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Potential for mitigating enteric methane emissions from agriculture through technical measures: a literature review

Potential for mitigating enteric methane emissions from agriculture through technical measures: a literature review

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Summary

Enteric methane emissions from the agricultural sector have gained traction as a potential source of greenhouse gas mitigation compared to emissions from more tractable sources, such as the fossil-fuel industry. The aim of the ensuing literature review is to evaluate the efficacy, cost-effectiveness, and state of development of technical measures for abating enteric methane emissions from agriculture, i.e., beyond reducing livestock production. We also provide a discussion of the current status of policy instruments for incentivising methane abatement.

We find that:

- Promising technical measures exist, of which the feed additive 3-Nitrooxypropanol is the frontrunner with proven efficacy on reducing methane production in the rumen and with no adverse effects on animal productivity. However, long-run effects of the additive require more research.
- Additives with an effect on absolute emissions are currently not effective in grazing systems due to the need for regular supplementation. Measures that can be effective in all kinds of agricultural livestock systems are under development. Oral slow-release technology, genome editing and permanent methane mitigation via selective breeding or vaccination are examples of such.
- Lack of incentives for farmers to implement mitigation measures is preventing widespread implementation. Appropriate economic policy is required to facilitate utilisation of technical measures. Such novel policy is proposed by New Zealand and Denmark, suggested to be implemented during 2025 and 2027[1], respectively.

1 Introduction

Globally, agriculture emits 21 % of anthropogenic greenhouse gases (GHG) (Reisinger et al., 2021). Enteric methane (CH_4) emissions from ruminants is the largest source of agricultural emissions with roughly 6 % of global anthropogenic GHG emissions (Vranken et al., 2019). Methane is the second highest contributor to global warming, next to carbon dioxide (CO_2), (Roques et al., 2024) and its implications are particularly strong as it has an effect which is 28 times stronger than CO_2 over a 100-year period (Kelly & Kebreab, 2023). Moreover, methane has a short-lived atmospheric lifespan of about 10 years, meaning reductions have a relatively quick effect on global warming (Nisbet et al., 2020). The strong effect in combination with the short lifespan makes limiting enteric methane

[1] The Danish government assigned expert group suggest gradual implementation of the tax, starting in 2027 and full taxation during 2030.

emissions an impactful, and arguably necessary, contributor to reaching the 1.5°C target by 2050 (Vranken et al., 2019). The importance of methane abatement is politically recognised through the Global Methane Pledge, which has been signed by over 110 countries with the goal of reducing methane emissions by 30 % by 2030 compared to the 2020 level (Beauchemin et al., 2022).

Enteric methane emissions have continuously increased over recent decades in tact with the demand for ruminant-based food products and is projected to keep increasing (Reisinger et al., 2021). Such emissions have historically been considered relatively difficult to mitigate (Nisbet et al., 2020). One reason is that cars, for instance, can be manufactured in ways that results in vehicles with less emissions, while methane emissions from cows are biological, and harder to reduce without simply reducing herd sizes. However, potential for cost effective mitigation in the agricultural sector is increasing with recent technical advancements (Ungerfeld, 2022).

The large climate impact of methane emissions, short atmospheric lifespan and anticipated increased demand for ruminant based agricultural products has led to a an explosion of research in an attempt to develop effective technical abatement strategies and measures (Nisbet et al., 2020). The aim of the ensuing literature review is to identify and evaluate the efficacy, cost-effectiveness, and state of development of the most relevant technical enteric methane abatement measures beyond reducing livestock production. We also provide a discussion of the current status of policy for incentivising methane abatement.

The Google scholar database was scanned for publications including the search terms:

“agriculture” AND “methane” AND “policy” AND “enteric”.

We are interested in technical measures, but do not explicitly include “technical” in the search string to broaden the result spectrum and, for instance, not exclude policy relevant papers, such as taxation analyses in the agricultural sector that are not focused on the technical mitigation measures themselves. We still expect to capture relevant articles about technical measures through the search terms. The first 200 publications published no earlier than 2010 were reviewed by title, abstract and finally the main text if the article was considered relevant. The literature review then proceeded with a snowballing technique whereby reference lists of key publications were scanned to identify novel studies that were missed by the main search. Lastly, a deep dive into relevant research fields selected through the scanning was done to gain a more complete overview of the literature.

Enteric methane abatement measures can, in most cases, be divided into one of the following extensively researched subgroups: management, breeding, nutrition or rumen manipulation (Beauchemin et al., 2020; Temesgen et al., 2021). Such technical mitigation measures can be incentivised via economic policy. Policy interventions are less researched than the technical measures in a methane mitigation context, which could be explained by lack of empirical examples. This, as agriculture has been historically exempted from GHG mitigation policies (Svarer et al., 2024).

The paper is structured as follows: Chapter 2 briefly describes the methane-producing enteric fermentation process in ruminants and associated metrics. Chapter 3 presents the efficacy, cost-effectiveness, and state of development of the most prevalent technical abatement measures. The status of policy for incentivising methane abatement is outlined in Chapter 4. Lastly, in Chapter 5, we conclude about the current potential for technical mitigation of enteric methane emissions from agriculture.

2 Enteric Fermentation Process

Methanogenesis is the name of the complete methane creating process via ruminant feed digestion. The simplified process starts with consumption of carbohydrates via feeds, which are fermented by microbes, and hydrogen (H_2) is produced in the process. The hydrogen is then utilised by microbes known as methanogens to produce methane, which is mainly emitted via belching (Roques et al., 2024). A detailed explanation of the entire process can, for instance, be found in Hook et al. (2010) or Ungerfeld (2020). Methanogenesis is important to ruminants' health since metabolic hydrogen would otherwise be continuously gathered in the rumen (Galyean & Hales, 2024) and possibly have negative effects on digestion (Honan et al., 2021).

Methane emissions are commonly measured via the following three metrics: i) Methane production (g CH_4/day), ii) methane intensity (g CH_4/kg product) and iii) methane yield per unit consumed fodder (g CH_4/kg dry matter intake (DMI)) (Marumo et al., 2023). Methane production is interchangeable with absolute emissions, while intensity and yield improvements are relative measures that do not necessarily imply less emissions per animal. Methane intensity can, for instance, be improved upon through productivity enhancements (Roques et al., 2024). Methane yield connects emissions to DMI, which provides useful information as DMI has been recognised to clearly affect methane emissions (Galyean & Hales, 2024).

3 Technical Measures for Enteric Methane Abatement

3.1 Management Strategies

Enteric methane mitigation through management strategies aim to reduce emission intensity by increasing animal productivity and, therefore, enable production of the same quantity with fewer animals (Beauchemin et al., 2020). Productivity improvements have the potential to be an effective strategy with implied economic incentives for farmers, as the gains are not purely environmental (Hristov et al., 2013). For instance, Eskhult et al. (2023) study the relationship between agricultural productivity and emissions by simulating the production level of 2013 with the productivity of 1985 and 2013, respectively. They conclude that productivity improvements allow identical output with 7 % lower methane emissions in 2013. However, absolute abatement relies on the herd sizes being reduced (Hristov et al., 2013). The likelihood of this can be questioned, as farmers could be economically incentivised to increase production given the increased productivity and thereby partially, or completely, off-set the potential absolute emission reduction (Beauchemin et al., 2020).

Examples of management strategies include changing first calving age, replacement rate and grazing management to reduce emission intensity. Dall-Orsoletta et al. (2019) found that reducing replacement rate by 10 % or setting first calving age to two resulted in 13.6 % and 8.7 % lower methane intensity respectively. The lower emissions were a result of reduced numbers of animals required to produce a given quantity and farmers can, thus, lower feed-related expenses while maintaining the same level of production and be economically rewarded for environmentally friendly management strategies.

Grazing management can reduce emission intensity or yield via improved forage quality. Young plants are of higher quality as they include less neutral detergent fibre (NDF) and more fermentation-friendly carbohydrates (Temesgen et al., 2021). High quality forage has been observed to increase productivity of animals and, therefore, reduce emission intensity (Beauchemin et al., 2020). Consumption of younger forage plants also leads to digestibility improvements and, hence, less emissions per DMI (Gerber et al., 2013).

Chiavegato et al. (2015) studies the effect of grazing management on enteric methane emissions through the anticipated effect on forage quality. The management strategies consist of alterations in stocking rate and density, which is expected to impact forage quality. Stocking rate is the overall number of animals per hectare pasture, while stocking density is the liveweight of grazing animals per hectare. The former is calculated based on pastures utilised over the course of a year, including pasture sections that are currently ungrazed and in a resting period. The latter is based on the particular part of the overall pastures grazed at a given time. The experiment shows that forage quality is affected by grazing management, but emissions remain unchanged. Chiavegato et al. (2015) suspect that enough high-quality forage remains for cows to be able to selectively eat, despite the overall quality being worse. Therefore, it is likely that the efficacy of grazing management strategies as emission mitigation tools are farm specific.

Farmers are in theory economically incentivised to run livestock operations efficiently by default, i.e., with little to no improvements to be made in productivity given current conditions. Management strategies as an overall concept is, thereby, limited and farm-specific, with the highest effectiveness likely being in developing countries, as they generally utilise a higher number of animals with low productivity to produce any given quantity (Hristov et al., 2013).

3.2 Breeding

Selective breeding abates emissions by facilitating the continuation of breeding lines with lower natural emission rates. It is a promising mitigation measure as it is permanent and cumulative over generations (Roques et al., 2024). The permanent and cumulative effect allows for potentially cost-effective emission abatement (de Haas et al., 2021b). Differences in emissions between individual animals, breeds and time have been observed, which has led to positive prospects of breeding as a mitigation tool (Cassandro et al., 2013). Some level of heritability of enteric methane production has been consistently estimated and agreed upon across the research. Heritability is measured on a scale of 0 to 1, where 0 means no genetic heritability and 1 implies extreme heritability of a particular trait (Roques et al., 2024). de Haas et al. (2021a) estimate emission heritability of dairy cows to 0.23, which is in line with Roques et al. (2024), who presents a heritability between 0.11 to 0.45 for cattle and between 0.13 to 0.29 for sheep based on previous research.

Selectively breeding for low emissions comes with the risk of indirectly and negatively affecting other desired traits, such as productivity (Hristov et al., 2013). This risk is further exacerbated by the fact that the genetic basis of ruminant methane emissions requires more research (Roques et al., 2024). In addition, direct selection of animals with low emission traits is expensive as methane emissions are costly to measure individually and accurately, with respiratory chambers being the gold standard (Roques et al., 2024). Therefore, indirect selection for traits with lower measurement costs that are correlated with methane emissions is a more cost-effective mitigation strategy (Cassandro et al., 2013). For example, feed-efficiency is believed to be associated with emissions, but the correlation is not consistent across individuals as external factors affect the relationship. Hence, reducing emissions by breeding for animal traits associated with low emissions (for instance feed-efficiency) does not only reduce costs, but will also result in suboptimal identification of animals with low natural emission rates, which implies lower mitigation potential (Fouts et al., 2022).

The required time commitment of selective breeding studies has resulted in limited experimental studies within the field. However, de Haas et al. (2021b) simulated the effect of implementing low emissions into Dutch breeding goals, and estimate it to decrease methane intensity by 24 % by 2050. Rowe et al. (2019) conducted a novel in vivo study on selective breeding for emission reduction spanning over ten years in New Zealand. Out of 1000 sheep, the breeding lines of the 200 most emission friendly ones emitted, on average, 10-12 % less than the breeding lines of the control group.

Breeding based on genomic information is an innovate approach within the selective breeding field. DNA is analysed and compared to a DNA database with the purpose of identifying and selecting animals with low emissions levels (Roques et al., 2024). The difference between selective and genomic breeding is that the former measures actual emissions, or traits associated with actual emissions, while the latter selects breeding lines while only studying DNA. The strategy does have a high barrier to entry as thousands of DNA-samples need to be gathered and analysed to establish a reference group (Pickering et al., 2015). Genomic breeding is in the development stage and more research is required to establish potential pleiotropic effects, which could imply negative consequences for farmers by, for instance, reduced productivity. Similarly to traditional breeding strategies, genomic breeding also has a permanent and cumulative effect on emissions. Additionally, methane mitigation via breeding is not limited in pastoral grazing systems, in contrast to feed supplementing measures (see below). Hence, breeding is a promising measure with potential for absolute emission reduction (Roques et al., 2024).

If in vivo studies can establish effectiveness of selective breeding, it will likely exit the development stage and have potential to be an effective mitigating measure, given that methane measurement techniques are accurate and cost-effective. Genomic breeding provides an alternative to direct emission measurements and could very well develop into a cost-effective way to identify and select breeding lines with low-emitting animals.

3.3 Nutritional Dietary Measures

Nutritional abatement measures reduce emissions by dietary means without methanogenesis being directly affected. Instead, methane emissions are reduced by, for instance, facilitating the digestive process. Hence, nutritional strategies often affect emission intensity, rather than absolute emissions (Roques et al., 2024).

3.3.1 Lipid supplementation

Extensive research has proven the efficacy of dietary lipid supplementation, such as oils, as a strategy to reduce enteric methane emissions (Gerber et al., 2013). Lipid is a chemical umbrella term for fats and fatty acids (Honan et al., 2021) and they have potential to reduce emissions via several channels (Beauchemin et al., 2020). Firstly, almost all lipids are not digested in the rumen, which directly leads to reduced emissions as less organic matter is processed in the rumen (Caro et al., 2016). Secondly, they limit available hydrogen for the methanogenic process via hydrogenation (Temesgen et al., 2021). Lastly, by facilitating propionic production, which reduces emissions by competing for hydrogen (Honan et al., 2021). The first channel is strictly nutritional, while the latter two could be regarded as rumen manipulation. Hence, lipid supplementation is not a purely nutritional dietary measure but is still mainly categorised as one throughout the literature (Arndt et al., 2021; Beauchemin et al., 2020; Roques et al., 2024). By supplementing lipids equal to a small fraction (less than 4 %) of dry matter intake, emissions can be reduced by up to 20 %.

The proven abatement effect makes lipid supplementation one of the most promising dietary agricultural GHG abatement measures (Caro et al., 2016). However, potential negative side-effects on milk and meat quality are preventive factors (Beauchemin et al., 2020). Newer research suggests that such production effects occur when the level of lipid supplementation is too high (Roques et al., 2024). Additionally, Caro et al. (2016) estimate lipid supplementation to affect other GHG channels than enteric methane and conclude that manure-based methane emissions are anticipated to decline, while manure-based nitrous oxide emissions increase, which dampens the net mitigation potential. Furthermore, Lipids are relatively costly to supplement (Beauchemin et al., 2020), but the strong and evident abatement effect still implies cost-effectiveness relative to other dietary nutritional alternatives (Gerber, 2013).

3.3.2 Increasing feed concentrates

Increasing the level of feed concentrated with nutrients in the diet has been clearly and consistently observed to reduce methane yield and intensity throughout the research (Martin et al., 2010). The reduction is a result of concentrate-rich diets being more digestible than entirely forage-based alternatives such as grass pasture or silage (Caro et al., 2016). The reason being that increased levels of concentrates imply a greater share of starch in the diet relative to cellulose that is present to a higher degree in forage-based diets. Starch has a quicker digestion and fermentation process and, thus, results in lower emissions per kg DMI (Beauchemin et al., 2020). However, the effectiveness of concentrates as a tool for emission mitigation may depend on several factors including grain type, animal-specific fibre digestibility and rumen function, which complicates the matter (Gerber et al., 2013). Additionally, the opportunity cost in terms of food for human consumption, makes an increasing level in animal diets a politically difficult issue (Roques et al., 2024) and it is unclear whether net total GHG emissions decline when the production of the concentrates themselves is included in the analysis (Gerber et al., 2013).

Overall, nutritional emission abatement measures have been proven to be effective methane mitigators, but suffer from drawbacks, such as uncertainty regarding net GHG effect, negative production effects or opportunity cost of human consumption, that hinder widespread implementation of the measures. Implementation is also restricted in grazing systems due to difficulties of regular supplementation. Furthermore, emission reductions are generally in terms of intensity, which requires reductions in animal stocks to translate into absolute abatement (Roques et al., 2024).

3.4 Rumen manipulation

Rumen manipulation reduces enteric methane emissions by impeding enzymes that are necessary for the methanogenic process and, hence, affect the methanogenic pathway directly. The direct effect implies that rumen manipulation does not only reduce emission intensity, but also absolute emissions (Roques et al., 2024). It has been recognised as the most effective enteric methane mitigation strategy (Kelly & Kebreab, 2023) and some measures with this characterisation have also been proven to not have adverse effects on production or product quality (Arndt et al., 2021).

3.4.1 Nitrooxypropanol (3-NOP)

Nitrooxypropanol (3-NOP) is a feed additive that inhibits enteric methane emissions by catalysing the last step of methanogenesis (i.e. methane production) (Roques et al., 2024). It is proven as an emission mitigator on beef and dairy cattle with research estimating the effect to range between 20 to 80 % depending on animal type, feeding system, and dose (Searchinger et al., 2021). Although, meta analyses suggest that the effect often is estimated to be between 25 to 30 % (Hristov et al., 2022; Kebreab et al., 2023). Melgar et al. (2020) specifically study dose dependency of abatement in an experimental study and find that abatement increases with dosing. The studied dosing range is 0-200 mg/kg DMI with a methane reduction ranging from 22 to 40 % and an average of 31 %. However, methane production was not statistically further reduced above a 3-NOP dose of 100 mg/kg DMI. This result is in line with the meta study of Searchinger et al. (2021), who conclude that the relationship between methane and 3-NOP dosing often is capped at 40 % abatement. However, some exceptions exist throughout the literature. McGinn et al. (2019) finds a reduction of methane production by 70 % with a dose of 125 mg/kg DMI and Vyas et al. (2018) estimates a dose of 200 mg/kg DMI to reduce methane production by 84 %. Meta analyses by Dijkstra et al. (2018) and Kebreab et al. (2023) attempt to explain the variation in the results of experimental research regarding cattle and conclude that several factors impact the mitigation effectiveness of 3-NOP. These include NDF and crude fat share of the diet, dose, and type of production (dairy/beef cattle).

However, the research regarding 3-NOP consists of few studies about the long-tern effects (Hristov, 2024). van Gastelen et al. (2024) contributes to the research with an experimental long-term study of 3-NOP on dairy cows spanning over 12 months. They find an average reduction of methane production (g CH_4/kg) by 20 %. Notably, their result indicates a non-continuous reduction in abatement effect. The reduction over time was primarily evident within each segment of the lactating period (early, mid and late lactation) and the abatement effect was on an upward trajectory during the last weeks of the experimental period. The authors conclude that length of supplementation seems to reduce the mitigation effect, but also that variation in diet is evidently impactful and perhaps even more than the length of the supplementation period.

In contrast to meta analyses by Kebreab et al. (2023) and Dijkstra et al. (2018), van Gastelen et al. (2024) does not find NDF share of diets to impact the abatement effect of 3-NOP. In addition, the authors also find supplementation of the additive to positively impact product characteristics through increased milk fat and protein. The findings highlight the need for more long-term studies to assess the long-run effect of 3-NOP on methane emissions.

Despite the variation in the estimated effect, the literature unanimously concludes that 3-NOP significantly inhibits methane emissions. Additionally, Arndt et al. (2021) conduct a meta-analysis and find that 3-NOP has no negative effect on animal production or product quality. Research regarding the effect on sheep is limited. Only one experimental study by Martínez-Fernández et al. (2014) is published and estimates the effect to roughly be in the same range as the research regarding cattle, with emission reduction of about 25 % by supplementing 100 mg 3-NOP per sheep and day. The promising research has led to an assessment of 3-NOP by the European Food Safety Authority (EFSA) who has confirmed the efficacy and safety of the substance for dairy cows (Bampidis et al., 2021). Based on the extensive research and the positive evaluation of EFSA, 3-NOP is the active substance in the first commercially approved feed additive with environmental benefits in the EU as of February 2022 (Palangi & Lackner, 2022).

The cost to farmers of purchasing 3-NOP could be a significant barrier to an industry-wide implementation, as the additive is developed in the private sector and patented. Therefore, there is an uncertainty regarding future costs, but they are likely to be reduced as the ingredients themselves are not costly (Searchinger et al., 2021). It is evident that 3-NOP is a promising measure for emission abatement with no observed health risk or adverse effects on production, possibility of being mass-produced at low unit cost and with a consistently estimated effectiveness.

3.4.2 Macroalgae species

Feed additives based on macroalgae species alter methanogenesis by binding with enzymes that would otherwise be used in the methanogenic process (Roques et al., 2024). In particular, the red macroalgae species Asparagopsis taxiformis and Asparagopsis armata are the most extensively studied with promising results (Lileikis et al., 2023). The species have been estimated to reduce methane production by up to 98.9 % in vitro (Honan et al., 2021). A long-term in vivo study on 21 beef steers over 147 days by Roque et al. (2021) estimates the effect on methane yield to be between 45 and 68 %, depending on low (0.25) or high (0.5) dosing measured as percent of DMI. The paper finds no adverse effects on average daily gain (kg/day), but some reductions in DMI. Negative, unintended effects on product quality or animal productivity of supplementation have occasionally been observed throughout the research (Roques et al., 2024). For instance, reduced milk yield (Roque et al., 2019; Stefenoni et al., 2021) increased Ideoine concentrations with associated human health risks at consumption (Fouts et al., 2022) and reduced volatile fatty acids in the rumen, which causes energy losses for the animal (Honan et al., 2021). However, most studies with an Asparagopsis dose below 1 % of DMI find no determinantal effects on product quality or health associated variables (Roques et al., 2024). Yet, studies with adverse negative effects remain a barrier to extensive implementation of the additive (Honan et al., 2021) and more long-term studies with large numbers of animals are needed to further understand the complete effects (Roques et al., 2024).

Asparagopsis supplementation is further limited by mostly being gathered in the wild and widespread commercial distribution would, hence, be difficult to implement. However, commercial cultivation is being attempted (Black et al., 2021). Moreover, regulatory barriers additionally complicate the use of Asparagopsis as a methane mitigator (Honan et al., 2021). Consequently, this type of additive seems effective as a methane mitigator, but the current combination of potential adverse production effects, regulatory barriers and difficulties to produce make widespread implementation difficult.

3.4.3 Supplementing nitrate

Supplementing nitrate in animal diets inhibits methane production by operating as a hydrogen sink, i.e. by reducing available hydrogen that would otherwise be utilised by methanogens and result in methane (Roques et al., 2024). Mitigation of methane production by up to 50 % has been observed and the effectiveness is most prominent in countries with low nitrate levels in forage, typically developing countries (Gerber et al., 2013). Feng et al. (2020) conducts a meta-analysis of nitrate treatment and conclude that the effect on emissions is evident and that the abatement potential is dose dependent with 20.4 % and 10.1 % reduction in beef and dairy cows on average, respectively. The dose dependency is problematic and has prevented widespread commercial implementation due to concerns for animal well-being via nitrate poisoning at higher levels of supplementation (Fouts et al., 2022). Higher doses can lead to nitrogen being absorbed into the blood via the rumen wall of the animals and cause nitrate poisoning (Roques et al., 2024). This potentially results in reduced feed intake and production, or reproductive failure, but the risk can be reduced by animal acclimatisation of nitrogen (Lee & Beauchemin, 2014).

A common aspect to consider for all additive based supplements is that research is concentrated on intensive production systems, such as those utilising stables and feedlots to fatten cattle. In cases where fodder type and intake is strictly controlled, dosing additives can be feasible, but effective distribution is currently a challenge for grazing animals and especially for freely grazing beef cattle (Smith et al., 2022). Hence, technical fixes are currently more likely to be a partial solution for intensive livestock systems with easier supplementation during winter when animals are not freely grazing. However, orally installed slow-release technologies are under development in an attempt to make feed additives feasible in grazing systems (Roques et al., 2024). Such technology is expected to be ready for implementation during 2026 (Svarer et al., 2024).

3.4.4 Vaccination

Rumen manipulation via vaccination could, on the contrary to regularly supplemented additives, be effective in grazing systems as an enteric methane mitigator (Beauchemin et al., 2020), by subduing microorganisms necessary for methanogenesis (Baca-González et al., 2020). Grazing livestock emit 37 % of anthropogenic enteric methane emissions and abatement measures that are applicable and effective in grazing systems are, therefore, highly sought after. Once developed, vaccination, selective breeding and genome editing (see 3.4.5 below) are the only complete potential solutions for grazing systems with absolute emission reductions in the current absence of oral slow-release technologies (Smith et al., 2022). The vaccination technology is in the early stages of development, with requirements of better understanding of the rumen methanogens and genomic information in order to develop effective antigens (Roques et al., 2024). The literature is currently limited and lacks consistent evidence of effectiveness in vivo (Baca-González et al., 2020), but significant research progress has been made with advancement in genomic understanding (Roques et al., 2024). Vaccination could become a cost-effective mitigation measure (Reisinger et al., 2021), but is not an option in the near future. The lack of literature indicates that it is uncertain whether or not it will even become available (Roques et al., 2024).

3.4.5 Genome editing

Somewhat similar to vaccination, microbial genome editing has recently gained traction and is suggested as a potential future mitigator of ruminant methane emissions (Khan et al., 2024). One way to genetically modify microbes is to use the CRISPR-technology (Mrutu et al., 2023). CRISPR (clustered regularly interspaced short palindromic repeats) was introduced in 2012 and has since been proven as a versatile technology that has been utilised on plants and drosophila. The technology allows for genetic modification of microbes in a precise and accessible way relative to other approaches within genetic engineering (Park et al., 2024). This makes it potentially applicable to cattle as the methanogen microbes have a vital role in ruminant methane production (Roques et al., 2024). Mrutu et al. (2023) suggest that the CRISPR technology has great potential by converting methanogens into acetogens, and, thereby, replace methanogenesis with acetogenesis to some extent. However, the authors state that trials attempting to increase acetate production have had a poor success rate.

A collaboration between the Californian universities of Davis, San Francisco and Berkely has been granted 70-million-dollar funding to research how CRISPR can be used to reduce enteric methane emissions. The research team consists of established researchers within the methane abating literature and technical experts, including Jennifer Doudna, the 2020 Nobel Prize winner in chemistry (Sicard, 2023). The technology is clearly in early stages of development, but the above-mentioned research indicates belief and potential of future efficacy in methane inhibition.

4 Status of Policy for Incentivising Methane Abatement

Enteric methane mitigation approaches, such as improved forage quality, can positively impact production. Other strategies, for instance rumen modification through 3-NOP or Asparagopsis supplementation, on the contrary, have minor to no impact on animal productivity. Simultaneous effects on emissions and production could partially off-set costs of emission abatement measures. However, regardless of production benefits (within realistic boundaries given current research), the costs will not be fully compensated for, and emission abatement measures will not be extensively adopted without creating the appropriate economic incentives, which implies a need for policy interventions (Roques et al., 2024).

Agriculture has been largely exempted from GHG mitigation policy, with no current non-energy agricultural emission tax implemented anywhere in the world (Svarer et al., 2024), but this is likely to change soon. New Zealand is set to implement agricultural emission pricing in 2025 (OECD, 2022) and in Denmark a government assigned expert group has recommended an agricultural carbon-equivalent tax complemented with climate-action subsidies (Svarer et al., 2024). Effectively taxing domestic agricultural sector for GHG emissions is problematic, as farm-specific methane measurements are very costly to obtain (Kumari et al., 2020) and would not be feasible from a cost-effectiveness perspective (Roques et al., 2024). Taxation based on animal averages would be suboptimal, since differences between individual animals, breeds and time have been observed (Cassandro et al., 2013). In addition, the sector is exposed to global competition. Hence, non-global carbon taxation will likely cause emission leakages due to shifts in production to other countries and little to no alterations in consumption patterns (Parry et al., 2022).

Leakages can theoretically be offset by emission-based border taxation of imported goods, which would reduce, or even prevent production shifts (Spiegel et al., 2024). For a boarder tax to effectively reduce emissions, it would have to be based on local, or at least regional, agricultural emissions per product, which is costly to measure. Additionally, violation of WTO-commitments could be a prohibiting factor and cause retaliation (Parry et al., 2022). Pérez Domínguez et al. (2021) simulated an implementation of a carbon-equivalent tax in the agricultural sector. They find that a global 150 USD carbon tax per ton CO_2e would result in 27 % reduced methane emissions by 2050. Increasing the tax rate beyond this resulted in sharply diminishing returns on emission abatement. The authors, therefore, conclude that carbon pricing cannot solve the GHG emission problem in the agricultural sector on its own. Development and implementation of technical mitigation measures are needed in combination with policy instruments that provide incentives to do this over time (to achieve so-called dynamic efficiency). However, the taxes themselves would also provide incentive to develop new measures, but revolutionary development is often costly and perhaps not individually economically profitable. Government funds dedicated to technical development would likely improve and speed up the process. Such structure is proposed by Svarer et al. (2024) and discussed below.

In light of the novelty of the proposed Danish climate tax on agriculture, carried out by a government assigned expert group and reported in Svarer et al. (2024), we summarise the main findings. They address the question of how an agricultural carbon-equivalent tax on non-energy-related emissions could be cost-effectively implemented, while simultaneously keeping farm closures and reductions in livestock numbers to a minimum. The resultant report is a step towards Denmark's ambition of fully incorporating agricultural GHG emissions into carbon-equivalent taxation by the end of the decade. The expert group states that a gradual implementation of a carbon-equivalent tax on producers (starting with a lower tax rate in 2027 and complete taxation during 2030) can be combined with partial subsidies to incentivise emission reducing practises and, consequently, reach climate goals. The expert group dismisses a consumption tax as a cost-ineffective instrument to efficiently incentivise individual abatement by farmers. Additionally, food consumption has a relatively low price elasticity of demand, which reduces the effectiveness of a consumption tax. A production tax would incentivise farmers to implement technical solutions, such as supplementing 3-NOP. Simultaneously, the proposal would reduce the economic burden on producers through subsidies and, thereby, also reduce farm closures. Technical solutions, they argue, can be further developed using the excess tax revenue not used to finance the subsidies. Nevertheless, full-time farmers will be financially affected with an increased average risk of bankruptcy by 0 to 15 percentage points, depending on the chosen tax rate. Moreover, measurement costs of farm-specific emission taxation are a concern throughout the literature (Roques et al., 2024). The expert group suggests that administrative costs could be minimised by calculating the tax based on data that is already mandatorily reported to the UN and the EU.

5 Concluding remarks

The aim of this literature review was to identify and evaluate the efficacy, cost-effectiveness, and state of development of the most relevant technical enteric methane abatement measures beyond reducing livestock production. It is evident that technical solutions are developing quickly and should be a part of future cost-effective mitigation of enteric methane emissions. A wide variety of measures have been shown to clearly impact methane emissions throughout the literature. However, all of the available measures have some type of limitation to varying extents. The effectiveness of management strategies is farm-specific and likely most impactful in developing countries where the greatest productivity improvements could be made. Dietary feed additives are suffering from estimated negative effects on production (lipids) or have the opportunity cost of human consumption (i.e., concentrates such as grains being used as food directly). In the current state of development, the rumen manipulative feed additives have shown the greatest potential. Macroalgae species have been estimated to perhaps have the largest impact on emissions, but mass production being difficult, some evidence of harmful effects on production traits, and lack of long-term studies are limitations. 3-NOP is another rumen manipulative feed additive. It is the technical front-runner with unanimously estimated emission abatement and approval as safe to administer to cows. The patented commercial feed additive with 3-NOP as the active substance, consists of cheap components, which permits cost-efficient mass production. Supplementation difficulties of feed additives in grazing systems is a problem, but it is projected to be solved by implementation of oral slow-release technologies in the near future. However, the long-term effects are not clearly established yet and require more research. Once developed, genome editing, vaccination and selective breeding could also be abatement solutions for all types of ruminant agricultural systems, but even though research progress has been made in genomic understanding, it is too early to conclude about potential efficacy, feasibility and time frame.

Moreover, 3-NOP, as well as other abatement measures within rumen manipulation, reduce absolute methane emissions. This is generally in contrast to nutritional and management strategies that primarily affect methane intensity. Intensity improvements can impact absolute emissions through reduced herd sizes, while still maintaining the same output given productivity improvements. However, given the economic incentive increased productivity implies, farmers are likely to increase production and consequently off-set potential emission abatement.

3-NOP is available on the market and ready to be implemented. The market could also expand and include additional measures with great development potential, such as vaccination or genome editing. However, farmers currently have little or no incentive to implement specific measures to reduce methane emissions from enteric fermentation. Extensive implementation of technical measures will not take place without appropriate economic incentives. Hence, the policy implication is that it could be desirable to create conditions that incentivise utilisation of technical measures and ultimately accomplishing common good by reducing agricultural GHG emissions of enteric methane. The Danish proposed tax-subsidy system could create such conditions in a cost-effective manner. It will be interesting at a later date to study exactly how Denmark intends to implement the necessary carbon accounting, and what incentives are created within the system to reward technical abatement implementation and development.

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