

Reducing climate-related emissions from agriculture

Selected options for the
Viable Cities' Finance Dashboard

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Summary

This report is based on a scoping exercise that identified and analysed agricultural mitigation measures that are adoptable under Swedish conditions and for which sufficient evidence exists for their operationalization in the Viable Cities Finance (VCF) Dashboard, a tool for municipal climate action and investment planning. An outcome of the scoping exercise is the parameter selection of the dashboard, which is a subsequent step in the tool's development. With this purpose, the report addresses the following research questions: Which mitigation measures can be adopted in Sweden? What are their mitigation potentials, costs and benefits?

The analysis combined peer-reviewed scientific literature with Swedish grey literature in a structured evidence synthesis. This mixed evidence base was necessary due to the report's objective of identifying technically robust mitigation measures, assessing their adoptability in a Swedish context and examining their relevance for municipal climate investment planning.

In total, we reviewed and coded 35 publications. For each measure, we extracted information on mitigation potential, implementation feasibility and constraints, and costs and economic considerations, as well as co-benefits and trade-offs.

The report presents various measures across four categories: soil management, livestock management, manure management, and machinery and vehicles. The findings show that Sweden has the possibility to implement and scale most of the measures, but the binding constraints are often implementation conditions, including policy coherence, stable incentives, coordination across actors, and the distribution of costs and risks, rather than a lack of ideas or technologies. Among the four categories, soil and manure management offer the strongest near-term mitigation potential, while livestock management carries the highest uncertainty because of the system-level scalability as well as dependence on behavioural and cultural change that is difficult to predict. The next step will be to translate measures into inputs that are ready for the VCF Dashboard and accompanying guidance for municipal users.

Abbreviations

CH₄	Methane	NI(s)	Nitrification inhibitor(s)
CO₂	Carbon dioxide	NTM	Nordic Trait Merit
DMI	Dry matter intake	N₂O	Nitrous oxide
ESR	Effort Sharing Regulation	RFI	Residual feed intake
FAME	Fatty acid methyl ester	RME	Rapeseed methyl ester
HVO	Hydrotreated vegetable oil	SLU	Sveriges Lantbruksuniversitet, Swedish University of Agricultural Sciences
LRF	Lantbrukarnas Riksförbund, Federation of Swedish Farmers	TWh	Terawatt hours
N	Nitrogen	VRT	Variable rate technology
NET(s)	Negative emissions technology/ies	VCF	Viable Cities Finance Dashboard
NH₃	Ammonia	Dashboard	

1. Introduction

Climate change is one of the most pressing challenges of our time, and reducing emissions has become a priority for many governments at the local, national and supranational level (Guterres, 2019). In Sweden, municipalities have started designing climate action plans, assessing sectoral emissions and selecting emission reduction measures (Viable Cities, 2022). Throughout this report, the term municipality is used to refer to Swedish *kommuner*, the primary unit of local government, rather than cities or urban areas, as the measures discussed are relevant across rural, semi-urban and urban municipalities alike.

The statistics on emissions provided in this report are based on annual reports from Naturvårdsverket. The statistics reported by Naturvårdsverket for the agricultural sector follow Sweden's national greenhouse gas inventory, which is compiled in accordance with UNFCCC reporting guidelines and covers territorial emissions only. Thus, external emissions, such as those from imported feed or fertilizer production, are not included.

The Swedish agricultural industry emitted around 6.3 million metric tons (tons) of carbon dioxide equivalents (CO₂eq) in 2024, making it the country's third highest emitting sector (Naturvårdsverket, 2025c). And while agricultural emissions have declined since the 1990s in Sweden, this reduction is largely explained by structural changes, such as reduced livestock populations and a decrease in agricultural land, rather than a systematic scaling of climate-smart interventions (Riksrevisionen, 2025). Substantial additional reductions are therefore still required to meet near-term targets such as the EU Effort Sharing Regulation (ESR), which requires emissions from sectors including agriculture to decrease by 40% by 2030 relative to 2005 levels (Regulation (EU) 2023/857 of the European Parliament). Sweden has set a more ambitious target of a 50% reduction by 2030 relative to 2005 levels (Naturvårdsverket, 2025b).

While municipalities have no direct regulatory authority over farming practices, they nonetheless hold indirect influence over local agriculture through land-use planning, advisory programs, public procurement, and so forth. Such decision-making power means that agricultural measures at the national and EU level are relevant for municipal climate planning.

Municipalities differ in their relationship to agriculture. Municipalities with significant rural land will find the measures in this report more relevant than predominately urban municipalities, a difference to bear in mind for the results of this report.

This report maps what can be done to reduce emissions from agriculture in Sweden in order to feed into the Viable Cities Finance Dashboard¹ (hereafter VCF Dashboard), a tool that supports Swedish municipalities with developing climate action and investment plans (Vanhuysen et al., 2023). While municipalities already rely on emissions inventories and climate planning frameworks to set targets and identify measures, these tools typically provide limited support for translating such measures into financially actionable investment decisions. The VCF Dashboard is designed to fill this

¹ [Viable Cities Finance Dashboard](#)

gap by integrating emissions data, mitigation measures and financial parameters into a single decision-support tool. It is a free-of-charge, open-source platform that includes emissions data for each municipality, more than 30 mitigation measures, and over 100 assumptions from which users can build scenarios and simulate climate impacts until 2030. For each scenario, the tool provides economic and financial implications, enabling municipalities to assess the business case and feasibility of different climate action pathways. It also offers a structured overview of available subsidies, grants and loans.

To further improve the dashboard, we asked the following questions to help refine next steps for researchers and municipalities: which of the identified measures can be adopted in Sweden? What is their mitigation potential, their costs and benefits?

The concept of adoptability is used in this report to refer to the extent to which a mitigation measure can be realistically implemented under Swedish conditions. Adoptability is reflected in implementation feasibility and constraints (e.g. agronomic conditions, infrastructure requirements, regulatory barriers); costs and economic considerations (including capital and operating expenditures and distribution of costs across actors); and co-benefits and trade-offs, which may incentivize or hinder uptake.

2. Methodology

This report combines an analysis of peer-reviewed scientific literature and Swedish grey literature. This mixed evidence base was necessary because the report's objective is not only to identify technically robust mitigation measures, but also to assess whether measures are adoptable in Sweden and relevant for municipal climate planning, both of which depend on contextual factors such as governance arrangements, infrastructure, regulatory constraints and stakeholder feasibility perceptions.

2.1 Literature search

We conducted our literature search between February and May 2025. We designed the searchers to identify agricultural mitigation measures relevant to Swedish conditions and, where Sweden-specific evidence was limited, to the wider northern European and comparable temperate contexts.

We searched for sources in two complementary tracks. We found peer-reviewed literature in Scopus, to identify scientifically supported mitigation measures and quantitative evidence on greenhouse gas impacts (carbon dioxide, CO₂; methane, CH₄; nitrous oxide, N₂O). And we selected targeted grey literature from the knowledge bank held by the Swedish University of Agricultural Sciences (Sveriges Lantbruksuniversitet, SLU), to identify policy and implementation conditions, adoption barriers, cost ranges and practical feasibility considerations relevant for Swedish municipalities and the farm sector.

In Scopus, we used the following search string, applied to title, abstract and key words:

(agricultur*) AND (climate) AND (Sweden or Swedish or Scandinavia* OR Northern Europe)

This resulted in 892 documents, of which 65 were reviews in English and Swedish.

Using the SLU knowledge bank (<https://www.slu.se/en/research/knowledge-bank/>), we conducted a keyword search using the terms *klimat*, *åtgärd* and *jordbruk* (climate, measure or action, and agriculture), which returned 100 results. These results constituted the initial grey literature corpus and were subsequently screened for inclusion and exclusion based on the criteria outlined below.

2.2 Screening of the corpus

We screened the results for relevance, including them if they met the following criteria:

- topical relevance: addressed one or more mitigation measures applicable to agricultural production systems (arable farming and/or livestock)
- outcome relevance: reported, reviewed or synthesized evidence related to greenhouse gas mitigation potential (CO₂, CH₄, N₂O) or provided information relevant to cost and implementation feasibility
- context relevance: included evidence from Sweden, the Nordics, northern Europe, or comparable temperate agro-climatic conditions, or provided generalizable evidence with clear assumptions
- quality threshold: peer-reviewed journal articles for the scientific track or credible grey literature from, for example, national agencies, established research institutes or major sector organizations.

Publications were excluded if they:

- focused primarily on mitigation measures that are not feasible in the Swedish context due to biophysical constraints such as climate limitations or clear incompatibility with Swedish production conditions
- lacked any meaningful linkage to mitigation outcomes or adoptability considerations
- addressed measures only at a highly conceptual level without actionable implications for measure design, abatement, costs or feasibility.

Search results were screened iteratively. We screened titles and abstracts for academic and executive summaries for SLU reports for relevance. For retained items, we did a full-text with a focus on extracting mitigation mechanisms; reported abatement ranges; preconditions for implementation; cost components and cost ranges; co-benefits and trade-offs; and Sweden-specific contextual factors.

2.3 Data extraction

For practical reasons, we retained 35 publications (Annex 1), which were reviewed and coded in a single evidence extraction spreadsheet. For each source, the spreadsheet captured bibliographic metadata; geography or context; agricultural systems; measures covered; and a short narrative summary.

For each identified mitigation measure, we extracted variables where available for mitigation and costs. Within mitigation, we selected for the mitigation mechanism and emissions channel: whether the measure primarily affects CO₂ (e.g. soil carbon), CH₄ (enteric fermentation), N₂O (soils/manure) or indirect emissions (e.g. fossil fuels).

We searched for mitigation potential – reported effect sizes, abatement factors, or percentage reductions, including ranges when multiple studies were available – and implementation feasibility and constraints, such as agronomic constraints (soil, climate, timing), infrastructure dependence, behavioural or workload considerations, and regulatory or market constraints.

For cost variables, we selected for costs and economic considerations: capital or operating expenditures, indicative of euros per ton of CO₂eq (EUR/tCO₂eq) or SEK-based estimates where available, and distribution of costs across actors (farmers, municipalities, other stakeholders). We also examined co-benefits and trade-offs, such as soil health, biodiversity, water quality, yields, leakage, and possible rebound or risk-shifting effects.

Annex 1 contains a list of the retained articles from our literature review. Annex 2 contains details of supplementary measures that were not retained for this report, given low relevance to the Swedish context (e.g. buffer strips).

We could group mitigation measures into four overarching categories: soil management; livestock management; manure management; and machinery and vehicles (the findings section below is organized accordingly; see Section 3). Where multiple sources reported similar information for the same measure, we prioritized in our extraction additional or Sweden-specific details, to avoid duplication and keep the dataset manageable. This is consistent with the report's purpose as an applied synthesis for tool development rather than a full systematic review (Collaboration for Environmental Evidence, 2013).

2.4 Limitations

This report is a structured evidence synthesis intended to inform selection and operationalization of measures for the VCF Dashboard. We do not claim the completeness of a systematic review or meta-analysis. Several limitations therefore apply.

The measures presented in this report are based only on literature-derived evidence, which therefore have not been validated with practitioners. Validation with local governments, farmers and other researchers is recommended as a next step to further assess the relevance and feasibility of the measures in a Swedish municipal context.

We also note that the evidence coverage is uneven across the measures we report here. Some appear often in literature focused on international contexts, but they are less well-evidenced in Sweden-specific contexts; other measures may be relevant in practice but underrepresented in the peer-reviewed evidence base. This creates a risk of over- or under-emphasizing measures based on publication patterns rather than Swedish mitigation potential.

The cost estimates we report here are not consistently comparable across sources due to differences in system boundaries, assumptions (e.g. time horizon, discounting), and whether estimates reflect private costs, societal costs or marginal abatement

costs. Where possible, we therefore report cost ranges and interpret them qualitatively in relation to adoptability and cost-efficiency, rather than producing a single harmonized ranking.

Finally, several mitigation measures, particularly those involving soil carbon and negative emissions technologies, are sensitive to local baseline conditions and persistence assumptions (e.g. permanence and reversibility). Reported mitigation potentials should therefore be interpreted as indicative ranges rather than point estimates and should be refined through Sweden-specific parameterization as part of further VCF Dashboard development.

3. Findings

In the following sections, we assess adoptability implicitly through feasibility conditions, cost structures and reported co-benefits and trade-offs. The sections below detail the measures we selected that can be applied to reduce emissions from agriculture in Sweden, in the following categories: soil management (Section 3.1), livestock management (Section 3.2), manure management (Section 3.3), and agricultural machines and transport (Section 3.4).

3.1 Soil management

Mitigation measures that are relevant for land and soil management include practices such as cover cropping, agroforestry, and applications that increase carbon sinks or methods that capture and store carbon while at the same time improving soil health, reducing the leakage of nitrogen (N), ammonia (NH₃) and other substances into the water (Kwon et al., 2021). We identified six such measures or practices: cover crops; ley crops; tillage methods; mineral, inorganic and synthetic fertilizers; biochar; and nitrification inhibitors and precision nutrient application.

Cover crops

Cover crops are fast-growing crops cultivated at the same time as or between plantings of a main crop (Lankoski et al., 2020), usually after the harvest season to keep the soil covered and active. They contribute to additional biomass, including root systems that decompose more slowly and increase soil organic carbon. Additional co-benefits include reduced nitrogen loss, improved soil structure and nutrition, and reduced risk of soil erosion (Rehn et al., 2024).

The feasibility for sowing cover crops is determined by the availability of suitable sowing windows, as the period between harvest and establishment of winter cereals and rapeseed is short (Rehn et al., 2024). Therefore, this measure is more feasible in the southern parts of Sweden, which have a milder and longer autumn season (Björksell et al., 2025). Common cover crops include ryegrass, clover, vetch, radish and other fast-growing grasses or legumes.

Catch crops, on the other hand, are a special type of cover crop planted during or after crop growing season and cultivated for taking up surplus nitrogen after the harvest of the main crop, thus reducing the nitrogen loss from the soil (Hellsten et al., 2017). In contrast to the cover crops that increase the soil organic carbon content, catch crops aim at reducing indirect N₂O emissions from N leaching by approximately 50% (Lankoski et al., 2020).

Catch crops became common in Sweden in the 1980s and 1990s to reduce nitrogen leaching from agricultural land, while only in the past 10 years have cover crops been used for carbon sequestration (Björksell et al., 2025).

Mitigation potential

In general, cover crops are said to store 300 kg C per hectare (C/ha) (Björksell et al., 2025). In long-term field trials in Sweden, ryegrass cover crops can increase the soil organic carbon by approximately 0.32 tons C/ha per year. Over a period of 30 years, cover crops in Sweden increased the country's total soil carbon stocks by 1.9 tons C/ha per year (Rehn et al., 2024).

According to the Swedish National Agricultural Board, 400 000 ha of Sweden's agricultural land can be used for cover crops. Similarly, the Royal Swedish Academy of Engineering Sciences and the Royal Swedish Academy of Agriculture and Forestry estimate that 440 000 ha can be used. This in turn corresponds to potential carbon sequestration of 0.48–0.53 million tCO₂eq (Björksell et al., 2025).

Costs

The costs for cover and catch crop seeds are generally low. However, establishing cover crops is not economically beneficial in all regions. Growth is lower in the northern regions due to the shorter autumn season, and biomass yields per hectare are often lower than those of ley crops, which means that the cost per ton of harvested biomass can be high (Björksell et al., 2025). Such crops also require additional labour, which needs to be considered from a cost-benefit perspective.

Co-benefits

Besides reducing nitrogen leaching, cover and catch crops provide several other co-benefits. The soil structure gets better as roots loosen and bind the soil, which makes it easier for water and air to move through. Additionally, roots and plants feed earthworms, fungi and bacteria which increases the biological activity and further supports both structure and nutrient cycling.

These co-benefits are also adaptation drivers, as climate change is expected to increase extreme weather events such as droughts and heavy rainfall. Improved soil structure and higher organic matter increase water infiltration and storage, which gives crops more water during dry periods. During heavy rainfall on the other hand, plant cover helps the water soak into the soil instead of running off, which reduces the risk for erosion.

Conclusion

Cover crops must be sown during a short window of time, after harvest and before planting winter cereals, which potentially limits use of this measure. Other limitations include the geographical scope of where this measure could be implemented as well as the increased labour and costs it implies for farmers.

Ley crops

Ley crops are perennial grass or grass-clover mixtures (such as clover and timothy) that are grown for two or more years as part of a crop rotation instead of annual crops (Rehn et al., 2024). They have similar effects as cover crops, but the carbon in residues of ley crops is predominantly allocated to the root system. The carbon-rich root system contributes to a stable soil organic carbon pool more so than agricultural residues.

Thus, systems that include ley can store more carbon than annual cropping systems (Rehn et al., 2024).

Mitigation potential

According to a report from the Federation of Swedish Farmers (*Lantbrukarnas Riksförbund*, LRF), intensifying existing ley cultivation to raise yields could increase carbon sequestration by 35 kg C/ha/year (Björksell et al., 2025), or about 0.13 tCO₂eq/ha/year. Expanding the ley area by 110 000 ha would store carbon corresponding to 0.26 million tCO₂eq by 2045 (Björksell et al., 2025). Rehn et al. (2024) estimate that including more ley in crop rotations increases soil organic carbon stocks by an average of 1.6 tons C/ha over three decades. The gain is concentrated in rotation of annual crops, where introducing ley adds about 0.3–0.6 tCO₂eq/ha/year. Rotations already dominated by ley, such as those on dairy farms, offer little room for further increase (Rehn et al., 2024).

The national commitment to increase the cultivation of ley has been manifested through several economic incentives; however, the greatly increased area of ley cultivation risks displacing other crops (Björksell et al., 2025). The Royal Swedish Academy of Engineering Sciences and Royal Swedish Academy of Agriculture and Forestry have estimated that 220 000 ha more ley could be grown by 2050, while the LRF considers half of the area a more cautious and realistic estimate (Björksell et al., 2025).

Costs

Sweden's Seed and Oil-plant Growers calculated the profitability of all the ley crops used in Sweden. The organization showed that several ley and forage seed crops, particularly white and red clover, as well as meadow grasses, are among the most profitable, with significantly higher net margins than, for example, wheat and barley. Therefore, increased cultivation of ley crops in rotation may not be an economic burden. The calculations are based on average seed prices for 2021–23, cereal prices for December 2025, seed companies' average yields and costs, machinery costs based on the machinery cost booklet (Maskinkalkylgruppen and HIR Skåne), list prices for plant protection and fixed plant nutrient prices of SEK 14, 34 and 10 per kg of N, P and K respectively (Sveriges Frö- och Oljeväxtodlare, 2021).

Co-benefits

Ley crops and other vegetated strips can be managed in a way that allows plants to flower and preserves variation in vegetation structure; therefore, they can support biodiversity in addition to sequestering carbon. In that case, it is crucial that ley is not harvested too early, as the crops provide habitat, nesting and breeding areas (Hoffmann et al., 2023).

Leguminous crops in crop rotations also reduce the need for fertilizers, as they fix nitrogen biologically from the air. Thus, it would reduce both the manufacturing related emissions (prior to application) as well as the soil emissions (after application) (Lankoski et al., 2020).

Conclusion

Increasing ley cultivation offers a solid contribution to soil carbon sequestration, while at the same time providing agronomic and biodiversity co-benefits. Although the mitigation impacts are lower than, for example, cover crops and the application of biochar, an increase in ley cultivation still represents a feasible and economically viable mitigation measure. However, given that a large portion of livestock areas are already covered with ley crops, the overall mitigation potential is somewhat limited; expanding it to arable systems may be a cost-effective complementary measure.

Minimum or no-till practices

Tillage practices influence soil carbon dynamics, nitrogen transformation and on-farm energy use, all of which affect greenhouse gas emissions. As a mitigation measure, the reduction potential for tillage varies substantially across climates, soil types, soil depth and crop systems and must therefore be evaluated in each context respectively (Lankoski et al., 2020). Conventional tillage disturbs soil and increases CO₂ emissions by accelerating microbial deionization and exposing soil organic carbon to oxidation. Furthermore, it may contribute to soil erosion and physical carbon losses, which is why reduced tillage methods have been presented as possible solutions to limiting carbon emissions (Kwon et al., 2021). No-till or limited tillage may, on the other hand, lead to an increase in dissolved phosphorous and herbicide runoff, with deleterious environmental impacts (Lankoski et al., 2020).

Minimum tillage

Minimum tillage can reduce climate-changing emissions by lowering, for example, machinery use while only partially disturbing the soil. The practice of minimum tillage would also sequester carbon in the soil (Kwon et al., 2021). Results in Denmark showed that minimum tillage had more environmental benefits than no-till (McVittie et al., 2014).

No-till

Tillage has been practiced to manage crop residues and to prepare seed beds for next crops, but it disturbs soil, increases physical soil carbon removal due to soil erosion, and leads to CO₂ emissions due to increased microbial activity (Kwon et al., 2021). No-till means eliminating ploughing and sowing seeds into the previous season's crop residues. Although it has been promoted as a measure that has potential to sequester carbon and reduce soil disturbance, studies report high regional variability (Kwon et al., 2021; Lankoski et al., 2020) and that carbon sequestration with no-till practices often is overestimated (Lankoski et al., 2020). It is also evident that in boreal regions, conventional tillage has reduced greenhouse gas emissions in clay and loam soils, meaning no-till practices could instead increase emissions in these areas (Lankoski et al., 2020). Another downside is that no-till would lead to greater fertilizer and pesticide use and expenditures for corn and wheat (Kwon et al., 2021).

In eastern Scotland, whose agro-climatic conditions can be compared to the southern Swedish region of Skåne, no-till practices resulted in an abatement rate of 0.70 tCO₂eq/ha/year, and 0.15 tCO₂eq/ha/year for minimum tillage (McVittie et al., 2014). The estimate for minimum tillage was identical in Zealand, Denmark – an island just outside

of Skåne's west coast. Given the agro-climatic similarities between these regions, the abatement rate for minimum tillage in Skåne is likely to be in line with these results (McVittie et al., 2014).

However, in boreal climates, for example in northern Sweden, the effect of minimum and no-till practices can be the opposite. In clay and loam soils, conventional tillage has been found to result in lower greenhouse gas emissions than no-till, with no-till increasing CO₂ and N₂O emissions while leaving CH₄ emissions unaffected. Additionally, the increase in soil carbon under reduced tillage is often found in the topsoil. This may simply reflect carbon being moved up from deeper layers, rather than more carbon being stored in the soil overall (Lankoski et al., 2020).

Costs

Cost differences are notable between minimum tillage and no-till practices. Minimum tillage is cost-effective and is reported to have negative abatement costs, which means that it increases the farm profitability (Lankoski et al., 2020). McVittie et al. (2014) also assessed the cost effectiveness of the tillage practices, measured as the change in farm gross margin per ton of CO₂eq abated. A negative value means that the practice is profitable for the farmer. In Zealand, Denmark, minimum tillage was profitable for all crops assessed (winter/spring wheat and barley), with gains of EUR 78–140 per tCO₂eq (mean yield impact), as low fuel and labour costs outweighed a small yield reduction (McVittie, 2014). Similarly, Lankoski et al. (2020), reported that profitability is largely driven by a reduction in costs associated with transport and machinery use.

In eastern Scotland, minimum tillage was also profitable for cereals and oilseed rape with gains of EUR 161–254 (mean yield impact) per tCO₂eq, but not for potatoes where a yield reduction in a high-value crops made it costly. No-till, on the other hand, carried a low cost of EUR 20–70 per tCO₂eq, because of the additional spraying needed to control the weeds (McVittie, 2014). This has also been noted in other articles. Kwon et al. (2021) reported that no-till practices can lead to higher expenditures for fertilizers and pesticides to maintain the yields, while Lankoski et al. (2020) highlighted that the cost effectiveness varies heavily depending on the specific region, crop and measurement depth of soil carbon.

Co-benefits

Implementing minimum or no-till practices imply environmental and operational co-benefits alongside some trade-offs. Minimum and no-till practices reduce the use of machinery which results in lower on-farm fuel consumption (Kwon et al., 2021). These practices usually reduce soil erosion, nitrogen and phosphorous runoff; however, as a trade-off, minimum tillage may increase the runoff of dissolved phosphorus and herbicides (Lankoski et al., 2020).

Conclusion

Minimum and no-till practices offer advantages such as reduced machinery costs, lower fuel consumption and decreased soil erosion (Kwon et al., 2021; Lankoski et al., 2020). However, the mitigation potential depends on geography. In boreal climate, such as northern Sweden, minimum tillage and no-till can increase greenhouse gas emissions in clay and loam soils, whereas in temperate regions they are more likely to reduce emissions (Lankoski et al., 2020). Most of Sweden's agricultural lands is located

in the southern Sweden, where the climate is temperate. Minimum tillage and no-till are therefore likely to be more effective there than in the north. Minimum tillage is generally profitable for farmers, whereas no-till tends to carry a small cost because of additional spraying needed to maintain yields (Lankoski et al., 2020; McVittie, 2014).

Mineral, inorganic and synthetic fertilizers

Mineral fertilizers, also called inorganic fertilizers, supply plant nutrients, mainly nitrogen, phosphorus and potassium (often referred to as NPK) in the form of mineral salts rather than organic material such as manure. Nitrogen fertilizers are produced synthetically from atmospheric nitrogen in an energy-intensive process while phosphorous and potassium fertilizers are made from mined minerals that naturally occur. The production of mineral fertilizers, particularly nitrogen fertilizers, is therefore associated with substantial climate emissions. Reducing their use would not only reduce production-related emissions but also soil emissions of N_2O (Lankoski et al., 2020), which has a global warming potential 298 times higher than CO_2 over a 100-year time horizon (Li et al., 2013). While higher fertilizer inputs increase yields and thus organic residues left in the soil, potentially improving soil carbon stocks, the gains are insufficient to compensate for the emissions generated during production and the resulting N_2O emissions from soils (Li et al., 2013).

Measures to reduce the impact of mineral fertilizers target either the manufacturing process or their application practices. This section focuses on application practices which aim to match the nutrient supply with the crop demand and thereby improve nitrogen use efficiency (Li et al., 2013). A widely cited approach is the optimization of precision application, the so-called 4R framework (right time, right type, right rate, right place) (Lankoski et al., 2020) or slow-release fertilizers (Li et al., 2013). Precision tools can support this, such as the Variable Rate Technology (VRT), which allows farmers to divide fields into zones and adjust the fertilizer rates to the characteristics of the soil (Kwon et al., 2021). The other approach, to use enhanced efficiency fertilizers, such as slow-release fertilizers, releases nitrogen gradually to better match the crop uptake (Li et al., 2013).

When it comes to the placement of fertilizers, deeper than 5 cm in soil has proven to have a significant mitigation potential in comparison to applying fertilizer on soil surfaces. Both nitrification and denitrification potentials decrease with soil depth; deep placement isolates the inorganic nitrogen from the most biologically active microbial soils in the upper soil layer, thus limiting the generation of N_2O (Li et al., 2013).

A major part of the emissions associated with mineral nitrogen fertilizers come from the production of NH_3 , the starting material for these fertilizers. This process is energy-intensive and fossil-based since CH_4 reacts with steam to produce hydrogen, which then is combined with nitrogen from the air to form NH_3 (Björksell et al., 2025; Kwon et al., 2021). “Green” NH_3 could instead be produced by using water, air and renewable electricity (solar, wind, hydropower) (Björksell et al., 2025; Kwon et al., 2021).

Mitigation potential

Reducing the nitrogen application rate to levels that satisfy crop needs is recognized as the most effective and universally agreed-upon method for lowering the N_2O emissions from mineral fertilizers (Li et al., 2013). For example, using polymer-coated fertilizers can reduce N_2O emissions 14–58%, with an average of 35%, and the use of nitrification inhibitors can reduce the N_2O emissions by an average of 38% (Li et al., 2013). Placing fertilizers deeper than 5 cm into the soil can mitigate N_2O emissions in minimum or no-till systems, particularly in temperate and humid climate regions (Lankoski et al., 2020; Li et al., 2013).

When it comes to manufacturing, producing green NH_3 by using renewable energy sources can reduce the manufacturing-associated emissions by 91%, from 2.55 to 0.22 gCO_2eq per gram of NH_3 produced, compared with conventional production based on steam CH_4 reforming of natural gas (Kwon et al., 2021). In a scenario where all mineral nitrogen fertilizers used in Sweden were fossil-free by 2045, Björksell et al. (2025) estimate that emissions would fall by 0.71 million tCO_2eq per year. Emissions from the production of nitrogen fertilizers used for crops in Sweden are not included in Sweden's territorial emissions data. Fossil-free fertilizers would therefore not affect Sweden's climate reporting, although they represent a significant opportunity to reduce emissions (Björksell et al., 2025).

Costs

The production of fossil-free mineral nitrogen is estimated to increase the price of nitrogen by around SEK 10 per kilogram (Hoffmann et al., 2023). Given that Sweden uses approximately 180 000 tons of mineral fertilizer nitrogen annually, transitioning completely to fossil-free production would result in an additional cost of SEK 1.8 billion per year (Björksell et al., 2025; Hoffmann et al., 2023).

However, the technologies would still require significant capital investments. A nitrogen sensor costs around SEK 250 000. Deploying 1000 such sensors to cover an area of 350 000 ha in Sweden would thus require an investment of SEK 250 million (Hoffmann et al., 2023). The overall cost effectiveness of precision application varies with farm size, with a cost up to EUR 39 per tCO_2eq for larger farms (400 ha), and from EUR 6 to EUR 332 per tCO_2eq for smaller farms (100–200 ha) (Lankoski et al., 2020).

Using high efficiency fertilizers and nitrification inhibitors adds approximately 25–30% to the cost of conventional mineral fertilizers (Li et al., 2013). For nitrification inhibitors, studies reviewed by Lankoski et al. (2020) report a cost effectiveness of EUR 61 per tCO_2eq in France and EUR 107–202 per tCO_2eq in the UK (Lankoski et al., 2020).

Co-benefits

Precision application and the 4R framework directly improves the nitrogen use efficiency, which decreases nutrient surpluses, thereby reducing nitrate leaching and nutrient runoff into surrounding waters (Lankoski et al., 2020). Furthermore, applying fertilizer at the correct rate using precision technologies will improve the alignment with crop nutrient needs. In cases where they can avoid overapplication, farmers can maintain or increase yields while avoiding unnecessary expenditure on excess fertilizer (Li et al., 2013; Hoffmann et al., 2023).

Conclusion

Implementing these measures in Sweden is feasible but would require financial and structural support to overcome high associated costs. Progress is already being made on the technical pathway, with green NH_3 produced with solar energy in southern Europe. Plans are under way to establish production of green NH_3 in northern Sweden using fossil-free electricity (Björksell et al., 2025).

However, absorbing the high investment and annual costs would require sustained public financial support or a market willing to pay higher prices for fossil-free products. Given current profitability levels, it is unlikely that the agricultural sector alone will be able to shoulder these additional costs. To achieve broad adoption, Sweden needs to scale investment support mechanisms such as the EU's Common Agricultural Policy (CAP) funds, Klimatklivet (EU-funded support via Naturvårdsverket for physical investments in greenhouse gas reductions) or similar. Programs such as Greppa Näringen, a Swedish agricultural sustainability initiative that provides farmers with free long-term advice and training to improve nutrient management, reduce environmental and climate impacts and maintain profitable farming, will be crucial to support farmers in applying new technologies effectively.

Biochar

Biochar is a carbon-rich substance produced from decomposed biomass that has been heated up in low-oxygen environments, in a process called pyrolysis. Biochar has a porous structure, high stability and high carbon content, which makes it ideal not only for carbon sequestration, but also soil improvement and fertility, water filtration and environmental remediation. Since it can be produced by crop and other biomass residues from agricultural land, it makes it one of the most promising negative emissions technologies (NETs) with the potential of “revolutionizing” sustainable practices (Afshar & Mofatteh, 2024) – especially for countries with landmass mainly covered by cropland and high production of crop residues (for example in Denmark) (Karan et al., 2023). Even in Sweden, where arable land covers a smaller share of the land area than in Denmark, a considerable amount of residue is left on the fields. About 60% of the straw from cereal cultivation is ploughed down rather than collected, and rapeseed residues are not collected at all. There is increasing interest in using such feedstock for biochar production (Rehn et al., 2024).

Mitigation potential

Biochar has substantial mitigation potential. According to Afshar and Mofatteh (2024), each ton of applied biochar can sequester 2–2.6 tons CO_2 , and biochar systems could deliver emission reductions of 3.4–6.3 billion tCO_2eq globally, about half of which is CO_2 removal (Afshar & Mofatteh, 2024). Another Swedish study modelled soil carbon changes over a 30-year period in an agricultural landscape in western Sweden (Rehn et al., 2024). In scenarios where biochar produced from 50% of the available straw residues was combined with cover crops and, in one scenario, increased ley cultivation, about 10 tC/ha , was sequestered in addition to the baseline, corresponding to an annual sequestration rate of around 0.33 tC/ha/year . Using 100% of the available residues nearly doubled the removal rate of CO_2 , reaching approximately 2.0–2.2 $\text{tCO}_2\text{eq/ha/year}$, with biochar accounting for 75–86% of the total

(Rehn et al., 2024). According to the same study, farmers expressed a clear interest in biochar, alongside cover crops and increased ley cultivation. However, they also expressed concerns over the workload it would entail to collect crop residues during the busy harvest season, from which biochar would be produced (Rehn et al., 2024).

A Swedish pilot study showed that small pyrolysis plants can deliver net CO₂ removal, provided that the plant is integrated in the farm's overall heating system, which improves the energy efficiency. However, several challenges, which vary on a local level, need to be addressed relating to seasonal heat demand, biomass availability and system design (Azzi et al., 2021).

Costs

Although biochar seems promising as a mitigation measure, the costs are quite high. It has a market value of approximately SEK 5000–10 000/m³ (for farmers and stakeholders), but the cost depends strongly on the biochar's density. The costs are much higher for private users – approximately SEK 12 000–40 000 per ton (Hellmann et al., 2022). On the other hand, to produce on-site biochar by installing a pyrolysis plant also implies high investment costs. There are still only a few facilities in Sweden, which makes it difficult to calculate the costs; however, one small-scale pyrolysis plant in Sweden is estimated to cost roughly SEK 5 million (Hoffmann et al., 2023), while large-scale industrial facilities can cost around EUR 20–25 million in capital investment costs (Amjed et al., 2024). Therefore, while biochar is both technologically and environmentally promising, it is not yet cost-competitive, since it has a higher cost than the marginal incentive of EUR 100 per tCO₂eq (Flam et al., 2024).

Co-benefits

Beyond carbon sequestration, biochar is expected to provide a set of co-benefits. Converting crop residues into biochar contributes to sustainable waste management by avoiding the burning of straw residues, which would release CH₄ and particles directly to the atmosphere. Biochar application can also have positive effects on biological, physical and chemical properties of soil, improving water retention, nutrient availability, and overall soil health. Because of its porosity, biochar can effectively retain nutrients such as nitrogen and thus avoid nitrogen leaching (Afshar & Mofatteh, 2024; Azzi et al., 2021). Therefore, when combined with nitrogen fertilizers such as urea, it slows the release of nitrogen, and it can decrease the need for both mineral fertilizers (Afshar & Mofatteh, 2024) and irrigation (Azzi et al., 2021).

Biochar also can be used as a feed additive for livestock, where it is reported to improve digestion, reduce odours, and lower greenhouse gas emissions from manure (Afshar & Mofatteh, 2024; Azzi et al., 2021).

Conclusion

Biochar is a promising mitigation option with well-supported carbon sequestration and potential soil co-benefits. However, the feasibility of implementation depends on several interrelated factors. The physical factors are local soil characteristics, the availability and reliability of suitable feedstock, and efficient solutions for integrating pyrolysis heat and energy flows into existing energy systems on farms. The economic factors are the investment costs of pyrolysis plants and the extent to which farmers

and municipalities are willing to allocate capital for them, the willingness and readiness of farmers to collect crop residues from on-site biochar production and whether operational costs are considered reasonable.

Nitrification inhibitors and precision nutrient application

Previously discussed in the context of synthetic fertilizers, nitrification inhibitors are also applied to organic manure and urine deposits from grazing livestock. By delaying the conversion of ammonium to nitrate, these inhibitors reduce the N_2O formed during nitrification and leaves less nitrate available to be converted to N_2O (Lankoski et al., 2020; Li et al., 2013). Through this mechanism, nitrification inhibitors can substantially lower the N_2O emissions that are associated with inorganic fertilizers, manures and urine deposition by grazing livestock (Li et al., 2013).

Nitrification inhibitors and precision nutrient application are two different practices that have complementary approaches to improving nitrogen management in agriculture. While the nitrification inhibitors are, as mentioned, a specific type of product used to slow down the N cycle, precision nutrient application is a broader strategy that lowers N_2O emissions by avoiding the overapplication of N fertilizer. Precision application increases nutrient use efficiency, and both practices also reduce nitrogen leaching and thereby contribute to improved water quality (Lankoski et al., 2020).

Mitigation potential

The effectiveness of nitrification inhibitors varies with land use. A meta-analysis found that higher efficacy in grasslands (an average 54% reduction in N_2O) than in upland fields (34% reduction) and paddy fields (30% reduction). A study in Ireland showed that the application of the nitrification inhibitor dicyandiamide reduced cumulative N_2O emissions by 50% to 70% during the first 50-80 days after urine application. However, the effect varied between years, and urine nitrogen rated. When emissions were followed for 360 days, the reduction was no longer significant (Selbie et al., 2014).

When applied to urine patches, the nitrification inhibitors have been shown to reduce N_2O emissions by 49-70% in Irish studies (Li et al., 2013). In Denmark, they are included as a part of the national climate plan and are estimated to have the potential to reduce N_2O emissions from soils by approximately 0.6 million tCO₂eq by 2030. A comparable mitigation potential is likely to exist in Sweden as well; however, this potential has not yet been quantified (Björksell et al., 2025). Two issues require further examination: (1) the need to better understand the potential unintended effects on soil microbial communities, and (2) assessing the cost effectiveness in a precise way, as the mitigation effects vary depending on site-specific conditions. This makes it difficult to get a general and reliable estimation of the mitigation potential (Björksell et al., 2025).

Costs

Unless nitrification inhibitors bring substantial yield benefits, their use has been judged uneconomical for farmers who do not receive carbon credit payments for the achieved reductions. The inhibitors add about 25–30% to the cost of nitrogen fertilizer and this cost is the main factor limiting their use (Li et al., 2013). Their abatement cost, meaning cost per tCO₂eq avoided, has been estimated at EUR 61–202. For precision nutrient

application the abatement cost ranges from EUR 0–332 per tCO₂eq and is highly context dependent, being considerably lower on large farms than on smaller ones (Lankoski et al., 2020). Further research is needed to assess the potential to implement nitrification inhibitors in a Swedish context from a cost-efficiency perspective.

Co-benefits

Nitrification inhibitors also reduce nitrate leaching and improve water quality (Lankoski et al., 2020). When the inhibitor dicyandiamide was applied to urine patches, nitrate leaching was reduced by 68–76% (Li et al., 2013). There are also possible trade-offs. Inhibitors can increase NH₃ emissions (Lankoski et al., 2020; Li et al., 2013) and may contaminate agricultural products (Lankoski et al., 2020). The LRF also highlights possible unwanted effects of nitrification inhibitors on soil microbial life as an issue that needs further examination (Björksell et al., 2025).

Conclusion

The reviewed literature presents nitrification inhibitors and precision nutrient application as effective measures for reducing N₂O emissions from soils, with precision application also improving nitrogen use efficiency. However, the mitigation effect of inhibitors varies between years, soils and land types, and their cost is the main factor limiting their use, which suggests that uptake will depend on economic incentives such as payment for the emissions reductions achieved. Within the scope of the articles reviewed in this study, it was clear that more context-specific research is needed to examine the cost-effectiveness, including under Swedish conditions.

3.2 Livestock management

The largest share of emissions in Swedish agriculture come from cattle and consists primarily of CH₄ from enteric fermentation. As CH₄ is far more potent than CO₂ as a greenhouse gas, it is crucial to reduce CH₄ emissions from cattle. Some of the literature signals a natural reduction of emissions due to the expected decline in the total cattle population, due to increased productivity of dairy cattle and the increase in prices for dairy products. Other measures include genetic manipulation and dietary interventions.

Reduced herd size

Reduced herd size would directly lower the CH₄ emissions from enteric fermentation: one estimate is a potential reduction of 2.6 tCO₂eq per livestock unit per year, averaged across a 3-year lactation period, while N₂O and CO₂ emissions would remain largely the same (Lankoski et al., 2020). Historically, herd sizes have declined as a result of increased efficiency and the adoption of new technologies in the sector, which have enabled the same or higher levels of production with fewer animals. Further reduction of herd sizes can be achieved by imposing policies such as taxes on ruminant animals (Lankoski et al., 2020; Li et al., 2013). It is also likely that the meat production in the EU overall will decline due to shifting consumer diets (European Commission. Directorate General for Agriculture and Rural Development., 2024; Smith et al., 2013), but these shifts should not be taken for granted. A study in France shows that people

prefer to lower their emissions in other ways rather than reduce meat consumption (Brunelle et al., 2017).

Mitigation potential

Reducing the herd size is considered an extreme but highly effective measure for reducing the greenhouse gas emissions, as it directly lowers CH₄ emissions from enteric fermentation (Lankoski et al., 2020). Indirectly, it would also lower emissions from the production from animal feed (Lankoski et al., 2020). A study in Finland (Lötjönen & Ollikainen, 2017) estimated the abatement rate of decreasing a dairy cow herd to be 2.6 tCO₂eq per livestock unit per year (Lankoski et al., 2020).

Costs

The financial costs of this measure are very high due to the profound decrease in farm profitability resulting from reduced milk and meat yields (Lankoski et al., 2020; Li et al., 2013). The cost effectiveness of decreasing dairy herd sizes is poor, estimated at EUR 519 per ton CO₂eq abated (Lankoski et al., 2020).

In addition, reducing herd size leads to lower manure production. To compensate for the resulting nutrient deficit, farmers may need to increase the use of mineral fertilizers, which could inadvertently raise the costs and the greenhouse gas emissions elsewhere in the system (Lankoski et al., 2020). Furthermore, reducing herd sizes conflicts with the needs of meeting protein demands for a growing human population (Li et al., 2013). In Sweden, this would likewise directly contradict the national food security strategy (*Livsmedelstrategin*) and the political decisions aimed at increasing domestic food production security (Björksell et al., 2025; Hoffmann et al., 2023).

Co-benefits

Co-benefits were identified in the reviewed articles as the reduction of nitrogen in the agricultural system and decreased excreta deposition, which lowers the risk of nitrate leaching into waters.

Conclusion

While reducing herd size offers a large and direct cut to greenhouse gas emissions, the measure is highly problematic from an economical point of view and directly contradicts the *Livsmedelstrategin*. Therefore, rather than reducing herd sizes, mitigation in Sweden should be focused on improving productivity and implementing dietary measures to reduce the enteric fermentation from cattle.

Genetic selection for low-methane and feed-efficient animals

Selective breeding for animals with inherently lower CH₄ emissions, for example through faster rumen passage or improved feed conversion efficiency, is a promising long-term mitigation strategy. It aims to breed ruminants naturally predisposed to producing less enteric CH₄ and utilizing feed more effectively (Björksell et al., 2025; Min et al., 2020). This can be achieved through several approaches: direct selection; indirect selection for feed efficiency; broad breeding indices; crossbreeding; and microbiome selection (Björksell et al., 2025; Min et al., 2020).

Direct selection means breeding animals that produce less CH₄. This is made possible by collecting CH₄ data from sensors installed in milking robots, which measure emissions from individual cows (Björksell et al., 2025). Indirect selection, on the other hand, means choosing animals that produce the same amount of milk or meat while eating less feed. This is done by selecting animals with high feed conversion efficiency or low residual feed intake (RFI). RFI is the difference between how much an animal actually eats and how much it would be expected to eat given its body weight and growth rate. Animals with low RFI eat less than expected for the same growths and are therefore more feed efficient (Min et al., 2020).

Broad breeding indices use combined scoring systems, such as the Nordic Trait Merit (NTM) system, which evaluates traits like feed efficiency, fertility and health for Holstein and Jersey cows in Sweden, Denmark and Finland (Björksell et al., 2025). Finally, microbiome selection refers to the new approach of looking at how genetics influence microorganisms in animals' rumen, which is linked to CH₄ production (Min et al., 2020).

According to an LRF report, methane-related traits have moderate heritability. Existing national and Nordic breeding strategies and goals focus primarily on economic profitability and animal health, rather than CH₄ emission traits. There is potential to include more data on methane-related traits, but the data need to be collected and incorporated into the system (Björksell et al., 2025).

The Swedish Methane Action Plan does not list breeding as a strategy. Instead, it highlights an expected reduction in herd size due to efficiency that will indirectly reduce CH₄ emissions from enteric fermentation (Regeringen & Regeringskansliet, 2022).

Mitigation potential

This measure is unique in the sense that the effects are permanent, cumulative and passed down to future generations. If direct CH₄ traits are included in Swedish breeding goals, the CH₄ emissions from dairy cows could be reduced by approximately 5% by 2030 and 20% by 2050 per kilogram of "energy corrected milk", or the formula to compare milk by energy contained (Björksell et al., 2025).

Selecting for a higher NTM index reduces CH₄ emissions per kilogram of fat and protein by 0.9% to 1.7% per 10 NTM units, depending on the breed. Furthermore, using crossbred animals can reduce CH₄ emissions by 4% to 7% (and up to as much as 9–10% with Jersey crosses), primarily because healthier cows lower the need for replacement heifers (Björksell et al., 2025).

Animal selection for feed efficiency is estimated to reduce CH₄ loss per kilogram of dry matter intake (DMI) by 10% to 20%. However, results vary and, in some cases, efficient (low RFI) animals produce less total CH₄ mainly because they eat less feed, not necessarily because they produce less CH₄ per unit of feed digested (Min et al., 2020).

Costs

To incorporate direct CH₄ traits into breeding programs, CH₄ outputs must be measured directly in barns. The high costs of this technology (equipment, measuring, etc.) limits the measure's broad implementation, making it economically

challenging to adopt on all Swedish farms. Instead, measurements on a smaller subset of herds are required to calculate breeding values (Björksell et al., 2025). Besides that, it has been proven difficult to identify specific genetic markers associated with RFI and feed efficiency. Another challenge is the complex process of selection, which has to be balanced against other factors such as stage of lactation, milk components, etc. (Min et al., 2020).

Breeding is a key strategy for achieving a sustainable and competitive livestock sector. However, realizing the full potential of breeding requires dedicated resources and coordinated support from both the industry and public authorities (Björksell et al., 2025).

Co-benefits

Improving feed efficiency can substantially increase farm profitability. In feedlot systems, such as those common in the US, a 10% improvement in feed conversion efficiency has been estimated to increase profits by as much as 43%. It should be noted, however, that this figure reflects intensive, grain-based production systems that are not typical in Sweden, where beef production is generally more forage-based. The underlying principle remains relevant, as animals with low RFI consume less feed while maintaining the same level of production, thereby reducing feed costs and contributing to cost effectiveness regardless of production system (Min et al., 2020). Furthermore, breeding programs like NTM select for healthier, more fertile and longer-living cows; with time, such programs might reduce veterinary interventions, such as antibiotics for mastitis, and lower the replacement rate of individual cows, which further reduces the overall herd carbon footprint (Björksell et al., 2025).

Conclusion

Genetic selection for low-methane and feed-efficient animals offers an effective, permanent and cumulative climate solution. In Sweden, utilizing and expanding data for the NTM system has the potential to reduce CH₄ emissions by up to 20% by 2050. Although adopting on-farm measurement technologies presents a bottleneck, the strategy might pay for itself through its extensive co-benefits.

Dietary interventions

Enteric fermentation – the breakdown process of food in animals' guts – is the largest source of emissions in the agricultural sector, due to the CH₄ produced during the digestive processes of ruminants. Livestock production in Sweden is dominated by milk production, supported mostly by grain and fodder crops (Naturvårdsverket, 2024). Large volumes of protein-rich feed, such as soybean meal from Brazil, are imported. Soybean cultivation is linked to high greenhouse gas emissions from land-use changes, as well as to loss of biodiversity (Lindberg et al., 2021).

A wide range of dietary interventions, such as feed additives, lipid supplementation, and other options, have been examined for their effectiveness in mitigating CH₄ emissions. The measures identified in our review encompass several strategies,

addressed as follows: (1) alternative feed ingredients, (2) diet composition adjustments, (3) supplements and additives, and (4) lowering dietary nitrogen.

1 Alternative feed ingredients

In Sweden, dairy operations could increase the use of agro-industrial by-products such as sugar beet pulp with rapeseed meal in concentrate feed. These by-product-based concentrates require less cropland than concentrates based on cereals and soybean meal, because the crops are grown primarily for other products (sugar, rapeseed oil, etc.) and only part of the cultivation burden is allocated to the by-product. In an assessment of Swedish milk production, replacing cereal and soybean meal concentrate with by-product-based concentrates lowered the land requirement by 35%, and the eutrophication potential by 20% per kg of milk. The carbon footprint was also 20% lower but only when emissions from land-use change, mainly linked to soybean cultivation, were included. On the other hand, the use of non-renewable energy was 30% higher because wet by-products, especially beet pulp, needs to be dried before added to animals' feed (Lindberg et.al., 2021).

2 Diet composition adjustments

The composition of diet highly influences the rumen fermentation pathways, which then influences CH₄ production. Grain-based diets high in starch have been shown to reduce CH₄ emission immediately, while forage-based diets, on the other hand, increase CH₄ production (Min et al., 2020).

3 Supplements and additives

Researchers have tested plant compounds and microbial additives in ruminant feed for their potential to reduce enteric CH₄ emissions. Tannins, natural compounds found in many plants are among the most studied. Laboratory studies show that they can lower CH₄ in two ways: by acting directly on the methane-producing microbes in the animal's stomach, or by acting on other microbes that help them. How well tannins work depends on the type and amount used. Other plant compounds such as saponins and essential oils have also been studied, as have probiotics such as yeast, and more research is needed before these additives can be recommended to farmers (Min et al., 2020).

4 Lowering dietary nitrogen

Manipulating diet can also change the composition of urine and thereby influence the N₂O emissions, although the evidence for this is conflicting. One example is hippuric acid which is a natural constituent of ruminant urine. Its concentration is higher in ruminants fed with protein-rich feeds than those with low-protein diets, which means that farmers might be able to change how much hippuric acid is in the urine by changing the plants growing in the pasture. In laboratory studies, adding hippuric acid to synthetic urine reduced cumulative N₂O emissions by about half. However, a field study in which the hippuric acid content of cattle urine was increased found no effects on the N₂O emissions. Therefore, more studies are needed to determine its potential (Li et al., 2013).

These biochemical approaches differ from the strategy of reducing the overall nitrogen load in diet, which is seen as one of the most efficient ways to reduce

nitrogen excretion while maintaining productivity. This can be achieved by balancing high-protein pasture with lower protein supplements, such as maize silage, which improves nitrogen use efficiency. Lowering the protein content of supplement feed has been shown to reduce estimated nitrogen excretion in urine and faeces by 20% (Li et al., 2013). However, nutrient trade-offs must be taken into consideration. Rapeseed meal and other phosphorus-rich feed ingredients can increase phosphorus in manure (M. Lindberg et al., 2021), which risks leaching to nearby waters.

Mitigation potential

Dry matter intake (DMI) seems to be a strong determinant of CH₄ production by animals, with an average emission rate of 15–25 g CH₄ per kg DMI (Min et al., 2020). The composition of diet also matters. Animals fed a concentrate-based diet have lower CH₄ emissions than those fed with a forage-based diet. Increasing the concentrate-to-forage ratio of the diet could therefore reduce CH₄ emissions (Min et al., 2020).

Fat supplementation is another diet-related mitigation strategy. Research shows that an increase in dietary fat of 1% could reduce emissions by approximately 4% (Lankoski et al., 2020).

Among feed additives, 3-Nitrooxypropanol (3-NOP, sold under the name Bovaer) can reduce CH₄ emissions from enteric fermentation of dairy cows by approximately 30% when applying the recommended dose of 60–80 mg 3-NOP per kilogram of forage dry matter. Red algae additives have even higher mitigation potential, but results vary widely between studies. In a meta-analysis, red algae reduced CH₄ production by 65% in beef cattle, while the effect for dairy cows (10%), was statistically insignificant (Björksell et al., 2025). Tannin-rich diets can decrease CH₄ production by up to 20% and still retain the same animal productivity, provided that protein levels are adequate (Min et al., 2020). In Swedish milk production, feed additives have been estimated to reduce CH₄ emissions by 6% by 2030 and 15% by 2050, and a similar potential is assessed for beef production (Hoffmann et al., 2023).

Costs

The feed additive Bovaer (3-NOP) is estimated to increase production costs by around SEK 0.10 per kilogram of milk. If it were used for half of Sweden's total milk production, this would imply an annual cost of roughly SEK 140 million. Red algae additives are currently more expensive with an estimated additional cost of SEK 0.50 per kilogram of milk or SEK 13–25 per kilogram of slaughter weight for young cattle (Hoffmann et al., 2023).

The cost effectiveness for fat supplementation, on the other hand, varies from EUR 137 to EUR 335 per ton of abated CO₂eq. It should be noted, however, that this range is based on estimates for the EU27 member states and for France, and not solely on Swedish conditions (Lankoski et al., 2020).

Substituting cereal and soybean-based feeds with byproduct-based concentrates in Sweden would not have significant implications on the costs per kilogram of

milk under current market conditions. This makes it a more cost-neutral alternative (Lindberg et al., 2021).

Co-benefits

The inclusion of tannins in animal diets can improve protein utilization and improve milk quality if the concentration of omega-3 fatty acids is increased. Replacing human-edible cereals and the imported soybeans with byproduct-based concentrates would improve land-use efficiency (Lindberg et al., 2021).

Conclusion

Many of the suggested interventions above show potential; however, more evidence is needed to understand their long-term efficacy, scalability and implications for animal health. Some products that have already reached the market are under renewed scrutiny: media recently reported that Danish dairy farmers found serious health issues in their cows after the mandatory introduction of the methane-reducing feed additive Bovaer (Funseth, 2025). These types of incidents underline the importance for robust research and risk assessment that ensures dietary mitigation interventions are both environmentally effective and sustainable for farmers and animals.

3.3 Manure management

Manure management refers to the process in which animal excretion is captured, stored, treated and used (Li et al., 2013). On a global scale, manure production and use contribute to more N₂O emissions to the atmosphere than the production of synthetic fertilizer N (Li et al., 2013). While cost-effective and valuable as a fertilizer, as it includes various nutrients such as N and P, manure also releases greenhouse gases in all stages, including transport and application.

Several of the articles in our literature review show that measures have both benefits and disadvantages. For example, while spreading manure on soils would improve soil health and carbon sequestration, its transportation would generate additional emissions. Therefore, mitigation measures within this sphere need to be carefully examined. Another challenge is the variability of manure characteristics, soil conditions, weather and climate-related factors, which makes manure-based measures highly context dependent (Rehn et al., 2024).

Livestock farming in Sweden produces approximately 22 million tons of manure each year (Björksell et al., 2025). Spreading this manure requires land. As an illustration, Rehn et al. (2024) studied an agricultural landscape in the municipalities of Mellerud and Vänersborg in western Sweden consisting of around 39 000 ha of arable land. They estimated the manure by the area's livestock using VERA, a calculation tool from the Swedish Board of Agriculture. The area required for spreading it within the EU Nitrates Directive (Council Directive 91/676/EEC) limit of 170 kg N/ha/year was 9500 ha, around one-fourth of the landscape's total area. Manure management therefore also has a land-use dimension beyond the emissions perspective (Rehn et al., 2024).

Manure storage in Sweden gives rise to about 0.6 million tons of CO₂ of emissions per year which corresponds to around 10% of the agricultural sector's total greenhouse gas emissions. These emissions consist of CH₄ and N₂O. Sweden reports lower CH₄ emissions from slurry manure storage compared to values used by other countries in their emissions reporting. One reason is that Swedish livestock farms have a long-standing practice of frequent and daily manure removal, where manure is quickly moved from warm stables to cooler outdoor storage. Because CH₄ is formed by bacteria and depends on the temperature, this limits its formation. Partly for this reason, the LRF finds that the mitigation potential is smaller here than for other emission sources, although further measures are still considered necessary and possible to implement (Björksell et al., 2025).

Manure collection

Emissions of N₂O can be released during manure collection from animal houses and standing yards. In animal houses, the level of emission is linked to the use of bedding materials such as straw. In slurry-based systems where the manure and urine are mostly stored in oxygen-free conditions with no bedding material, there is less opportunity for nitrogen to be converted to N₂O. Thus, emissions in these conditions are generally low or negligible. Cattle kept on straw bedding, on the other hand, emit around 4–5 mg N per square metre per day, although one study found no significant difference between slurry-based and straw-based systems for dairy cows (Li et al., 2013). Few studies have measured N₂O emissions from hard standing areas, such as concrete yards.

As noted above, moving manure quickly from warm stables to cooler outdoor storage is already a long-standing, standard practice in Sweden. This leaves limited potential for further mitigation in this area compared with other sources of emissions (Björksell et al., 2025). We have therefore not presented costs and co-benefits for this measure.

Manure storage

Reducing greenhouse gas emissions is mostly possible from the storage and processing stages of manure management, targeting mostly CH₄ and N₂O. Like with many of the mitigation measures discussed in this report, choosing the appropriate strategy requires navigating trade-offs between different gases and managing financial challenges. The emissions from manure storage differ depending on whether the manure is slurry (liquid) or solid (stored in heaps). Some studies argue that the emissions are even higher during manure storage than after field application (Clemens et al., 2006), and that the slurry emits less N₂O than solid manure (Li et al., 2013). These storage emissions depend strongly on temperature. They were 14.3–17.1 kg CO₂eq per m³ over 100 days of winter storage, compared with 40.5–90.5 kg CO₂eq per m³ over 140 days of summer storage (Clemens et al., 2006). Slurry normally emits less N₂O than solid manure, because the oxygen-free conditions in uncovered liquid storage limit the process that produces N₂O. On the other

hand, liquid manure has a much higher potential to produce CH_4 than solid manure (Li et al., 2013).

Mitigation measures for slurry manure

Interventions to reduce emissions of slurry manure storage include lowering the pH of the slurry below 6 through acidification, which would reduce not only N_2O , but also CH_4 and NH_3 emissions (Li et al., 2013). Other measures include natural surface crusts or engineered manure storage covers. In advanced configurations, gas-tight covers may be combined with CH_4 capture and flaring systems or biofilters to collect and treat emitted gases (Björksell et al., 2025). Other strategies for slurry include manure separation (from solid and liquid fractions), aeration (pumping air into stored slurry), dilution (adding water to reduce dry matter content) and anaerobic digestion (biogas production). While many of these strategies are still considered either uncertain or even negative (Li et al., 2013; Hoffmann et al., 2023), converting manure to biogas is considered more effective in several studies, since it would provide a substitute for fossil fuels (Kwon et al., 2021; Scherer & Verburg, 2017).

Mitigation measures for solid manure

When it comes to mitigating emissions specifically from solid manure storage, maintaining anaerobic conditions can significantly reduce N_2O emissions. One strategy is the compaction of manure, which reduces N_2O emissions by limiting oxygen availability, although it may increase the potential for CH_4 emissions. Straw is also used as an additive, though its effects vary (Li et al., 2013). In one experiment, anaerobically stacked farmyards manure emitted more greenhouse gas overall than composted manure (Amon et al., 2001).

Mitigation potential

Acidifying slurry manure is highly effective, with estimates showing CH_4 reductions of treated volumes by 87%. In Sweden, acidifying 20% of the slurry volume would reduce emissions by about 0.02 million tCO_2eq per year (Björksell et al., 2025). According to the Intergovernmental Panel on Climate Change (IPCC), a thick, dry floating crust can reduce CH_4 emissions from slurry tanks by 40% under the right conditions (Björksell et al., 2025; IPCC, 2023). Furthermore, in Danish trials, capturing gas under a canvas roof and flaring it reduced CH_4 emissions by 64% (Björksell et al., 2025). A 1-m thick biofilter filled with compost has also been tested in Denmark, and it removed almost all CH_4 (Björksell et al., 2025).

For mitigation of solid manure, covering the manure with an airtight material can reduce 12% of NH_3 , 99% of N_2O and 88% of the CH_4 emissions compared to uncovered heaps (Li et al., 2013). Compacting and converting the manure in storage reduces N_2O by around 30% (Li et al., 2013). For slurry, a study in Finland estimated the abatement rate of a floating cover on manure storage at is 0.6 tCO_2eq per livestock unit per year (Lankoski et al., 2020).

Costs

The cost effectiveness of simply covering slurry manure storage with a floating cover is estimated at EUR 670 per ton of CO_2eq abated (Lankoski et al., 2020). For reducing NH_3 emissions, however, covered storage is highlighted as one of the most cost-effective measures at EUR 0.5–5 per kg of nitrogen reduced (Hellsten et al., 2017).

Acidification technologies require high capital investment costs for specialized equipment. In Sweden, an acidification unit costs approximately SEK 900 000 (Hoffmann et al., 2023). Acidifying 25% of the volume of slurry manure from pigs and dairy cows in Sweden would require around 120 acidification units, resulting in a total investment cost of over SEK 100 million. These estimates assume that the slurry is acidified at spreading, not in storage. The purchase of sulphuric acid represents an operational cost; however, the reduction of NH_3 nitrogen losses is a saved cost (Hoffmann et al., 2023), since more nitrogen is available to crops and less mineral fertilizer is needed (Hoffmann et al., 2023).

The cost effectiveness of centralized anaerobic digesters varies widely, from a net saving of EUR 48 to a cost of EUR 130 per of CO_2eq abated (Lankoski et al., 2020). On-farm biogas investments require investment costs of SEK 5-7 million per GWh of biogas and typically depend on subsidies to be viable (Hoffmann et al., 2023).

In Denmark, the Expert Group on Green Tax Reform recommended three models for a carbon tax on agricultural emissions, including those from enteric fermentation, manure management, and manure applied on fields. Proposed marginal tax rates ranged from EUR 33 to EUR 100 per ton of CO_2eq (Flam et al., 2024). They found that a rate of EUR 100 would reduce agricultural emissions by almost 2 million tons CO_2eq by 2030, largely through lower production, particularly in the cattle sector. A lower rate of EUR 50 combined with subsidies for emission-reducing technologies achieved almost the same reduction, with roughly half the fall in production (Flam et al., 2024).

Such policies aim to incorporate the environmental impacts of livestock production into decision-making. But as with many other measures, adoption of advanced technologies requires significant investments. As a result, many of these policies include subsidies to mitigate the economic burden on farmers and incentivize the adoption of such technologies (Flam et al., 2024). While such technology adoption has a positive effect on climate and the environment, it might also imply higher labour costs, subsequently leading to higher consumer prices of agricultural products (Scherer & Verburg, 2017).

Co-benefits

Anaerobic biogas processing could turn manure into a renewable energy source that could either be used on-farm or sold (Kwon et al., 2021). Acidification directly targets and reduces NH_3 volatilization, which means that more nitrogen is retained in the manure (Hoffmann et al., 2023). While improving nutrient efficiency, it reduces the need for mineral fertilizer inputs (Hellsten et al., 2017). A trade-off is that acidification discourages biogas production, unless the slurry is acidified in the field just before application (Hellsten et al., 2017).

Conclusion

Mitigating greenhouse gas emissions during the stage of manure storage can considerably reduce emissions from the treated manure, although the total potential in Sweden is smaller than for other emission sources (Björksell et al., 2025). The measures are often associated with high investment costs and complex chemical trade-offs. Technologies such as acidification, anaerobic digestion and advanced bio-filtered covers are highly effective at reducing CH_4 , while their effect on N_2O is mixed. They can also provide strong agronomic and energy-related co-benefits. However, due to the

expense per unit of abated carbon and the high capital investment costs for certain technologies, widespread adoption of these manure storage measures is unlikely without financial support, subsidies, carbon credit mechanisms, or even direct emission pricing (OECD, 2023).

Manure application on land

While manure serves as an organic fertilizer that can increase soil carbon (Kwon et al., 2021), it is also a source of N_2O and NH_3 emissions. In grassland systems, excreta deposited by grazing livestock, mostly in urine patches, can contribute to more N_2O emissions than fertilizers do. The emissions from applied manure are largely affected by timing, rates and placement, although the effect of application methods on N_2O has not been well studied (Li et al., 2013).

Solid manure can only be placed on the surface of grasslands. Slurry manure can be applied on the surface, spread evenly across a crop (“surface broadcasting”), applied in narrow bands using trailing hoses that place the slurry in lines onto crops (“band spreading”), and applied in bands under crop leaves (“trailing shoe”), or slurry can be injected directly into the soil (“injection”), in shallow open slots or deep closed slots (Li et al., 2013).

Other mitigation measures include nitrification inhibitors, restricted grazing and dietary manipulation. Some of these measures overlap with soil-related mitigation options; see sections 3.1 and 3.2 of this report.

Mitigation potential

Similar to precision application of synthetic fertilizers, reducing manure nitrogen inputs to match crop demand is a reliable way to mitigate N_2O (Li et al., 2013). Furthermore, low-emission application techniques such as slurry injection and trailing hose systems substantially reduce NH_3 volatilization compared to surface. With injection, for example, only 9% of the manure nitrogen is lost as NH_3 , compared with 40% with broadcast spreading (Lankoski et al., 2020). In Sweden, transitioning completely away from broadcast spreading to trailing hoses could reduce NH_3 emissions by approximately 700 tons, while expanding rapid incorporation could reduce them by a further 400 tons (Hoffmann et al., 2023).

Costs

In Sweden, the transition to trailing hoses alongside requirements for rapid soil incorporation for manure is estimated to cost between SEK 29 and SEK 44 million annually (Hoffmann et al., 2023).

Co-benefits

Low-emission techniques such as injection, rapid soil incorporation and acidification are primarily intended to reduce NH_3 volatilization. By retaining a greater share of plant-available nitrogen in the soil, these methods improve nitrogen use efficiency and can thereby reduce the need for mineral fertilizers, which is a direct economic benefit for the farmer (Hellsten et al., 2017; Lankoski et al., 2020). Additionally,

injection technologies improve water quality by reducing phosphorous runoff (Lankoski et al., 2020).

However, there are some trade-offs. When manure is used as a fertilizer, it must be transported to the fields, which consumes fuel that should be counted against the net emission reductions (Kwon et al., 2021; Li et al., 2013). It has also been noted that techniques that reduce the NH_3 emissions (like injection) may increase N_2O and CH_4 emissions (Lankoski et al., 2020; Li et al., 2013).

Conclusion

Mitigation measures for manure and mineral fertilizer application largely overlap, as manure application functions as an organic fertilizer. As a result, similar technologies, costs and co-benefits apply in both cases. In sum, low-emission techniques effectively reduce NH_3 losses and phosphorous runoff but may increase N_2O , and under certain conditions, even CH_4 emissions. Widespread adoption of advanced spreading and acidification technologies in Sweden will require substantial investments. A consideration of environmental trade-offs, and targeted financial support is thus necessary. In general, many mitigation measures for manure management in Sweden are still under development or require further investigation to be accurately quantified (Björksell et al., 2025).

3.4 Machinery and vehicles

In 2024, agricultural machinery and vehicles emitted 0.56 million tCO_2eq in Sweden (Naturvårdsverket, 2025a). Emissions from this category have not declined compared to 1990s levels despite new technologies and renewable energy sources. The measures often sit at the intersection between the agriculture and energy sectors, which focus on electrification and replacing fossil fuel-based energy with biogas and other sustainable energy sources (Kwon et al., 2021).

We identified three measures of interest: electrification of machinery and vehicles; switching fuel to biogas; and switching fuel to biodiesel.

Electrification of machinery and vehicles

The electrification of vehicles involves transitioning from fossil fuels to electric motors powered by batteries. In agriculture, electrification is so far an option mainly for machines used in and around farm buildings, which move short distances. For field machinery is not yet considered a workable alternative due to long charging times. Electric machines are also more expensive than their diesel equivalents. These higher investment costs are generally not reflected in higher prices for the commodities that farmers sell, so farmers have to bear them themselves. The LRF reported that any investments of this kind, such as energy conversion in agriculture, would largely not have been made without financial support. At the same time, farmers' interest in investing in electrified machinery is high (Hoffmann et al., 2023), which signals that there is an implementation potential should there be relevant policy and financial

incentives. Klimatklivet is one such an example, as it can finance the electrification of work machinery (Hoffmann et al., 2023).

Mitigation potential

Electrification can reduce diesel use, but most of the reduction in machinery emissions would come from the switch to biofuels. Electrification offers a substantial CO₂ reduction potential. In Sweden, replacing 6000 fossil-fuel yard loaders could save 16 million L of diesel annually. When combined with efficient driving and the use of biofuels (hydrotreated vegetable oil, HVO), the electrification of yard machines contributes to an estimated emissions reduction of 421 000 tCO₂eq per year when only combustion is counted, or 650 000 tCO₂eq from a life-cycle perspective, for Swedish agricultural machinery (Björksell et al., 2025).

Costs

To illustrate the costs of transitioning to electric machinery, the Swedish Federation of Farmers used contribution calculations on machinery costs per dairy cow from the Rural Economy and Agricultural Societies (Hushållningssällskapet) for southern Sweden. The model is based on a farm with 120 dairy cows using a loader and a tractor with a mixer wagon (Hoffmann et al., 2023).

For 2000 larger livestock enterprises replacing a 3- to 4-ton compact loader (for example, Volvo L25 Electric), the capital cost is approximately SEK 1.3 million per machine, compared to SEK 600 000 for a diesel equivalent. This results in an incremental cost of SEK 700 000 per machine. For 2000 farms, the total additional costs would be approximately SEK 1.4 billion. For 4000 medium-sized livestock enterprises replacing a smaller compact loader, the electric version costs around SEK 729 000, compared to SEK 463 000 for the diesel equivalent, giving an additional cost of about SEK 1 billion (Hoffmann et al., 2023).

Co-benefits

Electrification of vehicles and agricultural machinery will contribute to improved local air quality and reduced noise levels. Other co-benefits have not been mentioned in any of the articles we reviewed.

Conclusion

The electrification of vehicles and machines within the agricultural sector is still in an early phase, currently limited by high investment costs and by the lack of workable technology for field machinery. These obstacles currently make it unprofitable for farmers to transition, since the increased costs can generally not be recovered through income from agricultural products (Hoffmann et al., 2023).

Parallel to the need for electrification, specific measures are required for the agricultural production of renewable energy. This includes investments in, for example, solar energy, biogas and systems for energy storage and control devices, contributing to the development of electrification-friendly infrastructure. Thus, the transition requires comprehensive economic policy tools to become a reality. State support and financial incentives are crucial.

Biogas

Biogas is produced when bacteria break down manure, crop residues and other types of farm waste into a gas consisting of primarily CH_4 and CO_2 (Kwon et al., 2021). Sweden produces approximately 6.5 million tons dry weight of crop residues annually, which indicates that feedstock is available to advance biofuel production (García- Condado et al., 2019).

Biogas can be used for several purposes – fuel, electricity and heat (Björksell et al., 2025) – and the leftover mass can even be used as a fertilizer. In Denmark, initiatives have emerged in which farmers trade raw manure at low cost for use in anaerobic digestion facilities or as input for biofuel production (Bonnichsen et al., 2020), which could potentially be done in Sweden too.

As a mitigation measure, biogas works mainly by replacing fossil energy. The largest gain is achieved when the gas is upgraded and replaces petrol, diesel or fossil gas (Björksell et al., 2025). Digesting manure also captures CH_4 that would otherwise be emitted from manure storage, and the size of this saving depends on, for example, manure storage technology and temperature, as previously mentioned (Lankoski et al., 2020). Some CH_4 leaks from digesters, engines, and upgrading, and this leakage accounts for a large part of the climate footprint on farm-scale plants (Björksell et al., 2025).

As an energy source, biogas could potentially meet the high on-farm energy demand or even be used in other sectors (Kwon et al., 2021). In the Swedish reports that have been reviewed in this study, this has not been mentioned as an alternative. Instead, biogas is presented as a sustainable but expensive action. It is estimated that 100 biogas plants would require high investment costs of several billion SEK (Hoffmann et al., 2023). In 2022, Klimatklivet allocated SEK 1.8 billion of its total budget of SEK 4 billion for funding for biogas plants and production. Many of the applicants were farmers (Hoffmann et al., 2023).

Installing more biogas plants and creating a co-sharing infrastructure among farmers, based on Danish examples, is listed as a priority for Swedish biogas production despite high investment costs. To offset at least some of the high costs of producing energy compared to fossil fuels, both solar energy and biogas receive tax exemptions (Hoffmann et al., 2023).

Mitigation potential

Producing upgraded biogas and liquid biogas has a low climate footprint of 31 $\text{gCO}_2\text{eq/kWh}$ and 51 $\text{gCO}_2\text{eq/kWh}$, respectively, compared with about 240 $\text{gCO}_2\text{eq/kWh}$ for the fossil fuel they replace (Björksell et al., 2025). In Sweden, increased manure-based biogas production is estimated to avoid 0.3 million tCO_2eq by 2030 and up to 0.6 million tCO_2eq by 2045 by replacing fossil energy (Björksell et al., 2025).

Costs

Substantial investments are required to be able to utilize the full potential of biogas production and consumption in Sweden. Investments are needed for upgrading the

raw gas to vehicle gas for liquefaction, for example, for use on farms as transport fuel. Currently, this technology is only available for larger plants; however, technological developments are expected to enable small-scale solutions in the future. The LRF report assumed that at least 50% of Sweden's manure-based biogas potential could be realized by 2030, which corresponds to about 2 TWh per year. If new plants have the same capacity as those currently receiving support, 4 GWh each, this translates to roughly 430 new plants (Hoffmann et al., 2023).

The LRF assumed that the additional biogas from these new plants would be used as follows: heat and electricity (20%), vehicle gas (40%) and liquified biogas (40%). It is difficult to estimate the costs, since they differ by size, technology applied and the time of the investment. However, the LRF estimated the investment costs to be SEK 1.7 billion for heat and electricity production, SEK 4.1 billion for vehicle gas and SEK 4.8 billion for liquified biogas, based on the example costs of SEK 5, 6 and 7 million per gigawatt hour respectively (Hoffmann et al., 2023).

The LRF presents biogas as a promising mitigation measure. However, it has large investment and production costs that will require financial support, such as from Klimatklivet, and smart infrastructure where both facilities and power can be shared across farms. Biogas-driven on-farm machinery can be an option, although the availability of such machines remains limited and challenges related to distribution and refuelling persist, together with the implementing costs (Hoffmann et al., 2023).

Co-benefits

Depending on the farm's infrastructure, biogas can be used in a combined heat and power unit to generate electricity and heat for the facility, with the potential to sell off surplus energy (Björksell et al., 2025).

Conclusion

Biogas has one of the largest mitigation potentials linked to Swedish agriculture, although avoided emissions are credited to other sectors (Björksell et al., 2025). Implementing the measure on a large scale is technically feasible for larger plants, but financial challenges remain. To achieve widespread adoption, incentives and support frameworks such as Klimatklivet will remain crucial to help farmers overcome the initial capital costs. Sweden already subsidizes biogas produced from manure through a production support up to SEK 0.40 per kWh. Continuous subsidies and tax exemptions will ensure that operating these plants remains economically viable for the farmers over time (Hoffmann et al., 2023).

Liquid biofuels (HVO and biodiesel)

There are several different types of liquid biofuel that can replace diesel such as FAME (fatty acid methyl ester), which includes RME (rapeseed methyl ester) and HVO (Björksell et al., 2025). The LRF considers fuels as the first stage in making agricultural machinery fossil-free, since they can be used in existing engines (Hoffmann et al., 2023).

Only a small share of fuel use consists of pure biofuels such as HVO or RME, while most consumption is diesel blended with biofuels under *reduktionsplikten*, the Swedish requirement for such blending (Hoffmann et al., 2023). In 2023, the blending requirement in Sweden was just over 30%. In 2024, it was reduced to 6%, then raised again to 10% in 2025 (Björksell et al., 2025; Hoffmann et al., 2023).

Mitigation potential

Replacing diesel containing a 6% biofuel blend with 100% HVO in Swedish agricultural machinery would reduce emissions by approximately 300 000 tCO₂eq per year (direct combustion) or 672 000 tCO₂eq (full life cycle) (Björksell et al., 2025). Alternatively, transitioning to 100% RME would give an estimated reduction of 141 000 tCO₂eq (direct combustion) or 497 000 tCO₂eq (full life cycle) (Björksell et al., 2025).

Costs

The LRF compared fuel prices in November 2023. Excluding VAT and after the diesel tax refund, diesel subject to *reduktionsplikten* cost around SEK 15 per litre, while HVO cost SEK 24, so nearly a SEK 10 difference. When scaled to total consumption, this corresponds to SEK 2.5 billion per year, assuming the whole machinery fleet can run pure HVO (Hoffmann et al., 2023). Although this is a large additional cost, the switch does not require investment in new machinery.

Co-benefits

Fossil-fuel diesel can be directly replaced by HVO in existing agricultural machinery without major problems, and HVO is covered by the warranty on most new machines, meaning it can reduce emissions without new capital investments. New tractors from Valtra and Fendt can also run on RME with the warranty maintained (Björksell et al., 2025). Biofuel production can use agricultural and industrial by-products: for example, HVO is often produced from vegetable oils and animal fats (including residues from slaughter), thereby minimizing waste and supporting resource efficiency (Björksell et al., 2025).

Conclusion

Liquid biofuel represents a technically feasible mitigation option in Swedish agriculture. Fuels such as HVO and RME reduce emissions substantially and are compatible with most of the existing machinery fleet. Although they imply higher costs in comparison to conventional diesel, they can be used on today's machinery, which makes them the first stage of transition. One remaining challenge remains the distribution of biofuels to farms (Hoffmann et al., 2023).

4. Discussion

We set out to identify agricultural mitigation measures that are adoptable under Swedish conditions and sufficiently evidenced to be operationalized in the VCF Dashboard for municipal climate action and investment planning. Our central finding across the evidence base is that the primary constraint is not the availability of mitigation options, but the alignment of costs, incentives and institutional conditions required for their implementation.

Many measures generate clear public value in the form of emissions reductions, improved water quality, soil health and resilience, yet the direct costs and operational burdens are often borne by farmers. As a result, adoptability depends critically on stable incentive structures, risk-sharing arrangements and coordination across actors, rather than purely on technical feasibility. This has direct implications for municipal decision-making: enabling conditions are not peripheral, but integral to the mitigation potential of the measure portfolio.

Each of the categories of measures analysed focus on specific greenhouse gas mitigation possibilities. The evidence suggests important differences in mitigation potential, scalability and certainty, which we discuss here with regard to relevance for municipalities and the incorporation into the VCF Dashboard.

For soil management measures (CO₂ and N₂O channels), options such as cover and catch crops, precision nutrient management, nitrification inhibitors, biochar and, in some contexts, reduced tillage offer moderate but relatively scalable mitigation potential, particularly when adapted to local agronomic conditions. Catch and cover crops are the largest of these in the estimates by the LRF, at 0.18 million tCO₂eq by 2030 and around 0.5 million by 2045, compared with 0.05 million for biochar. Nitrification inhibitors reduce N₂O emissions by 35–40% in meta-analyses, but their potential has not been quantified for Sweden in this report. Additionally, their abatement cost is high, at EUR 61–202 per tCO₂eq. The evidence base for these measures is comparatively strong, although outcomes are context dependent, especially for tillage practices, where effects vary by soil type and climate. These measures are therefore well suited for inclusion in decision-support tools, provided parameter ranges reflect local variability.

For livestock management measures (primarily CH₄), interventions such as feed additives and dietary adjustments can offer high mitigation potential at the animal level, but their system-level impact and adoptability remain uncertain due to dependencies on regulatory approval, supply chains, animal health considerations and farm economics. The feed additive Bovaer reduces enteric CH₄ by around 30% at the recommended dose, at a cost of around SEK 0.10 per kg of milk, yet the estimated effect for Swedish milk production is 6% by 2030 and 1% for 2050. One limitation is that most additives can only be given when animals are housed, whereas Swedish cattle graze in summer. Considering animal health and breeding, the LRF puts the potential at 0.64–0.74 million tCO₂eq by 2045 – one of the largest in its assessment. The evidence base is growing but remains uneven, particularly with respect to long-term effects and scalability. These measures are therefore relevant but often fall into the category of indirect or influenceable measures for municipalities.

For manure management measures (CH₄ and N₂O), several interventions, including storage covers and acidification and anaerobic digestion, demonstrate large reductions for manure that is treated. Acidification can cut CH₄ from treated slurry by 87%. The national potential is nevertheless small because emissions from Swedish manure storage are already low. The technical evidence for emission reductions is relatively robust, but costs are high and implementation is capital-intensive, leading to strong dependence on subsidies, coordination and infrastructure.

For machinery and on-farm energy measures (CO₂), liquid biofuels, biogas and electrification offer a clear and relatively certain emissions reductions, though of very different magnitude. Replacing biodiesel with HVO would cut emissions from agricultural machinery by about 300 000 tCO₂eq per year, and an added fuel cost of around 2.5 billion per year, whereas electrifying 6000 yard loaders would save 16 million litres of diesel. Liquid biofuels are therefore the first stage in of transition as electric alternatives are not yet workable for field machinery. Biogas stands out as a high-impact but system-dependent measure, requiring aggregation of feedstock integration with local energy systems, and thus aligning closely with municipal enabling roles.

Our findings indicate that no single measure dominates across all criteria. Instead, the most robust strategy for municipal climate planning is a portfolio approach, combining:

- scalable soil measures with relatively strong evidence;
- high-impact but capital-intensive manure and energy system interventions; and
- selected livestock measures where feasibility conditions are met.

Crucially, the effectiveness of this portfolio depends on how measures are combined and supported, rather than on individual measures in isolation. This reinforces the relevance of scenario-based tools such as the VCF Dashboard, which allow municipalities to assess trade-offs, complementarities and financial implications across measure combinations.

Sweden's agricultural context, characterized by limited agricultural land, strong food security considerations and high innovation capacity, further underscores the need for targeted, context-sensitive implementation strategies. While the technical mitigation potential exists, realizing it at scale requires aligning economic incentives, governance structures and local conditions.

4.1 Recommendations and next steps

The immediate next step is to translate the reviewed measures into VCF Dashboard-ready inputs and accompanying guidance for municipal users. This includes the following steps, for researchers and municipalities:

- Shortlist measures for VCF Dashboard inclusion based on adoptability in Sweden, evidence strength and parameter availability.
- For each included measure, provide parameter ranges (abatement factor, eligible activity level, capital or operating expenditures, lifetime/persistence, co-benefits/trade-offs) and an uncertainty rating.
- Develop short notes on municipal levers per measure: what municipalities can directly do versus influence, when it comes to convening, co-financing, land-use planning, local infrastructure support, advisory collaboration and procurement where relevant.
- Workshops with municipalities should be held to validate assumptions and identify where Sweden-specific parameterization is needed next, for example, related to local baseline conditions and uptake constraints.

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Annex 2. Other measures

Buffer strips

Buffer strips or buffer zones refer to the vegetated land along the edges of fields near watercourses. They have several functions such as reducing nutrient runoff trap sediments and pesticides, reducing the risk of soil erosion, creating habitat for pollinators and beneficial insects and improving water quality (Haddaway et al., 2018). Although buffer strips can contribute to carbon sequestration in the roots of perennial plants (Lankoski et al., 2020, p. 116), they are not their primary function. Buffer strips can still function as a mitigation measure by replacing land that could have been cultivated, thereby reducing cultivation and tillage-related emissions (ibid), but that should be considered more as an indirect effect than a mitigation measure. Research indicates that wider buffer strips can reduce carbon dioxide emissions, although the extent of the reduction is not quantified. However, they don't affect emissions of nitrous oxide or methane.

In 2011, Denmark implemented a Buffer Zone Act, stipulating that 50 000 ha of 10-m wide mandatory strips along all watercourses and lakes had to be implemented. After three years the policy was revised following a boycott from Danish farmers and lawsuits who claimed that the policy prevented them from carrying out agricultural production on their own land (Haddaway et al., 2018). Therefore, this measure is unlikely to gain social acceptance in Sweden where only 10% of the land area is used for agriculture, compared to nearly 60% in Denmark (as per the World Bank Open Data, <https://data.worldbank.org/>, in 2023).

Because buffer strips function primarily as an adaptation and environmental protection measure and are unlikely to be implemented at a large scale in Sweden, further analysis of cost and related aspects was not pursued.

Renewable natural gas

Purifying and upgrading biogas, for renewable natural gas, can be used as a substitute to conventional natural gas. On a life-cycle basis, such biogas production can result in net greenhouse gas emissions reductions of 136% for dairy manure and 317% for swine manure compared with fossil natural gas. This is primarily due to the avoidance of methane emissions from unmanaged animal waste (Kwon et al., 2021, p. 4642).

None of the other articles from the Federation of Swedish Farmers (*Lantbrukarnas Riksförbund*, LRF) or the Board of Swedish Agriculture mentioned it as a potential mitigation measure, which is why no further elaboration and its implementation potential in a Swedish context is done within the scope of this report.

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