and-social-responsibility.html). The key points of particular relevance to avoid "greenwashing" in the context of reducing agricultural greenhouse gas emissions are:

1. Substantiation: Claims must be qualified and explicit in what they relate to. Marketers must hold robust documented evidence to substantiate the claims.
    a. Absolute claims about environmental benefits must be supported by a **high level** of substantiation. If evidence is inconclusive or there is significant division of scientific opinion this must be made clear. This may include lack of statistical significance, or wide 95% confidence intervals across studies.
    b. Relative claims using terms such as "greener" must have verifiable evidence and the method of comparison should be made available to the audience either within the advert or signposted to within the advert.
2. Scope of claims: Environmental claims must consider the entire lifecycle of the product (e.g., from manufacture to disposal of wastes after use). Claims about limited aspects of the products lifecycle are acceptable but this must be explicit and made clear to the audience.

Claims must be within the context of the evidence and must clearly define under what circumstances emissions reduction claims apply. They must not overstate efficacy or extend beyond the production systems and diet type for which it has been tested.

For example, if a company made the claim: "Product 'X' reduces enteric methane by 20%" this is insufficient in a number of ways.

- It does not specify the unit (e.g. is it 20% of methane production, or 20% of methane per kg of feed intake, meat or milk produced?)

- It does not specify if this is for one particular class of animal, or if it holds true for all animals that it can be fed to.
- It does not specify if the response varies with diet type (e.g., is it as effective on high concentrate diets?)
- It does not specify the production system in which it has been tested or is suitable for.

Caution is required with the wording of claims, and they must make clear under what conditions the claim applies. It is also important that companies sign post studies testing product efficacy, including those with a negative or less favourable result.

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7. Mechanisms to incentivise adoption

7.1 Introduction

It is often assumed that, because methane represents a loss of energy to the animal, reductions in methane emissions should save energy and result in faster growth or more milk. If this is the case, current market rewards for increased productivity should incentivise innovation, drive adoption and result in methane mitigation.

In general, reducing methane is not associated with improved animal performance. The symbiosis between methanogens and bacteria allows bacteria to continue to digest plant cell walls, so the gain, in terms of energy saved when methane is inhibited, may be offset by consequent reductions in digestibility. This question has been comprehensively reviewed by Ungerfeld (2018) and Ungerfeld et al. (2022), but a general conclusion is that reductions in methane *per se* have little effect on animal performance.

This does not necessarily mean that the interventions reviewed here have no effects on productivity, but such effects are likely due to mechanisms other than methane mitigation. Therefore, other mechanisms are needed to incentivise the uptake of methane mitigating supplements and technologies.

A wide range of instruments are available which can influence farmers' actions and thus the environmental performance of food production. So far, despite the role of food production and consumption in GHG emissions being well understood for decades, little policy or industry action has been taken to reduce emissions from the sector. In the last reform of the European agricultural support system (Common Agricultural Policy), a substantial share of the spending was required to target climate change problems. However, the policy framework, which mostly consisted of supporting voluntary action, has achieved limited GHG emission reduction (European Court of Auditors 2021). Indeed, agricultural emissions in Europe and in the UK have been stagnant in the past three decades (Brown et al. 2021; European Environment Agency 2022), though some improvement can be found when looking at emission intensity of production in the dairy and pig sectors (Defra 2021). This limited progress is calling for urgent implementation of effective policy frameworks. With the UK transitioning to a new agri-environmental policy and societal forces demanding more intense climate action, the choices in how to incentivise farmers to reduce their GHG emissions (and increase carbon sequestration) for both the government and supply chain actors are plentiful and complex. Co-ordination between the different – sometimes contrasting – policy goals and between government-led and industry-led initiatives is important for improving the overall efficiency of industry and policy instruments.

As part of a report exploring the efficacy and feasibility of methane-reducing feed additives, this brief review explores four broad types of interventions: (i) Voluntary standards and industry incentives (ii) Product labelling, (iii) GHG trading, and (iv) fiscal incentives, regarding to what extent they could be used to incentivise farmers to administer methane-reducing feed additives to their cattle. Past experiences on the effectiveness of the instruments (in different contexts, often targeting different environmental outcomes and in countries other than the UK) are presented, along with considerations on how feed additives could be included in the policy and supply chain landscape in the UK.

7.2 General considerations

Successful environmental policies can be characterised by five features: they are effective (achieve their goal), achieve the effectiveness at the lowest possible cost, equitable (fair and have no undue impacts on competitiveness), flexible to adapt to changing circumstances and enforceable (Stern 2008). Regarding the first two points, three key aspects characterise the most cost-effective policies – even though it is usually difficult to achieve them all. They aim for specific environmental outcomes, target farms where action is most feasible and allow farmers flexibility in achieving the outcome (Lankoski & Cattaneo 2010). In the context of GHG emission reduction and specifically the use of feed additives for ruminants, the first point can be achieved if the instrument and its monitoring is outcome-based, or, if action-based, the action is very strongly linked to the outcome (i.e., very specific guidance for implementation is provided, aiming to achieve a specific reduction goal in each animal and across the herd). Assuming direct measurement of methane emissions on farm is not feasible, the next options are proxy measurements (e.g., milk MIR spectra), and if these are too costly, verified consumption of the supplement by the targeted animals is needed, or at least the verification that the supplement has at least been offered to the animals (verifying that the supplement has been delivered to farm does not sufficiently show that it has been consumed). The second point would suggest narrowing down the target population of cattle farmers by certain criteria, linked to higher feasibility of action, like herd size, level of farming intensity, proportion of grazing, time spent housed, and in the case of beef farming the type of farm (e.g. suckler, store, finisher), rather than the policy covering any farmer with any number and types of cattle; this would also reduce transaction costs of the policies (Grosjean et al. 2016). This would also be needed specifically for methane reducing additives which have only been proved to be effective for certain types of animals (breed, age) and certain feeding regimes. Finally, flexibility for farmers to decide on their action can be provided if a wider goal of GHG reduction is defined for the farm, and the use feed additives is one of the many options available.

An important aspect of both compliance (and thus environmental outcome) and transaction costs is how farmers actions of applying feed additives are verified. As scientific literature on transaction cost tells, some policies incur very low costs (less than 5% of payments) while others require more money to run than what is involved in the payments (Rørstad et al., 2007). These costs depend on both the type of the policy and the details of its implementation, for example, the same authors found that price support and tax applied to commodities (like milk price support, fertiliser tax) are "cheap" agricultural policies, while those aiming for specific public good outcomes which need to be verified individually and/or need individually defined contracts (for example a very specific landscape) are on the expensive end.

Following the aspects mentioned by Rørstad et al. (2007) and Mettepenningen et al. (2011), **Error! Reference source not found.**1 shows a few e xamples of how transaction costs might be lower in the case of feed additives to cattle.

Table 11 Potential ways to reduce transaction costs (following Mettepenningen et al. (2011); Rørstad et al. (2007))

Lower transaction cost if…	Potential examples for feed additives
… information does not need to be gathered for the monitoring but can rely on existing information collection (for example, the outcome can be estimated by a proxy metric which is already collected)	GHG emission information is currently not collected, nor the composition of feed If certain compound feeds contained the additives, then having information on the feed fed to animals can be a proxy If detailed farm management data was to be routinely gathered for other purposes too (e.g., to estimate other GHG emissions and reactive nitrogen emissions) then the share of costs for feed additives would be lower
… the extent of public good provision does not differ between the agents	If it is assumed that every farmer who applies the feed additive achieves the same amount of GHG reduction (i.e., not differentiating the GHG effect by the type of feed additive, the dose, or the proportion of animals who are treated)
… the target population is fairly homogenous, therefore many of the agents can be signed up with no variation in the contracts	If the contract does not need to consider specific farm management aspects, which is likely to be the case in feed additives (as opposed to e.g. biodiversity goals)
… the target population covers a substantial share of the whole population	If farmers with large herds are targeted
… the transactions are recurring and long-term (this also reduces the uncertainty for the farmers)	If the scheme does not need to be renewed annually and the farmers are guaranteed for the long-term duration of the scheme
… there is more trust between the contracting parties	If the contracting parties have worked together before and or if their incentive structures are more aligned
… there is less complexity for both parties	If the sign-up procedure is easy, the management instructions are straightforward, and the need for data provision is minimised

7.3 Voluntary standards and industry initiatives

Voluntary standards are defined by (groups of) companies or (third-party) non-profit organisations and they aim for certain environmental and/or social outcomes. Third-party standards tend to be communicated to the consumers with visual signs (labels) on the products produced by those adopting these standards – they are strongly linked to ecolabels. Examples of long-standing third-party voluntary standards in the food industry are the FairTrade certification and the Marine Stewardship Council, both founded in the 1990s. Voluntary standards in the UK include the organic label by the Soil Association, the Red Tractor Scheme and the LEAF initiative.

The above third-party certification schemes have well-defined requirements towards the producers and transparent mechanisms. On the other hand, voluntary standards self-imposed by supply chain actors can be less transparent, as they are not monitored or enforced by third-party actors. In response to the publication of the first UK carbon budget in 2008 a wide range of agricultural industry players (including the National Farmers' Union (NFU) and the Agriculture and Horticulture Development Board (AHDB)) developed the Agriculture Industry GHG Action Plan, with the goal of achieving an annual 3 Mt CO_2e (7%) GHG emission reduction by 2020 – the last annual report was published in 2012. Similarly, in 2019, the NFU pledged to achieve net zero emissions from farming in the UK by 2040, but a clear financial commitment and monitoring and evaluation activities are not defined. These programmes defined roadmaps to achieve their goals, the effort to achieve these goals is mostly down to the individual farmers. These initiatives can help farmers to raise awareness and can also show society and the government that the industry is ready to take action.

Unilateral initiatives of individual companies covering their supply chain (e.g., Arla's Climate Ambition) can be considered as another category of voluntary standards.

Arla's 'Climate Check' was introduced in 2019. This is an LCA tool to calculate emissions and identify potential mitigation measures. Completion of the check is mandatory for organic suppliers and voluntary for conventional suppliers, with the process audited by Ernst&Young. Farmers are paid an incentive via the milk price to complete the survey. In 2021, 94% of Arla suppliers, representing 98% of their milk supply, completed the Climate Check (Arla Climate Check Report, 2022). Across all Arla milk suppliers. Emission Intensity was 1.16kg CO2e/kg FPCM in 2020 and 1.15 in 2021 (Arla, 2022). Arguably it is too early to judge the effectiveness of this voluntary approach (i.e., is Emission Intensity falling quickly enough?), but noteworthy that Arla is now introducing a direct financial incentive to reward emission reductions (see 'Direct payment', below).

Vertical integration is increasingly present in the food supply chains, driven partially by higher demand for product quality (Fischer et al., 2009). Some of these supply chain contracts now cover environmental sustainability and require farmers to do environmental audits or implement sustainable practices on their farms (Glover et al., 2014; Pretty et al., 2008b). Larger processors and retailers, like Danish Crown, Arla, Danone, Sainsbury's and Tesco are increasingly requiring their producers to meet sustainability criteria they set. For example, Sainsbury's target in Scope 3 emissions (i.e. those emissions which arise during the production of the items they are selling) is to reduce them by 30% by 2030. These supply chain contracts allow processors and retailers to make self-declared environmental claims, through corporate social responsibility communications or direct communications with the consumers via information displayed on the products and in the shops.

7.3.1 Effectiveness of the instrument

Some voluntary standards have very important roles globally, and especially in developing countries: one sixth of coffee and one fifth of banana was produced under sustainability standards in 2009 (Potts et al., 2010). However, there is some debate about the effectiveness of these standards, especially in cases where multiple independent standards compete on the same market certified production can substantially be higher than demand, driving down price premiums (Dietz & Grabs, 2022). Furthermore, unintended consequences of environmental schemes might contribute negatively to local food security (Oosterveer et al., 2014).

In the UK European production sustainability schemes have a slightly less pronounced role: likely to be the biggest initiative, organic production, resulted by 2017 in the conversion of just over 7% of agricultural land, as a combined effect of market demand and subsidies through the Common Agricultural Policy over many decades.

The environmental effects of organic farming is well researched, and knowledge exists about voluntary standards targeting developing countries (e.g., Brako et al., 2021; Ssebunya et al., 2019), but there is very little information on the environmental performance of other standards. Organic farming tends to perform better than conventional in terms of on-farm biodiversity and area-based environmental pollution (e.g., nitrogen leaching per hectare) but these effects are usually offset by the reduced yield which necessitates larger areas for production (Clark & Tilman, 2017; Seufert et al., 2012; Tuomisto et al., 2012).

Commonly evaluation for industry standard schemes (like the GHG Action Plan) and initiatives of private companies is not publicly available, apart from rare examples, like the 2008 assessments on Unilever sustainability initiative (Pretty et al., 2008a; Pretty et al., 2008b). Especially in the case of industry-wide standards monitoring of uptake might not be present and the complex and changing incentive structure of the supply chain is an obstacle in attributing impact to the initiative.

7.3.2 Considerations for UK policy landscape and policy mechanism

Here we discuss the opportunities in unilateral company initiatives, as third-party standards are discussed in the section below.

Given the international nature of food supply chains, integrating the requirement for feed additives into supply chain contracts would require a UK-specific incentive for the processor/retailer to exist, otherwise it might only happen when there is strong enough demand in the whole market of the food supply actor. This UK-specific incentive might arise from the demand side, i.e., UK consumers or consumers of the exported products willing to pay more for low GHG emission milk and beef. To achieve the desired change on farms, this route would benefit from third-party monitoring to generate credibility about the lower emission claims (akin to the Soil Association monitoring organic certificates). Incorporating feed additives into their farm action toolkit might become desirable for processors and retailers if they can show the emission reduction via their Scope 3 emission estimates (i.e., the carbon footprint models used for these emission calculations can account for the feed additives).

Just like with monitoring of the administration of feed additives on farms when incentivised via fiscal instruments, there are important considerations at the farm level for voluntary standards, like verifying the number and type of animals receiving the feed additives and the dose and type of the additive.

7.4 Product labelling

Sustainability labels (ecolabels) provide information on individual products about their environmental and/or social sustainability attributes. They can be self-declared (linking to voluntary standards discussed above) or certified by third parties; they could consist of a single "stamp", like certification labels or might present quantified environmental information (Allison & Carter, 2000). All forms of ecolabels intend both to change consumer choices and to capitalise on consumers' willingness to pay for products with reduced harmful environmental or societal impact (Bastounis et al., 2021). Ecolabels are diverse and plentiful, even only considering those relating to food products: according to Gruère (2013), there were over a hundred ecolabels related to food products already in 2012.

7.4.1 Effectiveness of the instrument

For ecolabels to reduce environmental harm actions on both ends of the supply chain are needed: consumers need to have preferences for the products with environmental claims and producers need to adhere to production methods which have a lower environmental impact over the lifecycle of the product. Nevertheless, the effectiveness might be hampered by wider consumption changes, like consumers starting to purchase more of the lower environmental impact product, increasing overall production (Bougherara et al., 2005), or changes in consumption pattern elsewhere, when an increase in the consumption of the ecolabel product causes an increase in the consumption of higher environmental products by people with lower purchasing power.

Studies reviewing empirical evidence show that ecolabels in most cases are effective in increasing the demand for low-environmental impact products, both in hypothetical settings (purchase intentions) and in actual purchase behaviour; the findings are similar when only GHG related labels are considered (Potter et al., 2021). Different demographical groups show different response to ecolabels, for example in the case of food carbon footprint labels: particularly women and those with higher education tend to have more positive attitudes to them (Potter et al., 2021; Rondoni & Grasso, 2021). However, only a small proportion of consumers are regularly buying products with ecolabels; the largest label, organic production is linked to a moderate conversion of agricultural production methods (see above).

Ecolabels take various forms and have diverse content. They might contain only a logo or textual information or both, their environmental claims vary (e.g., organic, low GHG, low pesticide use). Potter et al., (2021) found no evidence that the label format made a difference in effectiveness, however, some individual studies point to that, even to the possibility of label type and demographics interacting (Teisl et al., 2008). Furthermore, if a label is linked to a third-party certification scheme it is more effective (D'Souza et al., 2007; O'Brien & Teisl, 2004). Third-party auditing can even benefit the companies using the ecolabels as it reduces consumer uncertainty (e.g. suspecting "greenwashing") and thus the "dilution" of the effect of the label (Harbaugh et al., 2011; Lyon & Maxwell, 2011).

While a wide variety of supply chain actors can benefit from ecolabels, their motivations can easily differ from each other. On the one hand, environmental non-governmental organisations aim for high environmental effect, while the producers' interest is to achieve price premium and increase their reputation at the lowest cost (Ibanez, 2016). An increased overall reputation might even lead to investment in more polluting product lines (Dosi & Moretto, 2001). At the same time the real behaviour of consumers is complex, and so called "behavioural biases" hamper the efficiency of ecolabeling schemes, which makes Grolleau et al., (2016) conclude that they are not enough for a sustainability transition, but rather are useful to complement regulatory interventions. Indeed, a combination of instruments (label and environmental tax) can be more optimal than individual instruments (Disdier & Marette, 2012).

The availability of evidence on the effects of ecolabels on the environment is varied. As summarised in the previous section, organic farming has a different environmental footprint than conventional farming, though not necessarily better overall due to the higher land use requirements (lower yield). Ecolabels targeting developing countries are often shown to have a positive effect on livelihoods and the environment (see previous section), but evaluation on the environmental performance of other labels, like LEAF farming and the Carbon Trust label could not be found by the authors.

7.4.2 Considerations for UK policy landscape and policy mechanism

According to the Ecolabel Index Database, currently 87 ecolabels exist in the UK. While most of these would not be relevant for livestock products produced in the UK, there are a few schemes related to organic, sustainable, and low-carbon farming. Probably the largest scheme is the organic certification run by the Soil Association, which follows general organic standards. LEAF is a UK farming membership scheme promoting sustainable farming, while the Red Tractor scheme focuses on product quality and animal welfare. Similar in its goals but a global scheme is the Global Good Agricultural Practice (GAP). More relevant to GHG emissions, the Carbon Trust's carbon footprint label certifies products for a variety of carbon footprint "achievements", like having lower emissions than the market standard or being carbon neutral. CarbonNeutral® certification is given to companies which prove to be caron neutral. Furthermore, as a pilot scheme in Sweden, a label was created to promote low carbon beef produced with seaweed feed supplement (*Asparagopsis*).

Creating another label about methane reducing feed additives might not be an effective way of informing consumers as it would make the already complicated label-landscape even more complex, where consumers would not be able to compare the claims of this specific label with the environmental claims of the other labels. Furthermore, awareness of specific labels grows slowly and an information campaign to increase awareness can be costly. This leaves the opportunity of integrating the use of feed additives into an existing label. While some feed additives could be compatible with organic production, it is probably not likely that the organic certification would require the use of methane reducing feed additives in the near future. Similarly, the LEAF and Red Tractor schemes have their distinct goals where GHG emission reduction might not fit currently. Best suited for the use of feed additives could be carbon certification by the Carbon Trust. However, the standard of evidence required for certification by The Carbon Trust is not known and there are cases where certificates have been granted for feed additives not authorised as Feed Additives for methane mitigation (see below). The number of food products using these labels is still small (e.g., some dairy products, Quorn products), and consumer awareness might not be substantial yet, but the label reflects best the environmental outcome of the use of feed additives. Especially the category "Lower CO_2"would be suitable, showing that the lifecycle carbon footprint of the product is significantly lower than that of the dominant products and no alternative product exists with a lower footprint. However, it might not be suitable for individual farms but rather for groups of farms or processors/retailers selling the ruminant products.

The Carbon Trust provided Wyke Farms with a Product Carbon Footprint Label, through LCA analysis (verified and certified in line with the PAS2060 standard) for its cheeses. We think it unlikely that any methane-mitigating feed supplements were used or valued in the LCA process used for this exercise.

The Carbon Trust has issued positive 'validation opinions' for several feed supplements, supporting their ability to reduce methane emissions (although a comprehensive list is not accessible from their website). Such opinions are based on an internal evaluation by The Carbon Trust of reports and data submitted by applicant companies and are time limited (two years). Historically, such opinions have been issued to feed supplier Alltech Ltd. for a yeast culture and an encapsulated urea, neither of which exert direct effects on methane production (although both may reduce emission intensity), and to Harbro Ltd for 'Rumitech', a mixture of sensory Feed Additives. Recently, a validation opinion was issued to Swiss company Vetos Europe for a product ('Anavrin') described as 'a synergistic compound of essential oils, tannins and flavonoids'. Full ingredient composition is not known, but it is likely that Anavrin, like Rumitech, Agolin Ruminant and (an early example of this product type) Crina are mixtures of authorised sensory Feed Additives. The example of Anavrin can be used to explore The Carbon Trust process.

Anavrin is a mixture of feed additives, none of which are authorised (in the EU or GB) as zootechnical Feed Additives with favourable effects on the environment (and no request for such authorisation has been made at the time of writing - a search of the OpenEFSA website (7th November 2022), generated no hits: Open EFSA (europa.eu)). This highlights a paradox, if not a contradiction. The product has a Carbon Trust 'validation opinion' to support its marketing as a methane mitigator, but its use for that purpose is not authorised.

7.5 Greenhouse gas emission trading

Emission trading is one type of so called "market-based instruments", which incentivise actors to reduce their negative environmental impact without prescribing narrowly how to achieve this goal; the incentive structure can be fine-tuned to achieve a desired reduction goal (DeBoe, 2020). They can be either compulsory, where certain types of companies must participate in them, or voluntary, where the buyers (usually in other sectors) are purchasing carbon credits for voluntary GHG offsetting as a cheaper alternative to reduce their own emissions, often to improve their corporate social responsibility image (both payment for ecosystem services, PES, and voluntary carbon markets belong to this category).

Probably the most well-known emission trading relates to GHG emissions, i.e., the European Emission Trading Scheme (EU ETS) started in 2005 and more other systems established since – covering mainly the power and industry sectors. Environmental markets in the wider sense have been around in agriculture for a long time: water markets exist in many countries and biodiversity offset markets have also been used for some years. Related to land use and agriculture, recent years have seen the establishment of voluntary GHG trading schemes. Notably, the UK Woodland Carbon Code provides a certification scheme where landowners can sell carbon credits given their afforestation project meets the required standards. The Peatland Code follows a similar design, allowing money flow from voluntary carbon markets to peatland restoration projects. The Sustainable Soils Alliance is currently developing a Soil Carbon Code, which would be based on soil carbon sequestration.

It is worth stating that there is no 'nutrition code', analogous to the Woodland Carbon Code or Peatland Code, that would cover methodologies to reduce GHG emissions (especially enteric methane) through improved nutrition, including the use of methane-mitigating feed supplements.

Carbon markets specifically designed for agricultural production already exist in a few countries: the Climate Action Reserve, based in California, has currently 771 projects, of which more than one fifth are agricultural GHG mitigation (mainly anaerobic digestion of livestock manure). The Australian Emission Reduction Fund is a government-led scheme where businesses (including agriculture and vegetation management) can obtain Australian carbon credit units, which in turn they can sell on auctions. There is over a thousand projects in its register, including hundreds of agricultural related ones (mostly soil carbon sequestration). In Canada, the Alberta Emission Offset System offers carbon market access to farmers.

By its nature, emission trading requires regular information about the emissions of the actors. As measuring GHGs is still not practical at the whole farm level, only for some emission or sequestration sources (e.g., changes in above-ground biomass estimated by lidar remote sensing (Zolkos et al., 2013)), proxies for emissions are used for estimating the emissions. Proxies can be a combination of inputs and farm practices (for example, the amount of nitrogen fertiliser used and whether urease or nitrification inhibitors were applied with them). The emissions can be then estimated either for part of the farming operations (for example only nitrous oxide emissions from soils) or for the whole farm. The latter is often done by whole farm carbon calculators, which is an emerging field. Dozens of farm carbon calculators exist globally, and many are used in the UK. Currently there is no standardisation between them, and their comprehensiveness varies greatly, especially regarding the ability to reflect the emission reduction achievable by various farming practices (Leinonen et al., 2019). Using emission proxies, particularly inputs and practices easily observable or recognisable for farmers, have the advantage of easy "translation" into farm actions. However, a large number of practices need to be modelled in the carbon tools in order to allow for flexible choices at the farm.

7.5.1 Methane mitigating supplements in Voluntary Carbon Markets

The leading Voluntary Carbon Markets, in order of credits issued (and as of 2018) are Verra (US-based non-profit), Gold Standard (CH-based non-profit, with WWF as founder), the American Carbon Registry and Climate Action Reserve (US (California)-based) (Source: www.arbonics.com/knowledge-hub/abc-verra-and-gold-standard).

For this report we have considered methodologies for the use of methane mitigating feed supplements (and projects applying those methodologies) provided by Verra and Gold Standard.

7.5.2 Methodologies

The Verra methodology applicable to methane-mitigating feed supplements is 'VM0041 Methodology for the Reduction of Enteric Methane Emissions from Ruminants through the Use of Feed Ingredients, v2.0', approved on 21st December 2021. Although version 1.0 of this methodology was developed by Mootral, Version 2.0 was written by two eminent scientists in this field, and 'expands the applicability conditions to include any type of feed additive approved for animal use and with scientifically demonstrated efficacy and increases the stringency of the procedures by which project proponents establish the enteric methane emission reduction factor.' The method provides two options for determining the emissions (kg CH_4) in both 'baseline' and 'project' scenarios: (i) direct measurement or (ii) calculation using the general equation:

Baseline emissions = (GEI x Ym x N x D) x EC

Where:

GEI = Gross Energy intake (MJ/d) = dry matter intake x GE concentration, Ym = methane emission factor, drawn from tabulated values, N = number of animals in the group, D = days in the period, EC = energy content of methane.

Essentially the same equation is used to calculate emissions during the 'project' (i.e., the period when the feed supplement is used), with the addition of an Emission Reduction Factor, expressing the percentage reduction in methane emissions caused by the feed supplement.

The methodology states: 'The enteric emission reduction factor must be established through a meta-analysis of at least three peer-reviewed publications in reputable journals that are listed in the Science Citation Index Expanded. The efficacy of feed additives is influenced by dose, diet, production system, type of animal, and random variation. Therefore, a meta-analysis that considers these factors is necessary to obtain efficacy estimates within the range of the data used for the meta-analysis.' It also states: 'The conditions of the project must not deviate greatly from the conditions under which the enteric methane emissions reduction factor is determined in the meta-analysis of published results.'

These requirements are slightly more rigorous than the EFSA process for authorisation of zootechnical Feed Additives (three animal experiments) in that a meta-analysis is required.

The Gold Standard methodology applicable to methane-mitigating feed supplements is ‘Reducing methane emissions from enteric fermentation in dairy cows through application of feed supplements’, version 0.9.1 (described as ‘for road-testing’) dated March 2019. This was written by a consultancy and DSM. Like Verra, GS allow two options, or ‘approaches’, to quantify the effect of a methane-mitigating supplement: direct measurement within projects or modelling. For the latter, they say:

‘The supplement impact coefficient RYmG,y shall be determined from data provided by the supplier of the feed supplement, based on peer-reviewed data. The data shall describe the efficacy of each specific supplement’s emissions reductions in in-vivo application and define applicability of the data, especially dependencies on feed composition and product application, animal type, environmental and management conditions as well as any other factors that could impact the supplements performance with regard to emission reductions.’ While this does not specify the number of studies, the standard of proof and rigour of evidence required by the Gold Standard and Verra methodologies are similar, and broadly similar to the EFSA criteria for establishing efficacy when authorising zootechnical Feed Additives.

7.5.3 Projects within methodologies

Projects using Verra and Gold Standard methodologies are summarised in Table 12

Standard and methodology	Project ID	Project name	Geography	Project proponent (owner)	Technology and technology owner	Project status
Verra VM0041	2072	UK Cow Credit	UK	Mootral	Mootral	Registered
Verra VM0041	2751	Mooh Cooperative	CH	Mooh Cooperative	Agolin	Registration requested
Verra VM0041	2761	US Beef Cow Credit	US	Mootral	Mootral	Under development
Verra VM0041	2997	Blue Ocean Barns	US	Blue Ocean Barns	Blue Ocean Barns, Brominata*	Under development
Verra VM0041	3003	Barry Callebaut	US	Barry Callebaut Sourcing AG	Agolin	Under validation
Gold Standard	10822	Barry Callebaut Dairy	US, NL	Barry Callebaut	Bovaer, DSM	Gold Standard Certified

* 'Brominata' is the brand name for *Asparagopsis* seaweed authorised for use in California and supplied by Blue Ocean Barns, Inc, under licence from Future Feed pty.

The projects 'UK Cow Credit' (Mootral), 'Mooh Cooperative' (Agolin) and 'Barry Callebaut Dairy' (Bovaer) are reviewed briefly below (i.e., considering one project for each additive).

In UK Cow Credit, the Emission Reduction Factor for Mootral is 20.7% for Holstein cows and 38.3% for Jerseys. These are the values reported by Vrancken et al. (2019) for reductions in methane concentration in exhalations and eructations measured using a Laser Methane Detector on one occasion 12 weeks after commencing Mootral supplementation, compared with values measured on one occasion four weeks later, after Mootral withdrawal. The same 15 Holstein and 15 Jersey cows were measured on both occasions. Thus, this project uses Option 2 (measurement) within Verra methodology VM0041. It assumes that methane emission (g/d) is proportional to methane concentration (mg/kg in breath). As with any experiment where treatments are imposed sequentially, there is a risk that responses to treatment will be confounded by other factors that do or may vary with time, such as stage of lactation, climate, diet composition or feed quality.

The validation report for the UK Cow Credit project, written by the Verification/Validation Body (VBB) contracted by Mootral, concludes that, because direct measurements were used, 'the efficacy of the supplement is valid'. This report also includes this response from Verra:

'It has been clarified that the study used as supporting evidence was conducted in the same environment, conditions, and location as the project activity. This is sufficient to justify the use of a single study to validate the supplement's efficacy. This finding is closed and no further response is required.

As this is a new technology with limited application experience, Verra would like to make it clear that we will require further supporting evidence beyond the Vrancken study to demonstrate the efficacy of the supplement for any application outside of the current project. Efficacy research should be conducted in vivo, be based on an appropriate sample size, explore durability of the effect over time and use reliable measurement techniques.'

This means that Verra are not accepting Vrancken et al. (2019) as sufficient evidence to support the use of Mootral on other farms. Further work is needed to widen the inference space. The Verra website does not provide any documents dated later than 4th November 2020.

In the 'Mooh Cooperative' project in Switzerland, the Emission Reduction Factor (applied to the baseline estimate of methane production, g/d) for Agolin Ruminant is 7.4%, based on a meta-analysis of three experiments (Klop et al., 2017; Hart et al., 2019 and Carazzco et al., 2020). This is marginally less than the crude mean reduction of 9.1% calculated for these three studies in this report (Table 5). The proposed standard of rigour (three in vivo experiments in the target species) is thus similar to that required by the EU regulatory process for zootechnical Feed Additives. The Mooh Cooperative project is not yet registered or validated, so it remains to be seen if the proposed approach is accepted by Verra.

According to the Gold Standard impact registry, 'Barry Callebaut Dairy' is a Gold Standard Certified Project covering the crediting period March 2019 to March 2020: however, no credits are shown as having been generated or sold and developments since 2020 are not known. Further information is not available from the Gold Standard project registry.

7.5.3 Effectiveness of the instrument

As carbon markets for agriculture are a recent phenomenon, their effectiveness has not been evaluated yet. A large number of studies have been carried out about the effectiveness of the EU ETS, and they conclude that it achieves the goal of emission reduction, though estimates on the actual effect vary, putting the annual emission reduction around 2-3% of the capped market (Narassimhan et al., 2018). It is important to note that participation in the EU ETS is mandatory in the covered sectors. In a broader study, comparing countries, carbon pricing mechanisms including carbon taxes were shown to slow down the growth in per capita GHG emissions (Kiss & Popovics, 2021), adding to the evidence on their effectiveness.

As summarised by Grosjean et al. (2016), multiple studies suggest that emission trading would reduce the overall cost of agricultural GHG mitigation in Europe compared to other policy instruments. Nevertheless, there are key obstacles in rolling out mandatory emission trading in the sector. First of all, transaction costs (particularly for smaller farmers) can be potentially high (**Error! Reference source not found.**2). Though an emission trading scheme might offer an advantage in this respect over individually regulated or incentivised practices. The scheme could cover all the GHG (or even nitrogen-pollution) related farm activities, without the need for further schemes, and the lower the number of schemes, the lower the transaction costs are (Mettepenningen et al., 2011).

When establishing a mandatory emission trading scheme, the fairness and equity are of high importance, and concerns decisions on payment thresholds (relative to current baseline emissions), the distribution of quotas and coverage of both emission sources (e.g., all or only soil carbon sequestration) and farms (size and activity considerations). With voluntary schemes these decisions are not needed, as every farmer who is willing to reduce their emissions could sell carbon credits. Voluntary carbon trading activities can also reveal key information for the architecture of mandatory schemes. However, by design, voluntary markets offer higher financial rewards for those who have not reduced their emissions yet than for those who have already made advances in GHG mitigation Grosjean et al., (2016), potentially creating a perverse incentive to increase emissions before joining the scheme. Furthermore, agriculture joining to voluntary carbon markets could contribute to the problems these markets might create, namely reducing the net zero efforts by other players (Climate Change Committee 2022), and risks a potential future conflict between voluntary sales of carbon credits and any mandatory requirements for farms to reduce their emissions.

7.5.4 Considerations for UK policy landscape and policy mechanism

While an emission trading scheme for agriculture does not exist in the UK, the elements and blueprints for such a scheme are available from existing carbon codes and carbon farming initiatives. The Sustainable Soils Alliance is currently developing a Soil Carbon Code, which would be based on soil carbon sequestration and other developments might also be in place. Given the rapid changes in this area, farmers and the industry might benefit from preparing for the opportunity of a voluntary carbon market in the UK by developing a protocol for carbon credit accounting from the use of feed additives (analogous to the Woodland and Peatland Codes). Starting points are provided by the Alberta Emission Offset System's "Quantification protocol for reducing greenhouse gas emissions from fed cattle", dating from 2016. and the voluntary standards of Verra and Gold Standard. All model an enteric emission factor based on diet composition in a broadly similar way.

7.6 Fiscal incentives

Fiscal incentives refer to payments provided for farmers given they implement the promoted practices or achieve a minimum environmental outcome on their farms. They range from requirements to receive basic support payments (i.e., cross-compliance and greening payments in the outgoing Common Agricultural Policy) to additional payments for further environmental actions, like the Countryside Stewardship schemes (similarly part of the outgoing Common Agricultural Policy) and the planned Environmental Land Management schemes in England. The former type of incentive can also be considered as a hybrid instrument, as it merges regulatory requirements with fiscal incentives (DeBoe, 2020).

7.6.1 Effectiveness of the instrument

The scientific literature around the environmental effectiveness of fiscal incentives is not conclusive but emphasises the important of the context and implementation details.

In both Denmark and the Netherlands the package of policies targeting the release of nitrogen compounds to the groundwater and waterbodies have been considered effective in reducing pollution, though they have not managed to achieve the target water quality levels (Dalgaard et al., 2014; van Grinsven et al., 2016). In both countries the policy package was mixed, consisting of a range of regulatory and voluntary instruments; one of the core elements was the Nitrate Vulnerable Zone stipulations as part of the cross-compliance. The Nitrate Vulnerable Zone restricts the use of livestock manures on agricultural land and for both countries covers their entire area. Importantly, the improvements have been achieved over two decades, with the specific requirements to farmers strengthening over time.

While strict nitrogen application rules contributed to improved water quality in some countries, the CAP, with its cross-compliance and agri-environmental payments, is generally not considered an overarching success for environmental sustainability. Overall, the policy has failed to provide the sustainability outcomes it set out to achieve, though certain elements of it were successful. Specifically, agri-environmental schemes targeting biodiversity enhancement have been effective in general, noting that this effectiveness depends on aspects like the type of the targeted area and the surrounding landscape (Batáry et al., 2015). Similarly, a study looking at fertiliser and agrochemical use as indicators for sustainable practices found that participation in agri-environment schemes improved environmental performance in four out of five countries (Arata & Sckokai, 2016). On the other hand, the greening payments, a form of cross-compliance targeting biodiversity, have not been successful (Pardo et al., 2020), neither the agri-environmental schemes aiming to reduce greenhouse gas emission (European Court of Auditors, 2021).

7.6.2 Considerations for UK policy landscape and policy mechanism

In the UK context, the new agricultural support scheme in England and Wales is changing to move away from direct payments: farmers will be supported to improve the environment and animal health and welfare (Defra 2020). The expected outcome is that most farmers will make changes on their farms, reducing the overall environmental burden of UK food production and modernising their farming practices. However, most of the options target crop production, leaving few supported practices for livestock farmers (Defra 2022). Enteric methane emissions are a particular GHG source area where so far there is no clear indication that any options will be proposed, i.e. there is a risk that government organised fiscal incentives are under-utilised for the purpose of promoting the uptake of feed additives. In contrast, in the Netherlands it is expected that methane mitigating feed supplements (such as Bovaer and SilvAir) will be incorporated into the Kringloopwijzer system ('Annual Nutrient Cycling Assessment') from 2023 onwards. Models to predict the efficacy of these supplements will be incorporated into Kringloopwijzer's existing Tier III model of methane emissions. Use of the Kringloopwojzer tool is mandatory for all Dutch milk suppliers, covering almost 100% of all Dutch farms.

7.6.3 Direct payment for use of methane mitigating feed supplements

There are examples of the use of methane mitigating feed supplements on farm being incentivised directly by the farmer's customer.

Arla recently announced the introduction of a Sustainability Incentive for UK dairy farmers applicable to milk produced from July 2023 onwards (press release: Arla earmarks up to 500 mEUR annually for rewarding climate activities on farm | Arla). This points-based system will reward farmers with up to €0.024/kg milk (rising later to €0.03/kg milk), with the most effective mitigation measures generating more points and more revenue. Use of Bovaer will not be one of the first tranche of options for earning points, as Arla's field trials with the product are not yet completed. If it is included at a later date, we understand that an app will be used to track product to farm (verifying delivery to farm) and calculate emissions according to the NDF and fat concentrations in the diet.

In Denmark, Danone are also understood to be incentivising the use of Bovaer through the milk price (increased milk price of €0.02/litre, N. Walker, DSM, personal communication). In this case, the incentive for the milk purchaser is anticipated growth in product (yoghurt) sales through their marketing of a 'green' product.

It would seem possible for Danone and Arla to generate carbon credits for the methane mitigation achieved through these projects, using the methodology developed by DSM for use within a methodology of Gold Standard (see below). Such credits could then be used by Danone and Arla against their own emissions or sold on voluntary carbon markets.

7.7 Commentary on the standard of evidence required to support operation of markets

In general, methane-mitigating feed supplements do not improve productivity, so, once authorised, their adoption, and the ensuing methane mitigation, will not be achieved without new market levers. (An exception may be Agolin Ruminant, where product adoption incentivised by benefits to feed efficiency is resulting in methane mitigation that is neither accounted for nor directly rewarded.)

Markets for methane mitigation are in the process of being created. The evidential requirements for current methodologies in voluntary carbon markets (Verra and Gold Standard) appear broadly similar to regulatory requirements for evidence to authorise market entry.

Leaving aside important questions of barriers to the use of voluntary carbon markets by individual farmers (low accessibility due to high cost and high time commitment), the adequacy of their evidential requirements can be questioned. Based on the evidence currently available we will, collectively, take credit for mitigation that has not really been achieved (i.e., make some Type I errors) and miss some opportunities to achieve real mitigation (i.e., make some Type II errors). Progressive improvement of the methodologies used by voluntary carbon markets is an important means of translating the promise of authorised methane mitigating feed supplements into real methane mitigation. Such improvement can only come if the pyramid of evidence continues to be built and used. This is an argument for continued public investment, in partnership with private, in applied R&D on existing authorised feed supplements (for example, to support experiments testing interactions between supplements, or a rolling programme to maintain a database of evidence and conduct meta-analyses).

Direct supply chains are at liberty to set their own standards of evidence (provided legal requirements have been met). In this context, it is perhaps encouraging that Arla is choosing not to rely only on the evidence used by DSM to secure EU regulatory approval for Bovaer, but are conducting their own trials (building the pyramid of evidence) before deciding whether to incentivise their suppliers, through the milk price, to use this product.

Finally, and as a challenge to what are fragmented dairy, beef and lamb sectors, the UK might move further, faster in achieving real methane mitigation by acting collectively, following the Dutch example with 'Kringloopwijzer'.

7.8 Conclusions

It can be concluded from the above summary that there is no "silver bullet" for significantly increasing the uptake of actions to reduce greenhouse gas emissions, but some general observations from past experiences with agri-environmental policy and industry initiatives emerge. Importantly, voluntary actions are useful to raise the profile of environmental issues and make possible practical solutions better known and accepted, but their impact is limited, both amongst producers and consumers, unless the financial compensation compensates for the implementation costs (Piñeiro et al., 2020). Mandatory participation in schemes provides much wider reach but buy-in needs to be built up before the requirements could be introduced and then potentially strengthened. It is noteworthy that incorporation of methane-mitigating feed supplements into the Dutch Kringloopwijzer system will start 10 years after the introduction of that system with a focus on curbing N and P pollution. Overall, often mixes of instruments are the most effective, applied at multiple scales (Disdier & Marette, 2012; Lee et al., 2019). It is worth to mention the role of evaluation in policy and industry instruments: continuous and *ex post* evaluation built in the instruments provide useful insights both for improving the instrument itself and for giving insights for better designs in the future (Knook et al., 2020).

Within such a progressive approach the role of supply chain actors is very important, especially in providing opportunities for voluntary participation, and thus "preparing" the wider sector for transformation. There is already an increasing number of initiatives across the food supply chain to promote sustainable agricultural activities, also in particular the use of methane reducing feed additives. With the interest in the supply chain for red meat products with lower GHG emissions, feed producers might include low-methane feed additives in their products, processors or retailers might require even more low-carbon practices from farmers, or domestic demand for red meet might drop. Such changes would impact the effectiveness and costs of any scheme, either with synergistic (e.g., more competition amongst low-carbon feed products can help farmers to get them at lower prices) or antagonistic (e.g., a strong drive for low-carbon meat from processors would drastically reduce the additionality of a scheme initiated elsewhere in the supply chain) effects.

At the same time the policy and economic landscape is rapidly changing too, not only regarding environmental regulations, but wider issues, like demand for products, income support policies, land tenure, the energy market. These rapid changes and new opportunities might create some confusion and even risk to participation in new initiatives. Involvement of third-party organisations and aligning to existing initiatives could reduce these obstacles and flexible instruments (e.g., carbon markets) and options with low public money payments (e.g., voluntary standards, product labelling) can reduce the adverse effects from sudden developments in the future market and policy environment.

While creating new initiatives, it is important to keep in mind the key characteristics of successful interventions: low cost, targeted environmental effect (with no "leakage" or rebound effect), equitability, flexibility and enforceability. It is often the details of the interventions which finally define how much these goals are achieved. These include the overall design, the engagement from farming during both the design phase and implementation, the monitoring activities, the scientific robustness behind the intended environmental effect, the quality and appropriateness of the advice given to the farmers. Furthermore, the synergies and trade-offs in pollutants (greenhouse gases, soil, water and air pollutants) and other environmental outcomes (like biodiversity) necessitate that key sustainability indicators are measured – at least on a sample of farms – to in order to identify any potential adverse outcomes of any instrument (like the increase in embedded emissions or land use in animal feed).

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