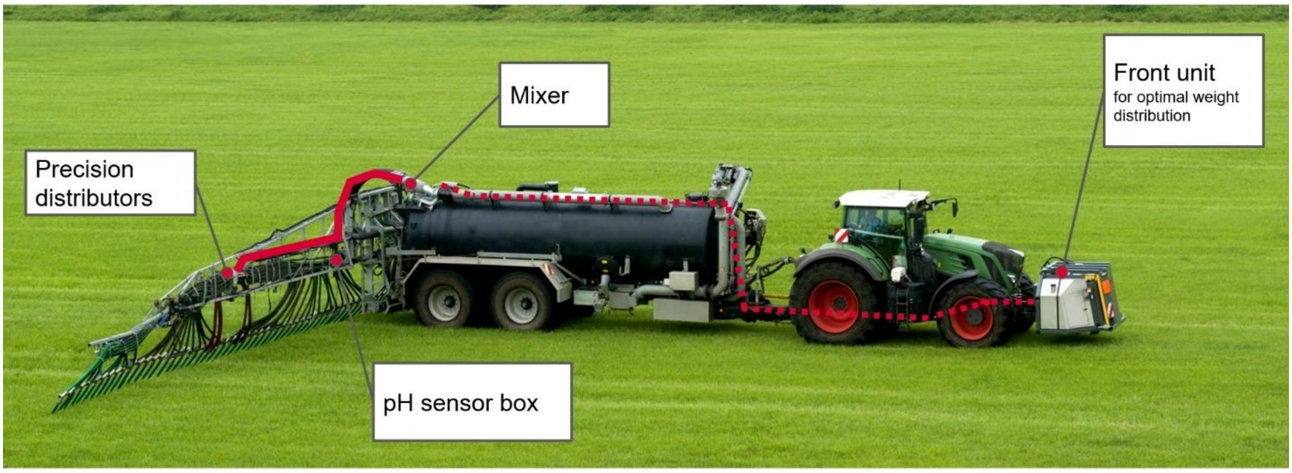
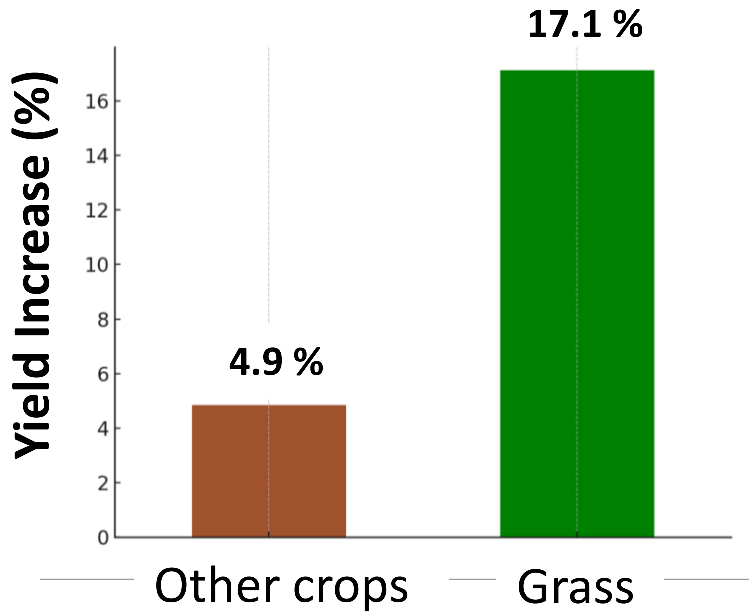
Analysis of 27 scientific studies using In Field Acidification in +60 field trails from 2010 to 2024





By Morten Toft, BioCover 18,08.2025 – Version 2

Prepared For RVO in Holland for revision of RAV list

Documentation available: https://www.biocover.dk/uk/articles/articles-from-research.aspx

Executive Summary

This report provides a comprehensive evaluation of in field slurry acidification as a mitigation strategy for reducing ammonia (NH_3) emissions in agriculture. Drawing on over 60 field trials conducted across Europe between 2010 and 2024, the report analyzes the effects of in-field acidification with special focus on ammonia emissions, crop yield, phosphorus solubility, and compliance with sulphate limits.

Key findings show that acidification can reduce NH_3 emissions by 50–95%, with the most effective results achieved using sulfuric acid doses of 2.6–4.4 L/m³ and target pH values of 6.0 – 5.5 While higher doses lead to stronger NH_3 reductions, doses of 2.5 L/m³ or less still provide substantial emission control (+/- 50%) and comply with agronomic recommendations on sulfur application. In Field Acidification showed an up to 20 % increased ammonia emission over slurry injection.

Grassland trials consistently showed yield increases with an average of 17 %, while results for cereals were more variable with 5 %. Acidification also proved comparable or superior to injection techniques, especially under dry conditions, with less physical disturbance to the soil resulting in significantly less $CO2_{eq}$ emission.

Phosphorus mobilization was mainly a concern when pH dropped below 6.0, with significantly lower risk at pH levels above 6.0. In wetlands, it is important to maintain a balance between emission reduction and P retention. In other areas, the increased P mobilization may be a benefit to agriculture with less need for mineral P application.

The report concludes that slurry acidification is a highly effective and scalable technology for reducing agricultural NH_3 field emissions. It offers many operational advantages over injections, but success depends on achieving appropriate pH targets, ensuring safe sulfur levels, and adapting to soil and crop conditions. Concerns about sulfur use are also addressed: applying sulfuric acid for acidification increases sulfate input to soils. While this is generally beneficial for sulfur-deficient systems, cumulative applications must be managed to avoid over-fertilization, particularly in regions with regulatory limits on sulfate (SO_4-S) application—commonly set between 40–50 kg/ha. Moderate dosing of 2.5 L/m³ allows compliance within these thresholds when slurry application is limited to 49–61 m³/ha.

The report is structured over three main topics:

- Ammonia emission efficiency
- Crop yield response.
- A comparative assessment between Sod injection and In Field acidification.

Morten Toft 18.08.2025

Section Title	**Page**

Introduction:

This synthesis is based on an analysis of 27 international reports and studies, including field experiments, lab measurements, and model-based assessments conducted between 2010 and 2024 across eight European countries.

The report summarizes evidence from more than 60 field trials, lab studies, and model-based assessments of slurry acidification techniques conducted across Europe. The goal is to evaluate the effectiveness of acidification in reducing ammonia (NH_3) emissions and its impact on use of Sulphate, solubility of P and crop yield.

Key Findings

1. **Ammonia Reduction Efficiency**
   - Acidification consistently reduces NH_3 losses by 40–95%, depending on acid dose, target pH, slurry type, and application method.
   - Highest reductions (>90%) were achieved in Finnish and German studies using target pH of 5.5 and acid doses of 2.6–4.4 L/m³.
   - SyreN systems and In field acidification performed well, especially under windy or warm conditions.
2. **Acid Dosing and Target pH**
   - Most trials used sulfuric acid (H_2SO_4) with dosing ranging from 1.7 to 9.0 L/m³.
   - Effective NH_3 mitigation typically occurred at pH 6.0 or lower.
   - Acid requirements were higher for biogas digestate due to its high buffer capacity.
3. **Yield Effects**
   - Yield effects varied by crop and conditions:
     - Grassland: Consistent positive yield effect (+400 to +1100 kg DM/ha).
     - Winter wheat: Mixed results; modest average gain (~+220 kg/ha), with some trials showing neutral or negative effects.
   - Best yield responses were associated with acidified digestate on grasslands.
4. **Environmental and Economic Considerations**
   - Acidification also reduces GHG emissions and has neutral to positive effects on soil biology.
   - Some concerns exist regarding heavy metal mobility (Zn, Ni) and P leaching, particularly on sandy soils.
   - Economically viable under regulatory or incentive frameworks; often costlier than injection without subsidies.

Effectiveness of Acidification on Low-pH Soils

While most acidification trials are conducted on soils with neutral to slightly alkaline pH, the effect of acidification on soils already below pH 6.0 is less studied. However, available data suggest that on acidic soils (pH < 6.0), the benefit of high acid volumes for reducing ammonia losses is less pronounced. This is because the natural soil environment already limits NH_3 volatilization, reducing the relative gain from additional pH lowering. In a two year field study, soil cation exchange capacity (CEC) influenced NH_3 emissions following Cow slurry application (R=0.53). Source: Thünen Institute Report on Acidification p. 8.

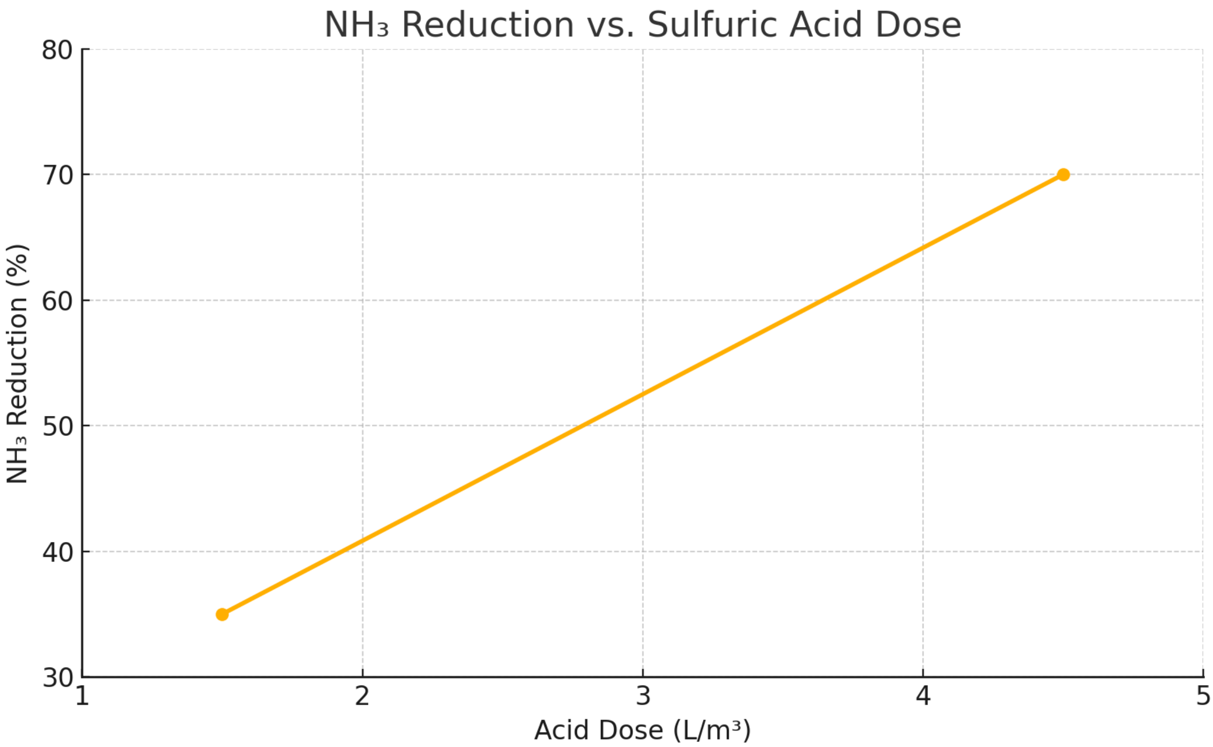
Phosphorus Mobilization Risks

Several studies indicate that phosphorus (P) becomes more water-soluble in slurry following acidification. The risk of P leaching is particularly relevant for grassland systems where slurry is not incorporated into the soil. Research suggests that significant increases in soluble P occur when slurry pH is reduced below 6.0, with the greatest mobilization observed at or below pH 5.5. While this may improve plant-availability of P, it also increases environmental risk in vulnerable areas, such as sandy soil or near watercourses.

If slurry pH is not reduced below 6.0, the risk of phosphorus release is considerably lower. Most trials indicate that soluble P levels remain largely unchanged or increase only slightly when pH is maintained above 6.0. Thus, maintaining slurry pH between 6.0 and 6.3 appears to strike a balance—offering moderate ammonia reduction benefits while minimizing P mobilization risk. This makes it a safer option for environmentally sensitive areas.

Top-Performing Strategies

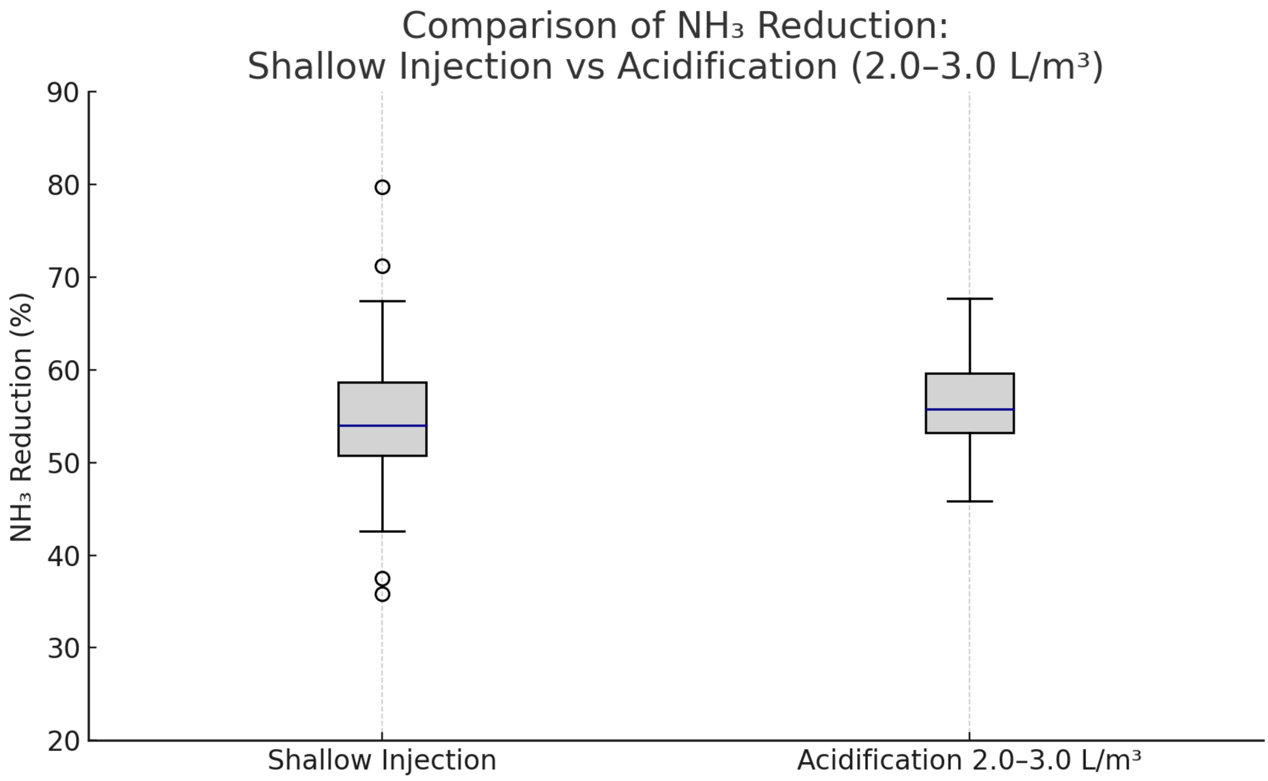
Study	**Slurry Type**	**Dose (L/m³)**	**pH**	**NH_3 Reduction (%)**
Triesdorf 2023	Cattle/digestate	4.5	6.5	70%
Pacholski 2015	Cattle/pig mix	6.5	6.2	68%
VERA 2010	Cattle and pig	2.4	6.4	43%



Average of all trails

Effect comparison with Injection Techniques

Quantitative comparisons from multiple trials demonstrate the differences in effectiveness between the two techniques. In the Seidel et al. (2013) study, for example, acidification to pH 6.0 reduced ammonia emissions by 68.9%**,** while shallow injection at 35 cm spacing achieved 60.6% reduction. Similarly, the Keskinen et al. (2022) trial showed 95% NH_3 reduction for acidification versus 43% for injection in a dry year. These findings show that, on average, acidification results in 5–20 percentage points greater NH_3 reduction compared to standard injection methods—particularly under dry and warm field conditions.

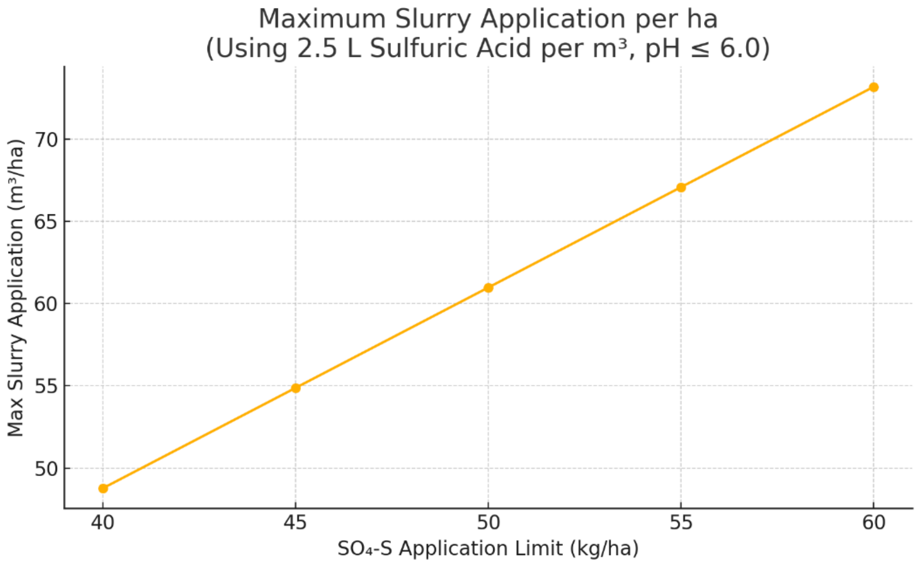


1 Average of all trails with acid dosage rate from 2-3 liter

Field trials comparing slurry acidification to shallow injection consistently show that both methods are effective in reducing ammonia emissions. However, acidification often provides comparable or superior emission reduction**,** especially under warm and dry conditions where injection effectiveness can decline. Studies from Finland (Keskinen et al. 2022) and Germany (Seidel et al. 2013) reported NH_3 reductions of 95–97% with acidification, while injection achieved 43–97%**,** depending on soil type and moisture.

In addition to effectiveness, acidification has the advantage of being less invasive to grassland surfaces, reducing the risk of sward damage compared to injection. Moreover, it is generally easier to apply and integrate into existing spreading systems like trailing hoses.

Conclusion on Dose 2.5 L/m³: Evidence from multiple trials, including the VERA-certified SyreN system, shows that ammonia reductions of up to 40–50% can be achieved with sulfuric acid doses at or below 2.5 L/m³, especially when target pH is kept near 6.0–6.3. While this is lower than the maximum reductions seen with higher doses, it represents a significant environmental benefit and is often sufficient to meet regulatory targets when combined with appropriate application methods (e.g., trailing hose). Therefore, acidification at ≤2.5 L/m³ is a viable mitigation strategy when balanced with operational and safety considerations.



Slurry Application Limits Based on SO_4-S Constraints Sulfur application via acidified slurry must comply with environmental regulations. Assuming 96% sulfuric acid contains ~32.6% sulfur (S), a dose of 2.5 L/m³ corresponds to approximately 0.82 kg S/m³ of slurry. Based on this:

- At a limit of 40 kg SO_4-S/ha, the maximum slurry application is ~49 m³/ha.
- At a limit of 50 kg SO_4-S/ha, the maximum slurry application is ~61 m³/ha.

These figures provide a guideline for compliant field practices using moderate acid doses.

Recommendations

- Promote acidification - especially for grassland applications (profitability)
- Prioritize pH targets ≤ 6.0 for effective mitigation and min. P leaching.
- Prioritize 2.5 l Sulphuric acid pr. m3 for balanced Sulphate application with app. 50 % ammonia emission reduction with a recommended ceiling of 50 m3 slurry pr. ha

Effects of in field Slurry Acidification on Crop Yields

Introduction

The average yield increase across all trials was 13.0%. When separating results by crop type, grasslands showed a significantly higher average yield increase (+17.1%) compared to other crops such as winter barley and winter wheat (+4.9%). Danish trials specifically showed yield responses like the international findings, with noticeable positive impacts on grassland productivity.

Slurry acidification is a technique widely used to reduce ammonia emissions from livestock manure, and an emerging benefit observed is its positive effect on crop yield. This report consolidates data from 2010-2024 field trials focusing on various crops under northern European conditions.

Field Trials Overview

- Countries covered: Denmark, Germany, Finland, Sweden, Estonia
- Crop types: Grassland, Winter Wheat, Winter Barley
- Techniques evaluated: Surface band spreading with and without acidification, Injection, and Broadcasting

Number of Trials by Crop Type

Crop Type	Number of Trials
Grasslands	10
Other Crops	36

- Grassland trials are predominant in regions where direct slurry incorporation is impractical.
- Other crop trials included winter wheat, winter barley, and maize assessments.

List of Trials with References

- Denmark:
  - 30 winter wheat yield trials using SyreN technology (2010-2017) [Danish SyreN Winter Wheat Yield Trials].
  - Comparison of SyreN, Infarm, and Injection systems (2010) [SyreN vs. Infarm vs. Injection - Denmark 2010].

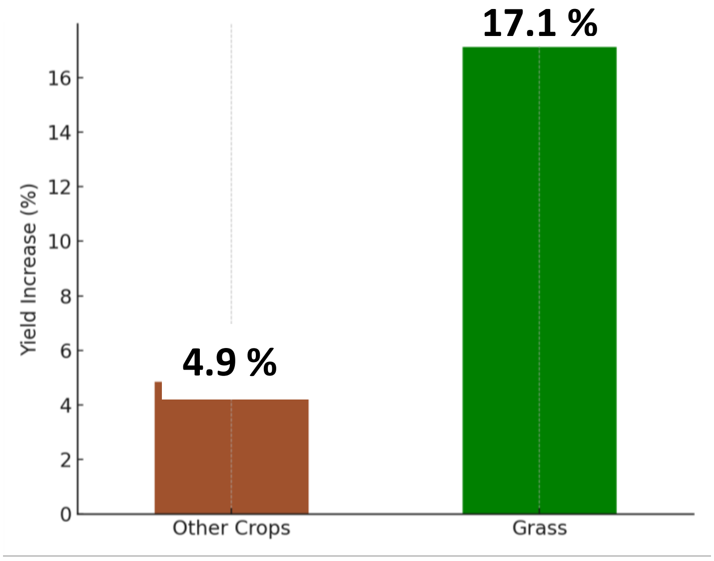
- Germany:
  - Acidification versus Injection field trials (2012-2013) [Acidification vs Injection on Grassland - Germany and Denmark].
  - Multi-site trials on acidification and injection techniques (2019-2020) [GülleBest Multi-Site Trials - Germany].
  - Triesdorf acidification trials (2023) [NH3 Emission Measurements with Acidified Manure - Triesdorf Trials].
  - Schleswig-Holstein field trials on organic fertilizers (2018) [Field Trials on Acidification of Organic Fertilizers - Schleswig-Holstein].

- Finland:
  - Boreal grassland acidification vs injection trial (2018) [Acidification VS Injection in Boreal Grassland - Finland].

- Sweden:
  - Acidification trials with cattle and pig slurry on grassland and winter wheat (2013) [Field Trials with Acidified Cattle and Pig Slurry - Sweden].

- Estonia:
  - Acidification impact on soil microbiology and crop yield (2017-2020) [Acidified Pig Slurry and Soil Microbial Effects - Estonia].
  - Trials on acidified slurry in grassland and winter wheat (2017) [Acidified Slurry in Grassland and Winter Wheat - Estonia].

Key Findings:



Average Yield Increase by crop Type (Grass vs. other crops)

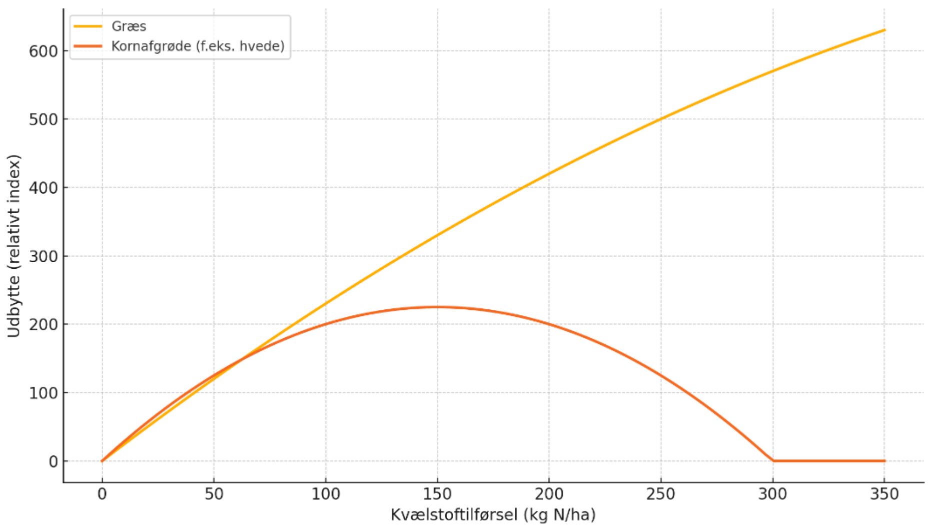
Crop Type	Average Yield Increase (%)
Grasslands	17.1%
Other Crops	4.9%

- Grasslands responded most positively to acidified slurry application.
- Acidification was especially effective under conditions where incorporation of slurry was not possible (e.g., established grassland).
- Winter cereals showed more moderate gains but still benefited from improved nitrogen availability.

The significant difference between grass and cereal crops can be explained by the crop response curves to nitrogen, where grass almost always benefits from more nitrogen and Sulphur and the cereals have a more limited response once the economical optimum has been reached.

The timing of slurry applications is also a major factor where cereal early spring applications are performed at significantly lower temperatures than grassland summer applications, leading to a higher volume of nitrogen for grasslands.

Response curves for nitrogen – Grass vs. cereals



Conclusions

Slurry acidification not only reduces environmental impacts but also significantly improves crop yields, particularly in grassland systems. The consistent positive results across different regions support broader adoption of acidification technologies, especially in dairy and mixed farming systems where grass yield is crucial.

Comparative Assessment of Shallow Injection and In Field Acidification of Slurry

Introduction:

This report is prepared for policymakers, administrative authorities, and researchers in the Netherlands as part of the revision of the RAV technology list. Its aim is to present a structured, evidence-based comparison of slurry injection and in-field acidification as competing methods for reducing ammonia emissions, improving nitrogen use efficiency, and ensuring sustainable nutrient management.

While both methods have been recognized as mitigation technologies, the analysis clarifies that acidification cannot be integrated with injection systems. The reason is that acidifying slurry significantly increases slurry volume during application, which causes the narrow slots created by disc injectors to overflow. This not only nullifies the purpose of injection application but also introduces operational risks and negates the emission-reduction benefit intended by injection. Furthermore, injections under these circumstances can result in undesirable slurry exposure to plant tissue and contaminate silage and fodder crops. If not needed, the injection slots are negative with severe soil disturbance and significantly increased subsidence and CO_2 release

The report provides a comprehensive comparison of shallow injections and in-field acidification for slurry management, focusing on both agronomic performance and wider environmental and operational factors. While both methods effectively reduce ammonia emissions, acidification offers several advantages:

- Greater working width and application speed – Increased capacity for slurry application
- Less soil disturbance and lower risk of sward damage
- Lower energy and fuel consumption
- Significantly lower $CO2_{eq}$ emissions
- Additional nutrient value through Nitrogen, Sulfur, Phosphorus and Manganese availability
- Enhanced compatibility with precision farming tools and ESG reporting
- Potential integration of nitrogen inhibitors for improved nitrogen retention
- Documented safety and regulatory approval for acid handling systems like SyreN and AutoZap

Particularly in regions like the Netherlands, where low soil pH dominates over 50% of farmland, acidification demonstrates elevated efficiency and can potentially reduce nitrogen deposition in Natura 2000 areas by over 30% compared to injection. Given the system's flexibility, lower cost, and sustainability benefits, acidification presents a robust, scalable, and climate-smart alternative to traditional Sod injection.

Acidification and shallow injection both offer valid benefits for reducing nutrient losses and improving fertilizer value. However, from a practical and environmental management standpoint, acidification offers greater flexibility, wider applicability, and additional co-benefits (e.g. Yield increase and better NPA, NUE, GHG reduction, reduced compaction, odor control, additive injection, extensive ESG documentation).

Further field trials on acidic soil effect on deposition to Natura 2000 areas are recommended. SyreN System can document the ammonia depositions to Natura 2000 areas, and it can replace modeling systems and deliver a valuable tool for compliance with regulatory requirements and reduce costly farm buy-out schemes. Because of low pH soils on approximately 50% of the agricultural area in the Netherlands - 80 % of Natura 2000 buffer zones - the effectiveness of acidification is expected to be significantly enhanced under these conditions. So far, indicated in one study with a significant effect R=53 %. With this effect confirmed, a 30 %

increased reduction of ammonia emission in Natura 2000 area can be expected with a potential cost reductio of 7 billion € in buy-out Schemes.

Acidification

Shallow Injection

2. Overview of Techniques

Shallow Injection:

Incorporates slurry below the soil surface using narrow slots (~30 cm spacing) and 8 to 12 m with.

Acidification:

Applies sulfuric acid (typically 2.0–3.0 L/m³) directly into the slurry during spreading, lowering its pH to 6.3 – 6.0 and using 12 to 36 m with.

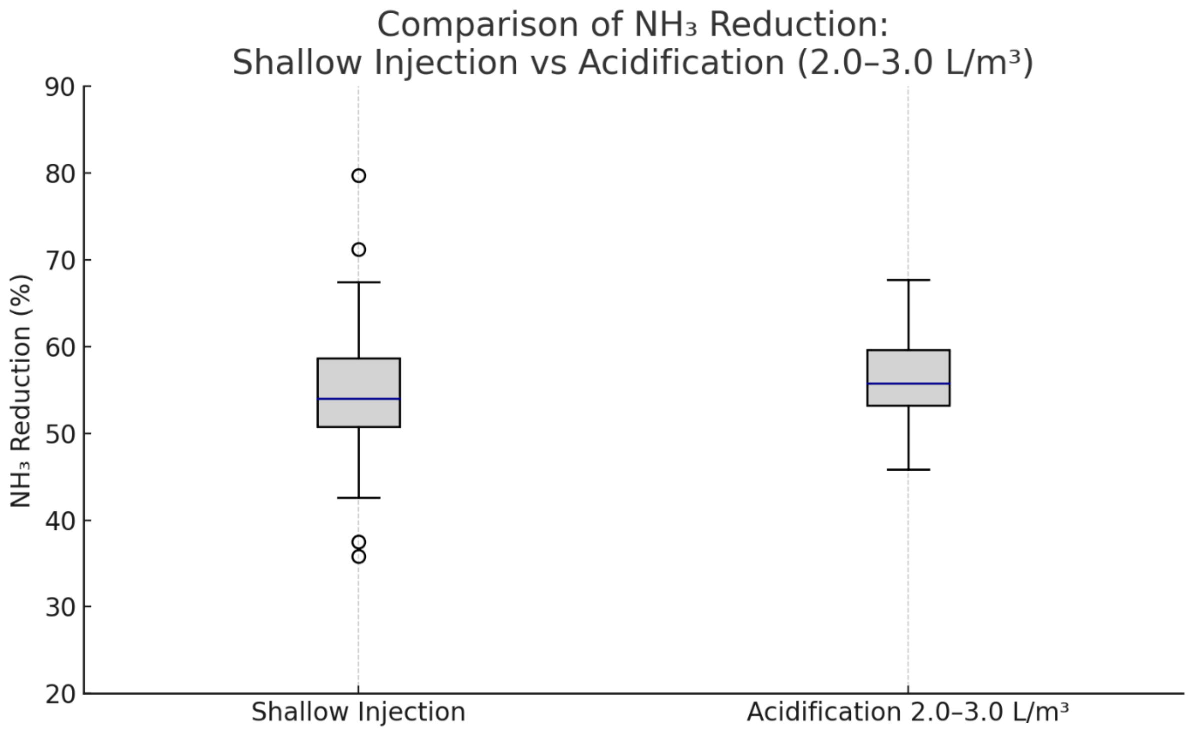


Figure 1: Boxplot comparison showing NH_3 emission reductions for shallow injection and acidification at 2.0–3.0 L/m^3. While median reductions are similar, acidification exhibits tighter consistency with less variability, supporting reliable performance under field conditions.

3. Agronomic and Practical Factors

Crop compatibility limitations for injection:

Shallow injection is often unsuitable for use in growing crops beyond grasslands due to the mechanical disturbance and physical damage caused by the disc coulters. This is particularly problematic for cereals, maize, and legumes, where injections can harm root zones and above-ground biomass. Acidification, applied via trailing hose / shoe systems, avoids such damage and can be safely used across a wide range of crop types without compromising plant health or yield.

Yield effects:

Comparative trials show that acidification often results in equal or higher crop yields than shallow injections, particularly on grassland. Average yield increases range from +400 to +1100 kg DM/ha for acidification, while injection can cause sward damage that offsets nitrogen efficiency gains. On cereals, the yield effect is more variable, but generally neutral to slightly positive for acidification. Injections are seldom used for other growing crops and lack comparative trails.

4. Soil and Nutrient Considerations

Micronutrient availability:

Acidification may enhance the availability of certain micronutrients, particularly manganese (Mn). In sandy soils with naturally low Mn availability, the drop in pH caused by acidification can increase Mn solubility, leading to improved uptake by crops. This can support better growth, especially in sensitive crops like cereals and maize.

Fertilization cost savings:

The sulfate added through acidification not only helps reduce ammonia emissions but also contributes to plant-available sulfur nutrition. This can partially or fully replace the need for separate sulfate fertilization (e.g., ammonium sulfate), leading to cost savings on commercial fertilizer inputs, especially in sulfur-deficient regions.

Sulfur contribution:

Acidification adds sulfate (SO_4-S), which benefits sulfur-deficient soils. Sulphur is not considered an environmental problem and there are agronomic standards, but no legal caps. As sulphuric acid normally constitutes 2/3 of the cost of acidification pr. m3 slurry, there is a natural incentive to limit the volume of acid to reduce the cost of acidification. Sulphate should be managed as close to crop need and not exceed 40–50 kg/ha.

Crop need for Sulphur

	S-need, kg pr. ha	*Typical amount of slurry, ton pr. ha*	*Needed kg S pr. ton*	*Liter H_2SO_4 pr. ton slurry*
Winter wheat, clay soil	15	30	0,5	0.9
Spring barley, sandy soil	10	30	0,3	0.6
Winter rape, clay soil	35	30	1,2	2.1
Silage grass, irrigated sandy soil	30	40	0,8	1.3

(Source: Torkild Birkemose – Videncenter for landbrug)

Phosphorus mobility:

Injections have no influence on P solubility, and it is thus not subject to increase P losses via runoff. Acidification does increases soluble P in slurry, especially below pH 6.0. However, the increased P solubility is an advantage in land-based nutrient management systems, where P availability for crop uptake is critical and where runoff risks are minimal. In such systems, acidification supports more efficient P use and may reduce the need for mineral P fertilizers. In waterlogged areas, care should be taken not to lower pH below 6.0, where the calcium-phosphorus bonding of P in slurry is dissolved and has been measured to increase the P plant availability up to 40 %.

Heavy metals:

Acidification may mobilize Zn and Ni slightly, particularly on sandy soils.

Soil pH buffering:

Injections do not affect soil pH. Acidification can reduce pH locally, but it is buffered over time. There is a theoretical need for application of up to 200 kg lime pr. year pr ha depending on acid dosage rate, but this need has not been confirmed in trails.

5. Infrastructure and Cost Considerations

Ongoing German MuD project (Sauer+ 2022–2027):

As part of a 5-year national innovation initiative, the Sauer+ project under the German "MuD" (Model and Demonstration Projects - https://saeureplus.de/) program is currently evaluating in-field acidification across 8 federal states (Bundesländer) using 8 SyreN systems. This comprehensive trial series is designed to document the sustainability, profitability, and operational performance of acidification technologies such as SyreN. The project supports broader knowledge transfer, contributes to policy dialogue, and provides scientific validation to further mainstream acidification as a reliable alternative to injections across the EU. It is now in its 3rd year of operation.

Results from the MuD first 2 years are positive – but tentative - as fertilizer trails should be seen over a min. 3 year period. First results from the MuD project will be available Autom / winter 2026

The yields derived from the enclosed study are robust in that they are gathered in the period from 2010 – 2024 and from many countries and subject to very variable conditions. In general, there are positive yields reported from 60 % of all trials and 40 % with no yield response or a slight negative response. As all trails are established at random selected date / time, they represent practical live variations, where the emissions because of climatic conditions are low in app 40 % of the window when slurry is applied.

With emissions lower than 5 kg N / pr ha, potential benefits from emission reduction cannot be expected to show a difference in yield. If there is a difference, it is often because the Sulphur contribution makes a difference or the extra plant availability from Phosphorus.

It is possible to identify the emission level by use of the SyreN e-missioN system. It is always recommended to use a low dosage of acid to cover the crop need for Sulphate during periods of low emission and to increase the acid dosage to min. pH 6.4 when the emissions increase. If acidification is to influence plant availability of phosphorus, pH must be lower than 6.0.

Profitability of acidification

In Field Acidification is used in 9 different EU member states. It has a very solid following on grasslands, where the emission losses are very high during the summer period and the emission reduction is almost always translated to solid yield increases. But there are a lot of different situations where the acidification is a significant benefit. It is almost a standard for use on winter rape where a +3-l acid ensures enough Sulphate availability and the N levels are enhanced. In many cases, acidification replaces ammonium sulphate mineral fertilizers that have a +/- 50 % cost increase over acidification. Grass also like the elevated Sulphate level. It is also use with injection of slurry for Mais, where the pH must be lowered below pH 6.0 to mobilize extra P as starter fertilizer for Maize. With small grains, the Sulphate effect is less pronounced, and attention should be given to use the e-missioN system to identify the periods with high emission where acidification is a benefit.

The price of acid is a very decisive cost factor. Depending on country, the price for acid may vary in the range from 0.30 € to 0.45 € pr. l. and the distribution cost of the acid can also vary considerably.

Budget figures for enclosed 27 studies: Other crops 4.9 % yield increase.

Example Wheat with 9 t/ha

Item	4.9% Yield Increase	Notes
Extra yield	4.33 dt/ha	1 dt = 100 kg
Extra revenue	€62,852	4.33 dt/ha × €29 × 500 ha
Acid use	60 L/ha → €9,900 total	€19.80/ha
Acid logistics	€2,000	€4/ha × 500 ha
Depreciation	€18,000/year	€90,000 over 5 years
Interest	€2,250/year	5% on average tied capital
Total costs	€32,150/year	Sum of above costs
Net benefit	€30,702/year	≈ €61.40/ha
Payback period	~2.93 years	Based on net benefit

Budget figures for enclosed 27 studies: Grass with 17.1 % yield increase

Example grass with 130 dt/ha silage pr. ha

Item	17.1% Yield Increase	Notes
Extra yield	2.36 dt/ha	1 dt = 100 kg
Extra revenue	€153,400	2.36 dt/ha × €130 × 500 ha
Acid use	80 L/ha → €13,200 total	€26.40/ha
Acid logistics	€2,000	€4/ha × 500 ha
Depreciation	€18,000/year	€90,000 over 5 years
Interest	€2,250/year	5% on average tied capital
Total costs	€35,450/year	Sum of above costs
Net benefit	€117,950/year	≈ €235.90/ha
Payback period	~0.76 years	Based on net benefit

Recognition and EU integration:

The SyreN system has EU-BAT, VERA verification and ETV Certification. It has received 15 international Awards for sustainability, CSR and innovation in agriculture. It is currently recognized as one of the 12 most advanced and accepted RENURE systems in the European Union, further supporting its qualification under nutrient recycling and emission reduction frameworks.

Use of nitrogen inhibitor:

The SyreN system includes an additive tank that allows for the optional injection of urease and nitrification inhibitors during slurry applications. This enables further stabilization of nitrogen in the soil and extends the agronomic benefit of slurry beyond pH control. When used in combination with acidification, these additives support even greater nitrogen retention, reduce greenhouse gas emissions, and enhance compliance with integrated nutrient management strategies. This includes optional injection of urease and nitrification inhibitors during slurry application. Commonly used products include Vizura®, N-Lock™, and Piadin®, all of which have demonstrated effectiveness in stabilizing nitrogen and reducing emissions. This enables further stabilization of nitrogen in the soil and extends the agronomic benefit of slurry beyond pH control. When used in combination with acidification, these additives support even greater nitrogen retention, reduce greenhouse gas emissions, and enhance compliance with integrated nutrient management strategies.

Odor control additives – iron sulfate:

SyreN system additive system also supports the use of iron sulfate ($FeSO_4$) to enable odor control during slurry application. Iron sulfate helps bind hydrogen sulfide and other odorous compounds, making it a useful complement in situations with high odor sensitivity or community proximity. The system's additive tank makes it possible to inject such supplements directly into the slurry stream. When injected during slurry tanker filling, the chemical reaction is activated during transport to the field for application. It must be noted that the use of iron sulfate also bonds parts of the water-soluble phosphorus. This could be an advantage in waterlogged areas like the Dutch polders.

Ammonia emission documentation importance in the Netherlands:

In especially the Dutch context, documentation of ammonia emissions is valuable due to the difficulty of accurately measuring mobile volatilization from field applications. Technologies like e-missioN, which offer real-time data tracking and transparent reporting on ammonia emission and use of nitrogen, are critical tools for enabling regulatory compliance and stakeholder trust. Such tools help overcome the limitations of conventional model-based measurement systems in one of Europe's most regulated and nitrogen-sensitive farming landscapes.

ESG compliance and documentation:

For Integrated Environmental and Agricultural (IEA) farms and others seeking to meet Environmental, Social, and Governance (ESG) standards, detailed documentation of nutrient use, emissions, and application accuracy is essential. Precision systems such as e-missioN not only fulfill regulatory requirements but also support ESG reporting and farm sustainability certification efforts.

Demonstration and education resources – Hof Vogelsang videos:

Practical demonstrations of acidification systems such as SyreN, AutoZap, and the e-missioN platform are available via a series of videos recorded at Hof Vogelsang. These include:

Establishment of field trails with SyreN System

https://youtube.com/watch?v=HWnwlPcw5DU&si=FOK8nY0DNNlNmr9V

Control of slurry spreading

https://www.youtube.com/shorts/SsKe3slRb64

e-missioN

https://www.youtube.com/shorts/LoYNR_MtXiE

Acidification – SyreN System

https://www.youtube.com/shorts/D5EVipz8HXI

Swefelsauer als stikstofhämmer:

https://youtube.com/shorts/QS7sez3gJg0?si=SxD1YL6cc6meKmMY

Acidification, NIRS and e-missioN

https://www.youtube.com/shorts/ZxYUVjYPFfM

Results from acidification 2024

https://www.youtube.com/watch?app=desktop&v=1NO3o1lvz3U

Precision farming and documentation – e-missioN System:

The e-missioN system integrates real-time monitoring of ammonium nitrogen efficiency (NPA) during slurry application. It utilizes data from over +600 ammonia emission trials with 30.000 measurements and combines NIR slurry characteristics, GPS tracking, weather data, and pH measurements to deliver high-resolution maps of nitrogen efficiency, ammonia emission and application accuracy. The system enables dynamic adjustment of mineral fertilizer rates post-application through VRA (Variable Rate Application) maps and generates full documentation for regulatory compliance and sustainable nutrient management. When paired with acidification, the system allows for optimal timing and quantification of acid benefit. This makes e-missioN a powerful tool for reducing overlap, improving yield, reducing GHG and enabling smart fertilizer planning in line with climate goals.

AutoZap filling system:

The AutoZap system is a specialized, vacuum-controlled safety valve for handling concentrated sulfuric acid during IBC tank filling. It includes an automatic shut-off trigger, a particle filter, and pressure-limiting components to ensure safe operation between 1–2 bar. AutoZap is designed to reduce human exposure risk, increase operator efficiency, and minimize acid spillage during transfer. It always refill to same level, from different residual volumes, facilitating knowing when the driver should expect a need for change of IBC tank. The system can be mounted on trucks and has proven compatible with acidification operations in field conditions.

Regulatory compliance and transport flexibility:

The SyreN system is ADR-compliant (dangerous goods transport) for sulfuric acid transport in Germany, meeting European safety regulations. In other countries such as Holland, Sweden, Finland, Polen, Baltic states and Denmark, exemptions exist for agricultural use of acid under certain conditions, allowing safe and simplified use without full ADR regulation. This enhances logistical flexibility for acidification deployment at farm level. Transport of IBC tanks outside of SyreN System is subject to ADR.

Logistical simplicity:

One key advantage of shallow injections is that this system avoids the need to manage, transport, and store sulfuric acid. This reduces logistical complexity, especially for farms without dedicated infrastructure or training for safe acid management. It also eliminates the need for acid delivery coordination and safety oversight.

Material durability and safety:

Modern acidification systems are constructed using non-corrosive materials for all parts in contact with sulfuric acid. This includes acid-resistant plastics (Teflon), 316 stainless steel components, and chemically treated hoses. These materials have proven durable over more than 15 years of operational use in commercial settings. Importantly, there have been no reported safety incidents in Denmark or other countries with regulated acidification systems, highlighting their long-term reliability and safety under field conditions.

To further improve operator and road safety, the SyreN system can is equipped with camera-based safety systems that assist with traffic visibility and secure pick-up and docking of IBC acid tanks, minimizing risk during refilling and transport operations.

Investment costs:

Acidification systems typically require an investment of around €90,000, depending on configuration and working width (e.g., boom-mounted SyreN systems). In contrast, a shallow injection setup for a 12-meter working width costs €100,000 or more, due to the need for heavier construction and soil-engaging components. This difference can influence farm-level adoption decisions, especially for smaller or mixed-crop farms.

The SyreN Light version is developed for field trial plots, research settings, or use with smaller tractors and slurry tankers. This lightweight configuration with a limited capacity for carrying acids offers lower entry cost with prices starting from €60,000, depending on specific equipment needs.

Weight and soil compaction:

Shallow injection equipment is significantly heavier than acidification systems, due to reinforced frames and components required to penetrate soil. This added weight can increase soil compaction risks, particularly under moist field conditions. In contrast, acidification systems mounted on booms or trailing hose systems are lighter and distribute weight more evenly, reducing impact on soil structure and enabling operation during a wider range of field conditions.

Maintenance:

In Field Acidification has a 15-year record for use with acid, there are no corrosion of parts in contact with acid. The pH sensor head has a maximum of 2-year life and is regarded as a wear part. Lack of maintenance of dry couplers can shorten their life expectancy. A budget for maintenance of 2.000 € pr. year over the lifetime of the SyreN system is recommended.

Sod Injection has a lot of moving parts with deep soil contact. Depending on soil type and use conditions, a need for replacement of these parts can be expected.

Flexibility:

Acidification is compatible with both arable and grassland cropping systems using the same slurry tanker. No other system offers the ability to be used in growing crops, grasslands and cultivated fields. It is also used with shallow- or deep injections, where increased P plant availability for Mais is a major feature. Used together with band spreading hoses or dragging shoe, In Field Acidification offers a 1-for-all crops systems where it can be turned on or off as the climatic conditions require.

5. Environmental effects - CO2eq

Foaming effect of acidified slurry:

Acidification of slurry often results in natural foaming of the slurry during application, which forms a temporary emission barrier on the slurry surface. This foam reduces the slurry's direct exposure to wind and turbulence, thereby limiting ammonia volatilization even further. The foaming acts as a passive cover, enhancing the effectiveness of acidification and making the application less sensitive to weather conditions compared to open-surface slurry spreading. The foaming effect is caused by the chemical release of bicarbonate (HCO_3^-) from the slurry when acidified. This chemical reaction is inevitable and not manually controlled. It does not contribute to extra GHG, as the release will happen when the slurry is spread, but in a much slower pace than when acid is added. The formation of foam is also has a very positive fertilization effect as the slurry is spread over a larger area – but without emissions - and where the dry matter is not concentrated in a band with risque of contamination of silage in a later harvesting phase.

as a by-product of this reaction contributes positively to emission reduction and is a unique advantage of acidification systems.

N_2O emissions and denitrification risk:

Shallow injections can promote anaerobic microsites in the soil due to its incorporation of slurry below the surface, especially in wet conditions. This can stimulate denitrification processes and lead to the formation of nitrous oxide (N_2O), a potent greenhouse gas. In contrast, acidification leaves more dry matter on the soil surface and does not create anaerobic conditions to the same extent. As a result, acidification carries a lower risk of N_2O emissions, supporting more sustainable nitrogen use and reducing overall GHG impact.

Fuel and energy use:

Shallow injections require significantly more diesel fuel and tractor power, due to the resistance of dragging injectors through soil and narrower working widths. Acidification systems operate with lower engine load and cover more hectares per hour. This results in reduced CO_2 emissions per hectare and lower fuel costs. Studies indicate that acidification can reduce diesel use by 20–30% compared to injection under typical field conditions.

Policy limitations and technical bias:

In the Netherlands, shallow injection is mandatory, and alternative technologies like in-field acidification face legal and political barriers. Despite demonstrated effectiveness, acidification has not been approved due to outdated trials and biased administrative advice, particularly from Wageningen University.

Sulfate application and soil sustainability:

Concerns over sulfate use with acidification are often overstated. Acidification applies sulfate only when crops can uptake it, unlike the year-round sulfate release caused by soil disturbance from injection. Acidification therefore poses lower long-term risk of leaching and aquifer contamination, especially when applied in buffer zones with acidic soils.

Cost-efficiency and scalability:

The switch to acidification with boom systems could reduce Dutch agricultural mitigation costs by up to €7 billion, based on investment and emission reduction to Natura 2000 areas, where low pH soil enhances the acidification effect. The cost saving is based on reduced need for farm-buyout schemes. Acidification systems are scalable and deliver faster deployment with less infrastructure than sod injectors. The switch to acidification with boom systems could reduce Dutch agricultural mitigation costs by up to €7 billion, based on investment and emission reduction modeling. Additionally, due to the ability to use wider working widths and faster speeds, acidification enables up to 25% more field capacity per hour compared to injection. This improved capacity translates into lower machinery hours, reduced labor costs, and more efficient seasonal planning.

Methane emissions:

Acidification technologies for barn- and storage facilities have a significant impact on reduction of methane emission. Both Sulphate and pH have a strong inhibitive effect on methane production from archaea bacteria. However, acidification used as In Field acidification has no impact on methane.

Waterlogged areas protection:

In general, the release of P from slurry is very desirable as the bonded P in slurry is not plant available. A pH of below 6.0 will break the calcium-phosphorus bonding and make the P water soluble and thus plant available. This effect has been identified as an app. 40 % increased effect of P in slurry. Although the effect is time limited, as plant available P is quickly adsorbed by microorganisms or plants, there is a risque of leaching of P from waterlogged areas. Thus, in waterlogged areas, the pH of the slurry should not be below pH 6.0 to avoid risque of leaching of P. A pH reduction to pH 6.4 with the use of iron sulphate, will eliminate any risque of P leaching.

Carbon footprint:

CO_{2eq} - emissions and subsidence on polder soil:

The slurry Sod injector penetrates 5-6 cm into the soil to create a slot to decrease the slurry exposure to volatility from climate parameters. Depending on soil moisture conditions, it can have a good effect but also a very varied performance when the soil is dry and the coulters cannot penetrate the soil. Depending on soil type, it can have a very negative effect on greenhouse gas (GHG) emissions. The Dutch polder soils are subject to huge subsidence because of the high organic matter contend. The slots create a + 58 % increased area for oxidation and it is repeated +/- 5 times a year. Subsidence on moore land is about 1 cm/y. This means an annual loss per hectare of about 12.2-ton OM or about 22.6-ton CO2 or 6.7-ton C. We have found no research to identify Sod injector CO_{2eq} impact on Dutch humus rich polder soils, but it is certain to be significant and could be as much as 3 Mio ton CO_{2eq} pr. year on the combined Dutch polder soil area.

A side effect from the increased oxidation is release of Sulphate from the organic material. This is suggested to be enough to eliminate dosage of S through mineral fertilizers. This is a risque for optimal crop yields as the S must be adsorbed by plants before adequate volumes of N can be adsorbed. Thus, if the mineralization is slow because of low temperatures or lack of oxygen, there is a risque of S deficiency and low adsorption of N, which leads to low yield performance.

It is a far better strategy to avoid the increased subsidence and dose the correct volume of Sulphate by sulphuric acid, which allows surface application of slurry and avoiding subsidence.

CO_{2eq} - N_2O emissions from soil:

N2O emission from agricultural soil constitute app. 40 % of all agricultural CO_{2eq} emissions. It is generated from the bacterial denitrification processes that reduce ammonium to nitrate. In short, aerobic conditions ensure full conversion of ammonium to nitrate with almost no N_2O, but anaerobic conditions lead to incomplete denitrification with a high N_2O emission.

This effect is often associated with waterlogged areas, where rainwater excludes the soil from access to oxygen, even though it may only be temporary. By placing especially, the slurry dry matter in a slot, the risque of anaerobic denitrification conditions is significantly increased.

The IPCC reference for injections is an increase of 1 kg N_2O pr. ha. The calculated CO_{2eq} is 300.

If acidification replaced injection on 1 ha, the avoided N_2O is:

1 kg/ha x 1 ha x 300 = 300 kg CO_{2eq} / ha pr year.

CO_{2eq} - Reduction in power consumption

The use of acidification requires a boom for surface application. This avoids the injection which is a power consuming process through the coulters and narrow work with. The difference has been measured to be 5-liter diesel pr. ha.

Calculation: 5 L/ha × 2.67 kg CO_2/L = 13.35 kg CO2eq avoided per ha

CO_{2eq} reduction in less use of mineral fertilizer

The effect in volume of nitrogen from acidification is highly variable depending on especially contend of ammonium nitrogen, volume of slurry used, pH and climatic conditions. A variability of 5 – 50 kg N loss pr. ha is normal and an average of 15 kg – 20 kg, depending on climatic region. Acidification is also commercially called stabilization of slurry, because the effect from the nitrogen in the slurry is much more predictable and can enable the farmer to reduce his application of mineral fertilizer without any loss in yields.

15 kg / ha x 1 ha x Haber-Bosch consumption 4 kg CO_2 / kg N = 60 kg CO_2 avoided pr ha

Above CO_{2eq} factors are variable depending on many factors. An estimate pr machine / farm operation should be made for ESG documentation and like. However, we believe it is safe to estimate a minimum effect from In Field Acidification to be 200 kg / ha pr. year.

6. e-missioN System

Introduction and Purpose

The e-missioN system is a digital technology designed to optimize the use efficiency of nitrogen in livestock slurry. Traditionally, farmers have relied on fixed normative values to estimate nitrogen availability, leading to inefficiencies, unnecessary fertilizer purchases, and environmental losses. e-missioN introduces Nitrogen Plant Availability (NPA) – a real-time measurement of how much nitrogen from slurry actually becomes available to crops under specific conditions.

Why It Matters

Nitrogen inefficiency in slurry use contributes to high costs for farmers, greenhouse gas emissions, and biodiversity loss. The global average nitrogen use efficiency of slurry is only about 30%, while NPA values can range from 20–90% depending on slurry composition, weather, and application method. By improving NPA, farmers can:

- Increase yields through better nitrogen management.
- Reduce mineral fertilizer purchases (often replacing them one-to-one with organic nitrogen).
- Lower CO_2 emissions linked to fertilizer production and nitrogen losses.

Technology and Data Basis

The system builds on a database of over 600 trails with 30,000 ammonia emission measurements across Europe and North America. Using on-board sensors (measuring slurry flow, pH, weather, dry matter, and ammonium content) combined with GPS, e-missioN calculates NPA dynamically during application. The system displays nitrogen efficiency in real time, enabling better decisions such as whether to use acidification or adjust application timing.

Key Functions of e-missioN

- **During slurry spreading**: Measures nitrogen losses, displays efficiency via a “traffic light” interface, and supports acidification decisions.

- **After application**: Provides maps (as-applied, NPA, gaps/overlaps, and VRA – variable rate application) for fine-tuned mineral fertilizer use.
- **Decision support**: Replaces static fertilizer planning with dynamic adjustments during the season.
- **Automatic documentation**: Generates nutrient accounting, compliance records, and sustainability reports for farmers, advisors, or contractors.

Factors Influencing Nitrogen Loss

1. **Slurry properties** (pH, dry matter, nitrogen content).
2. **Application method** (splash plate = high loss; injection or acidification = low loss).
3. **Climate conditions** (cool, moist, windless = best; hot, dry, windy = worst).

Economic Potential

- Avoiding overlaps and correcting gaps can save up to 8% nitrogen nationally in Denmark – equal to large reductions in CO_2 emissions.
- A practical case study showed savings of 2,300 € on 98 ha, with up to 47,000 € potential per season for 2,000 ha.
- Optimized NPA prevents both yield loss from under fertilization and cost waste from overfertilization.

Environmental Benefits

- Reduced greenhouse gas emissions (N_2O, methane, ammonia).
- Lower demand for energy-intensive mineral fertilizer production.
- Better protection of biodiversity by avoiding nitrogen oversupply in sensitive habitats.
- Contribution to EU Green Deal targets (–50% nutrient losses, –20% mineral fertilizer use by 2030).

Implementation
The system can be installed on any slurry tanker, either as a retrofit or OEM. Two levels exist:

- **Basic**: Nitrogen efficiency monitor.
- **Advanced**: Full decision support and documentation.

Key equipment may include ISOBUS terminal, slurry flow sensor, telematics, weather station, pH sensor, ECU, and optionally an NIR sensor for detailed slurry nutrient content.

Future Outlook
With rising fertilizer costs, climate regulations, and CAP reform, digital tools like e-missioN are expected to become standard practice. They enable farmers to maintain yields while reducing nitrogen losses, ensure compliance with environmental policies, and potentially generate carbon credits.

Conclusion
e-missioN represents a major step forward in slurry management. By turning nitrogen efficiency from a guess into a measurable parameter, it creates a win-win-win: higher farm profitability, reduced fertilizer dependence, and lower environmental impact. It is likely to become a cornerstone of sustainable nutrient management in European agriculture before 2030.

Enclosiere – Analysis of 27 international studies of in field acidification

Title: Ansäuern und Schlitzen – Was bringen neue Applikationstechniken für Gülle und Gärreste?

Authors: Dr. I. Bull, L. Kureck, C. Ramp
Event: 4. Dialog Wasserrahmenrichtlinie und Landwirtschaft
Location/Date: Güstrow, 30.10.2014

Summary of Key Findings

Objective:
The study evaluated the effectiveness of **in-field acidification and slot injection** of cattle slurry and digestate on ammonia emissions and crop yield under practical farming conditions.

Experimental Setup:

- **Material:** Co-fermented digestate
- **pH before treatment:** 7.5–7.6
- **Target pH after acidification:** ~6.0
- **Application Methods Compared:**
  - Trailing hose (with and without acid)
  - Slot injection (with and without acid)
  - Control (no treatment)
- **Measurement:** NH_3 emissions and wheat yield

Results:

- **Yield Improvement (compared to untreated trailing hose):**
  - +4.1 dt/ha grain
  - +0.3% crude protein
  - +0.7 dt/ha crude protein yield
  - +20% DM efficiency (MDÄ)
- **Nitrogen Balance:**
  - –12 kg N/ha net balance (indicating better uptake)
- **Ammonia Loss (estimated):**
  - Baseline: ~30 kg NH_3/ha (no acid)
  - Acidification reduced pH and likely halved NH_3 losses (not quantified in report)

Technical Aspects:

- **Acid Used:** Sulfuric acid
- **Typical Dose:** 0.5–3.0 L/m^3

- **S Contribution:** 0.58 kg S per liter → ~29–43 kg S/ha depending on slurry rate
- **Cost Estimate (per 30 m³/ha application):**
    - Acid cost: €20/ha
    - SyreN system: €15/ha
    - Yield increase worth €72/ha or
    - N fertilizer savings: ~€20/ha

Conclusions:

- **Acidification provided clear benefits**: higher yield, lower ammonia emissions, and better nitrogen efficiency.
- **Compared to injection**, acidification has operational advantages:
    - Less sward damage
    - Lower traction requirement
    - Greater working widths
    - Easier retrofitting to existing equipment
- **Sulfuric acid preferred** due to effectiveness, cost, and plant availability of sulfate.

Experiment Summary: Field Trials on Acidification of Organic Fertilizers in Schleswig-Holstein (Germany)

Source: S. Neumann, LLUR, presented Dec 7, 2018

Parameter	Details
Experiment Title	Mitigation of ammonia emissions by acidification of organic fertilizers
Year(s)	2017 and 2018
Slurry Type	Digestate (initial pH 8.7)
pH Before Acidification	8.7
Acid Added	Sulfuric acid (H_2SO_4), 4 l/m³ in pilot farms; reduced to pH 5.5–6
pH After Acidification	5.5–6
Measured NH_3 Emission Reduction	– 68% in 2017 (wheat) – 8% in 2018 (wheat, with technical issues) – 71% in 2017 (grassland) – 67% in 2018 (grassland)
Yield Effect – Wheat (micro plots)	+2 t/ha (at 100 kg N/ha) – 9.38 t/ha vs 7.39 t/ha (acidified vs not)
Yield Effect – Grassland (micro plots)	Slightly higher yield for acidified digestate (not always significant)
Yield Effect – Pilot Farms	Example: Bellin site – Acidified digestate: 116.6 dt/ha vs untreated: 81.6 dt/ha
Nitrogen Application Rates	100–360 kg N/ha

Experiment Summary: Acid Addition to Manure for NH_3 Emission Reduction (Aarhus University, 2021)

Source: DCA – Aarhus University, Forsuringsnotat 15.02.2021

Parameter	Details
Study Title	Ammonia emission from acidified slurry during application with trailing hoses
Year	2020–2021 (study and report), lab trials with 32 slurry samples
Slurry Types	Cattle, sows/piglets, finishing pigs, digested slurry
pH Before Acidification	Varies by type: Cattle ~7.0 Pigs ~7.1–7.2 Digested ~8.1
Acid Added	96% sulfuric acid (H_2SO_4)
Target pH for 25% NH_3 reduction	Typically 6.6–6.8 (varies with slurry type)
Required Acid Amount	To achieve **25% reduction in NH_3**:
Cattle: **2.2 kg/t**	
Pig slurry: **1.7 kg/t**	
Digested slurry: **1.8 kg/t**	
Max Acid Dose (90% confidence)	Cattle: 3.1 kg/t, Pigs: up to 3.0 kg/t, Digested: 2.3 kg/t
NH_3 Emission Reduction	Modelled using ALFAM2 – **≥25% reduction** achieved at stated doses
Yield Effect	Not part of this lab-based study

The study emphasizes variation in acid requirement depending on slurry buffer capacity, pH, and dry matter. Digested slurry tends to need more acid to reach equivalent pH due to higher bicarbonate levels

Experiment Summary: Acidification of Digestate in Winter Barley – Wehnen Trial Station (Germany)

Source: Kai-Hendrik Howind, LWK Niedersachsen – 2018 Data

Parameter	Details
Experiment Title	Digestate fertilization in winter barley with various application techniques
Year	2018 (sowing: Sept 2017; harvest: 17 July 2018)
Slurry Type	Digestate (fermented manure)
Acid Added	Sulfuric acid (H_2SO_4)
Target pH After Acidification	pH 6.0
pH Before Acidification	Not explicitly stated, but typically ~7.0–8.0 for untreated digestate
Application Methods	Trailing hose, trailing shoe, and disc injection (with/without acidification)
NH_3 Emission Reduction	Not directly measured, but inferred via Mineral Fertilizer Equivalents (MDÄ)
Yield Effect (Relative MDÄ)	
Trailing hose:	
– Without acid: 32.0% MDÄ	
– With acid (pH 6.0): 46.8% MDÄ	
Trailing shoe:	
– Without acid: 44.0% MDÄ	
– With acid (pH 6.0): 60.0% MDÄ	
Yield Efficiency vs Mineral N	
Trailing hose (pH 6.0): 66.4%	
Trailing shoe (pH 6.0): 76.7%	
Total N Applied	132 kg N/ha (organic only), 207 kg N/ha (organic + mineral supplement)

This trial shows clear benefits of acidification in improving the nitrogen efficiency of digestate—raising the mineral fertilizer equivalent by 14–16 percentage points depending on application method.

Study Summary: ALFAM2 Model for Predicting Ammonia Emissions from Field-Applied Slurry

Source: Hafner et al., *Atmospheric Environment* (2019)

This paper presents the **ALFAM2** semi-empirical model, developed to predict ammonia volatilization (NH_3 loss) from slurry application, based on extensive field data.

Parameter	Details
Experiment Title	ALFAM2 ammonia emission model from slurry application
Year(s)	Data from various trials (13 countries); publication in 2019
Slurry Type	Pig and cattle slurry only; dry matter ≤ 15%
pH Before Acidification	Typically ~7.5 (reference value)
Acidification Effect Estimate	Reduction factor of **2.13 per pH unit** drop (i.e., pH 7.5 → 6.5 cuts emissions by ~50%)
Acid Added	Not specified directly – inferred from pH effect in acidified trials
pH After Acidification	Modelled scenarios with pH 6.4 and 6.0
NH_3 Emission Reduction	
– pH 6.4 → 43–55% emission reduction	
– pH 6.0 → 60–70% reduction	
– Under high-emission conditions, reductions are **smaller** (e.g. 14–38%)	
Yield Effect	Not applicable – model-based study
Model Use Cases	Predicting emissions, mitigation strategy evaluation, emission inventories

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This is a **modeling study**, not a field trial, but it synthesizes data from 490 plots across 6 countries and is highly relevant for estimating NH_3 reduction from acidification strategies.

Experiment Summary: NH_3 Emission Measurements with Acidified Manure – Triesdorf Trials (Bavaria, Germany)

Source: Landwirtschaftliche Lehranstalten Triesdorf, MuD SäurePlus project (2023)

Parameter	Details
Experiment Title	Ad hoc ammonia concentration measurements after manure application
Year	2023 (spring and summer trials)
Slurry Type	Cattle slurry (spring), digestate (summer), both separated and unseparated
Acid Added	Sulfuric acid (varied doses: 2–7 L/m³)
pH Before Acidification	Spring: pH 6.8 (cattle slurry)
Summer: pH 7.7–7.9 (digestate)	
pH After Acidification	Varied from 7.1 to as low as 5.9, depending on dosage and sample
NH_3 Emission Reduction	
– Spring: **minimal effect** (cool, windy, wet – NH_3 baseline was low)	
– Summer:	
• Digestate pH 7.9 → ~70% reduction at 5 L/m³	
• Separated digestate showed 60% reduction (but emissions increased at 4 L/m³ dose)	
Temperature Conditions	
– Spring: 5–9 °C	
– Summer: up to 33 °C (hot, no wind)	
Yield Effect	Not included in this presentation
Key Observations	
– Too little acid → incomplete pH drop → risk of **increased emissions**	
– Separated slurry may release more NH_3 when acid is added due to breaking chemical bonds	

Experiment Summary: Ammonia Emissions from Cattle Slurry – Sweden, 2019

Source: Andersson et al., *Biosystems Engineering* (2023)

Parameter	Details
Experiment Title	Ammonia emissions from untreated, separated and digested cattle slurry
Year	2019
Slurry Types	Untreated cattle slurry (CS), separated liquid fraction (LF), digested slurry (BD)
pH Before Acidification	CS: 6.8 LF: 7.1 BD: 7.6–7.8
Acid Added	Sulfuric acid (96%) – CS & LF: ~8 kg/m³; BD: ~11 kg/m³
pH After Acidification	CS & LF: 6.0 BD: 6.7
Application Rate (kg TAN/ha)	CS: 65 LF: 64–72 BD: 56–60
Application Methods	Trailing hose, trailing shoe, acidified trailing hose, 20 & 50 mm injection
NH_3 Emission Reduction (70h)	Acidified:
CS –75%	
LF –88%	
BD –85%	
Trailing shoe (vs hose):	
CS –27%	
LF –16%	
BD –7%	
50 mm injection (vs hose):	
LF –37%	
Cumulative Emissions (untreated)	
CS –29% of TAN	
LF –23%	
BD –32%	
Yield Effect	Not reported
Additional Notes	Emissions peaked in first 6–14 hours. ALFAM2 model overestimated emissions from acidified slurries. BD had fastest early emission.

The study demonstrated significant NH_3 reductions through acidification and deeper injection. Acidified treatments especially showed strong early mitigation, with differences between slurry types influenced by pH, dry matter, and infiltration dynamics.

Experiment Summary: Acidified Slurry in Grassland and Winter Wheat – Estonia

Source: Estonian Crop Research Institute, Baltic Slurry Acidification Project (2017)

Parameter	Details
Experiment Title	Effect of acidified slurry on grassland and winter wheat
Year	2017
Slurry Types	Grassland: Cattle slurry Wheat: Pig slurry
Acid Added	Grassland: 5.14 L/m³ H_2SO_4 (96%) Wheat: 2.47 L/m³ H_2SO_4
pH Before Acidification	Grassland: ~7.6 Wheat: ~7.7
pH After Acidification	Grassland: ~5.5 Wheat: ~6.3
Application Rate	30.4 t/ha (grassland), 48 t/ha (wheat)
NH_3 Emission Reduction	Not directly measured, but sulfur (SO_4^{2-}) levels in soil increased significantly post-application with acidified slurry
Yield Effect – Grassland	
– Control: 4089 kg DM/ha	
– Untreated slurry: 4351 kg	
– Acidified slurry: 4232 kg	
➡ Yield not significantly higher for acidified vs untreated slurry	
Yield Effect – Winter Wheat	
– Control: 3968 kg DM/ha	
– Acidified slurry: 5675 kg	
– Untreated slurry: 5431 kg	
➡ Slight yield benefit for acidified over untreated slurry	
Protein Content (Wheat)	
– Untreated: 10.7% Acidified: 10.4%	
Disease Observations (Wheat)	Acidified slurry reduced Septoria and tan spot occurrence

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This project included highly structured scientific trials with careful control and replication. The benefit of acidification was more evident in winter wheat than in grassland, with modest increases in yield and reduced disease presence.

Experiment Summary: Acidified Digestate in Grassland – Denmark (Biogas Denmark & Linkogas)

Source: Bruno Sander Nielsen, Biogas Denmark Conference, Dec 2023

Parameter	Details
Experiment Title	Field trials testing adjusted acid dosing requirements for acidified digestate
Year	2023
Slurry Type	Primarily **digested biomass** (biogas digestate) and **cattle slurry**
Acid Added	Sulfuric acid (96%)
– 3 L/ton in trailing shoe treatment	
– 6 L/ton in trailing hose treatment	
– Reference standard: 11 kg/ton in regulations	
pH After Acidification	Approx. pH 2 (reported from high acid dose scenario)
Application Methods	Injection, trailing hose, trailing shoe, separation + spreading
NH_3 Emission Reduction	
– **3 L/ton acid + trailing shoe** ≈ same NH_3 reduction as **6 L/ton + trailing hose**	
– Separation + trailing hose also showed comparable NH_3 mitigation	
Yield Effect	Not reported in numerical terms, but focus was on **NH_3 and cost efficiency**
Key Conclusion	Acid dose can likely be **reduced by 50%** when using trailing shoe technique without losing NH_3 reduction benefits
Economic Notes	Acidification currently **5–600 DKK/ha more expensive** than injection

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This trial supports optimizing acid use depending on application method, particularly in **grassland fertilization**. Let me know when you're ready for the next one!

Experiment Summary: Danish SyreN Yield Trials (Winter Wheat, 2010–2017)

Source: SEGES PlanteInnovation – Martin Nørregaard Hansen

Parameter	Details
Experiment Title	Yield response following slurry acidification with SyreN technology
Years	2010–2017
Number of Trials	31 total trials (2–6 per year)
Slurry Type	Not specified, but typical for SyreN: cattle/pig slurry
Acid Added	Sulfuric acid
– Average: 2.1 L/m³	
– Range: 1.7–3.3 L/m³	
pH After Acidification	Average: 6.1
– Range: 5.8–6.3	
NH_3 Emission Reduction	Not quantified in this dataset, but inferred from pH and acid use
Yield Effect (Winter Wheat)	
– Range: –0.4 to +6.3 hkg/ha (hectokilograms = 100 kg)	
– Weighted average: **+2.2 hkg/ha = +220 kg/ha**	

This long-term Danish dataset confirms modest but mostly positive yield effects from acidifying slurry with the SyreN system, particularly when lowering pH to 6.1 or below. The largest benefit was observed in 2017 with pH 5.8.

Experiment Summary: GülleBest Multi-Site Trials – Germany (2019–2020)

Source: ten Huf et al. (2023), *Agronomy*, Vol. 13, Article 472

Parameter	Details
Experiment Title	Effects of Liquid Manure Application Techniques on NH_3 Emission and Yield
Years	2019–2020
Slurry Types	Cattle slurry (CS), Biogas digestate (BD)
Acid Added	Sulfuric acid to pH ~6.0
– Average: CS: ~3.6 L/m³ BD: ~5.2 L/m³ (98% H_2SO_4)	
pH Before Acidification	CS: ~7.4 BD: ~7.7
pH After Acidification	CS: ~5.9 BD: ~6.2
Application Methods	Trailing hose (TH), TH + acid, slot injection + trailing shoe (SI/TS), +/– nitrification inhibitor
NH_3 Emission Reduction	
– Acidification reduced NH_3 by **~65% (CS)** and **~63% (BD)**	
– SI/TS reduced NH_3 by **~26% (CS)** and **~18% (BD)**	
– Acidification was most effective overall	
NH_3 Emission Baseline	CS: ~19 kg N/ha BD: ~30 kg N/ha (with TH, untreated)
Yield Effect	
– All slurry treatments ≈ 7 t/ha	
– CAN (mineral): 7.9 t/ha	
– Control (no N): 4.5 t/ha	
– No significant yield difference between acidified and non-acidified slurry	
Nitrogen Uptake	
– Organics: ~150 kg N/ha	
– CAN: ~190 kg N/ha	
– N0: ~90 kg N/ha	
Key Observations	
– Acidification significantly reduces NH_3 but **does not always improve yield**	
– Soil pH, wind, and soil density affect effectiveness	
– Biogas digestate requires more acid than cattle slurry due to higher buffer capacity	

Our calculations revealed that soil pH significantly affected NH_3 emissions, showing a slight to medium effect strength (R = 0.47). Similar to the pH effect of liquid organic fertilizers, a high soil pH shifts the NH_3/NH_4^+ ratio towards NH_3, thereby increasing NH_3 emissions. Cow slurry (CS) application showed a slightly stronger response to soil pH compared to biogas digestate (BD) application (Table 5), suggesting that the pH buffering capacity of BD might be higher, potentially reducing soil pH effects. The adsorption of NH_4^+ to the soil's cation exchange sites might lower NH_3 emissions. However, in our two-year field study, soil cation exchange capacity (CEC) only influenced NH_3 emissions following CS application (R = 0.53) and had no effect on BD application (R = –0.01; Table 5).literatur.thuenen.de

Source: Thünen Institute Report on Acidification, page 8.

This is one of the most comprehensive multi-location trials to date, and it confirms the high mitigation potential of acidification while also showing that yield effects are context-dependent.

Experiment Summary: Acidified Pig Slurry and Soil Microbial Effects – Estonia (2017–2018)

Source: Edesi et al. (2020), *Soil & Tillage Research*, Vol. 202

Parameter	Details
Experiment Title	Effects of acidified pig slurry on soil chemical and microbiological properties
Years	2017 and 2018
Slurry Type	Pig slurry
Acid Added	Sulfuric acid (96%) to target **pH 6.0** (in-storage acidification system simulation)
pH Before Acidification	Not explicitly stated (typically pig slurry is ~7.5–7.8)
pH After Acidification	pH 6.0
Application Method	Field surface application on winter wheat
NH_3 Emission Reduction	Not directly measured, but implied by acidification use
Yield Effect	Not reported
Soil Chemical Effects	
– **SO_4-S (sulfate sulfur)** significantly increased 2 weeks after spreading, remained elevated until harvest	
– No significant change in **soil pH**, **NO_3-N**, or **NH_4-N** concentrations	
Soil Microbial Effects	
– No significant change in **dehydrogenase activity (DHA)**	
– No clear shift in microbial community (PLFA profile)	
– **Actinobacteria** abundance increased slightly (linked to nitrate)	

This study focused on **soil quality and microbial health**, not yield or emissions directly, but it confirmed that **acidified slurry did not harm the soil microbiome** under field conditions.

Experiment Summary: NH_3 Emissions from Acidified Digestate – Baasdorf (Germany)

Source: Baasdorf NH_3 Measurement Report, 22–23 September 2014

Parameter	Details
Experiment Title	Ammonia emission measurement: acidification of separated digestate
Year	2014
Slurry Type	Separated **liquid phase** of digestate
Application Rate	25 m^3/ha
Acid Added	Sulfuric acid (H_2SO_4):
– 0 l/m^3 (pH1 – untreated)	
– 2.5 l/m^3 (pH2)	
– 5.0 l/m^3 (pH3)	
pH After Acidification	Not numerically stated, but reduced by dosage level
NH_3 Emission Reduction	
– **Significant reduction** with increasing acid dose	
– Lowest cumulative emissions at **5.0 l/m^3**	
– Differences were **statistically significant ($p < 0.05$)** via Tukey-Test	
Measurement Duration	Over 24 hours
Yield Effect	Not measured

This trial clearly shows a dose-response relationship: higher sulfuric acid application resulted in greater ammonia reduction, and significance was confirmed with statistical analysis.

Experiment Summary: SyreN Technology for Ammonia Reduction – Denmark

Source: Danish Technological Institute (Frandsen, 2019); original test by Hansen (2011), AU-Foulum

Parameter	Details
Experiment Title	Ammonia reduction after slurry application using SyreN system
Year	2010 (May 4 and May 18)
Slurry Type	Pig slurry
Crop	Winter wheat
Application Rate	~31 tons/ha
Acid Added	
– 2.0 L/t (May 4)	
– 2.2 L/t (May 18)	
– Sulfuric acid (H_2SO_4) applied during spreading using SyreN system	
pH Before / After Acidification	
– May 4: 7.2 → 6.1	
– May 18: 7.9 → 6.7	
Application Methods	
– Reference: Trailing hoses (untreated)	
– Comparison:	
• SyreN (acidified) + trailing hoses	
• Shallow injection (untreated)	
NH_3 Emission Reduction	
– **Trailing hoses (untreated)**: 23% of NH_4-N emitted	
– **Shallow injection**: 11%	
– **SyreN (acidified)**: 15%	
➞ **SyreN reduced emissions by ~35%** compared to untreated trailing hoses	
Soil & Weather Conditions	
– May 4: 5.6°C, 2.2 mm rain, wind 4.0 m/s	
– May 18: 12.5°C, no rain, wind 3.6 m/s	
Yield Effect	Not reported
Measurement Duration	144 hours (6 days), with passive ammonia samplers

The study confirmed that the **SyreN system significantly reduces ammonia loss** during slurry spreading, with performance slightly lower than shallow injection but with the advantage of preserving surface application.

Experiment Summary: In-field Acidification of Separated Digestate – Denmark (Demonstration Trial)

Source: Mogens Kjeldal, DME (undated, likely ~2010s)

Parameter	Details
Experiment Title	Demonstration of sulfuric acid addition to separated digestate during field application
Year	Not specified (likely mid-2010s)
Slurry Type	Separated, digested slurry (from Fangel Bioenergi)
Application Rate	45 tons/ha
Acid Added – 0.6 L/ton – 1.3 L/ton – 2.0 L/ton (Sulfuric acid 96%)	
pH Before Acidification	7.49–7.54
pH After Acidification – 0.6 L/t: 7.10 → 7.32 – 1.3 L/t: 6.96 → 7.15 – 2.0 L/t: 6.91 → 7.05 (measured over 60 mins post-application)	
NH_3 Emission Reduction	Not directly measured, but strong pH drop observed immediately after application (largest drop with 2.0 L/t)
Yield Effect	Not tested
Nutrient Supply from Slurry (kg/ha) – Total N: 160 – NH_4-N: 140 – P: 6.8 – K: 90.9 – S: • 0.6 L/t: 17.1 • 1.3 L/t: 34.2 • 2.0 L/t: 54.5	
Observations – pH rises after application, stabilizing within 30 minutes – Effective pH control requires rapid infiltration into soil	

– Stationary acid dosing was practical with no foaming issues; mobile acid tanks may pose safety concerns

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This trial confirms that **on-field acidification is technically feasible and effective for pH reduction**, especially for separated slurry used in full fertilization regimes. However, it also highlights **logistical and safety challenges** when acid is handled in traditional slurry tanks.

Experiment Summary: Acidification vs Injection in Boreal Grassland – Finland (2017–2018)

Source: Keskinen et al. (2022), *Nutrient Cycling in Agroecosystems*

Parameter	Details
Experiment Title	Slurry acidification outperformed injection as an ammonia emission-reducing technique
Years	2017 and 2018
Slurry Type	Cattle slurry (from biogas pre-storage)
Application Rate	42.5 tons/ha
Acid Added	Sulfuric acid (93%)
– 3.3 L/ton (2017)	
– 2.6 L/ton (2018)	
– Target pH: 5.5	
pH Before / After	Untreated pH: ~7.3
– Acidified pH: 5.5 (2017), 5.6 (2018)	
Application Methods	
– Band spreading (untreated)	
– Shallow injection (untreated)	
– Band spreading of acidified slurry	
NH_3 Emission Reduction	
– 2017 (cooler, wetter):	
• Acidification: –97%	
• Injection: –97%	
– 2018 (warmer):	
• Acidification: –95%	
• Injection: –43%	
➞ **Acidification outperformed injection** (especially under warm conditions)	
Cumulative NH_3 Losses (kg/ha)	
– Untreated: 22 (2017), 10 (2018)	
– Injection: 0.7 (2017), 5.7 (2018)	
– Acidified: 0.7 (2017), 0.5 (2018)	
Yield Effect	
– 2017: No significant differences	
– 2018:	
• Acidified slurry: +29% DM yield	
• +65% N recovery vs untreated band spreading	
Apparent N Recovery	

– Untreated: 11–17%

– Injection: 15–19%

– Acidified: 13–28%

Soil Impact

– Acidification increased soil sulfur content

– No negative pH or microbial impacts detected

This well-controlled Finnish study demonstrates that **acidification is more effective and reliable** than injection for reducing NH_3 emissions in **boreal grassland** conditions, especially during warmer seasons. It also showed **measurable yield and N efficiency gains** with acidified slurry.

Study Summary: Life Cycle Assessment of Slurry Acidification Strategies

Source: ten Hoeve et al. (2016), *Journal of Cleaner Production*

Parameter	Details
Study Focus	Environmental impacts of **field acidification vs in-house acidification**
Scope	Denmark, pig slurry, system-level (housing → storage → field)
Slurry Type	Pig slurry
Acid Added – Field: 5.2 kg H_2SO_4/t to reach **pH 6.2** – In-house: 9.7 kg H_2SO_4/t to reach **pH 5.5**	
pH Before Acidification	~7.5 (typical pig slurry)
pH After Acidification	Field: 6.2 In-house: 5.5
NH_3 Emission Reduction – Field acidification: **–30%** – In-house acidification: **–71%** (covers housing, storage, field)	
GHG Emission Reduction – Field acidification increased **GHG impact** slightly due to acid & lime use – In-house acidification **reduced GHG emissions** overall	
Yield Effect (modeled) – Non-acidified slurry: 7.2 t/ha – Field-acidified: 7.4 t/ha – In-house acidified: 7.7 t/ha	
Environmental Impact Categories – **Terrestrial eutrophication potential (TEP):** • Field: –30% • In-house: –71% – **Climate change potential (CCP):** • Field: higher (acid & lime impact) • In-house: lower – **Marine eutrophication potential (MEP):** • Similar across methods – **Toxicity potential (TP):** • Mostly driven by zinc in pig slurry, unaffected by acidification method	
Effect of N Regulation	Acidification is **more beneficial under stricter N application limits**

Conclusion

- **In-house acidification** is **most effective** for reducing NH_3 and overall environmental burden.
- **Field acidification** helps but offers smaller overall benefits and can slightly raise GHG impact.
- **Regulatory frameworks** strongly influence the overall environmental advantage of acidification strategies.

Experiment Summary: SyreN vs Infarm vs Injection – Denmark (2010)

Source: Aarhus University, Notat til Miljøstyrelsen, Foulum (Tavs Nyord et al.)

Parameter	Details
Experiment Title	Evaluation of ammonia, odor and GHG emissions from acidification techniques
Year	2010
Slurry Types	Pig slurry (winter wheat), cattle slurry (grassland)
Application Rates	~31–37 tons/ha
Acid Added	
– SyreN: 1.9–2.9 L/ton	
– Infarm (in-stable acidification): ~3.3 L/ton	
pH Before / After Acidification	
– Pig slurry: ~7.2–7.9 → 6.1–6.7	
– Cattle slurry: ~7.4–7.8 → 6.4–6.5	
NH_3 Emission Reduction	Relative to untreated trailing hose application:
– Injection: –54%	
– **SyreN (acidified during spreading): –42%**	
– Infarm (pre-acidified): –59%	
Yield Effect	Not reported
Lugtemission (Odor)	
– Similar odor levels for untreated and acidified slurry (SyreN)	
– **Lower odor** from injected and iron sulfate-treated slurry	
Notes on Odor Chemistry	Acidification increases **H_2S emissions** short-term, which contributes to odor; iron sulfate reduces H_2S by binding sulfide
GHG Emissions	No clear increase from acidified slurry

Key Takeaways:

- **SyreN reduces NH_3 by ~42%**, but not as effectively as Infarm or injection.
- **Odor levels** immediately after spreading are not necessarily improved with SyreN alone.
- Acidified slurry with **iron sulfate** could reduce odor, but this combination was not fully tested.

Study Summary: Environmental Side Effects of Acidified Slurry – Denmark (Review)

Source: Aarhus University (DCE Report No. 257, 2018) – Jensen et al.

Parameter	Details
Focus	Potential side effects of using sulfuric acid-treated slurry on agricultural soils
Slurry Type	Pig and cattle slurry (generalized across Denmark)
Acid Added	Sulfuric acid (typical target pH: 6.0 or lower)
pH Before / After Acidification	~7.5 → ~6.0
NH_3 Emission Reduction	Recognized as effective; not numerically assessed here
Soil Microbial Effects	
– Temporary **pH drop in soil is not harmful** to microbial activity or invertebrates	
– **Short-term inhibition** of nitrification and denitrification around slurry patches	
– No lasting impact on microbial decomposition of N-compounds	
GHG Emissions	
– Methane emission **reduced**	
– N_2O emissions: No significant increase found in lab tests	
Soil Fauna (e.g., earthworms)	
– Mostly **positive or neutral** effects	
– Temporary avoidance behavior observed due to ammonia/acid	
– Long-term risk minimal at typical field pH (>5.5)	
Heavy Metal Mobility	
– pH reduction (0.5 units) can **double/triple Ni and Zn in pore water**	
– Greatest risk in sandy soils and with **pig slurry (high Zn)**	
– Risk for **cadmium** build-up from extra lime use	
Phosphorus Leaching Risk	
– Acidification increases **water-soluble P** in slurry (up to 2×)	
– Risk of P loss increases on **non-incorporated** slurry in grasslands	
Lime Requirement	Acidified slurry increases long-term lime demand to maintain soil pH

Key Takeaways:

- Acidification is effective for NH_3 mitigation but **requires good management** to avoid unwanted side effects.
- Attention needed in **zinc-sensitive areas** and **wetlands** (for P mobilization).
- No major microbiological risks identified under normal agricultural conditions.

Experiment Summary: Acidification vs Injection vs Broadcast – Germany & Denmark (2011–2013)

Source: Pacholski et al., RAMIRAN Conference Presentation, 2015

Parameter	Details
Experiment Title	Application techniques for reducing nitrogen losses and enhancing yields
Years	2011–2013 (multiple field trials)
Slurry Types	Cattle slurry and co-fermented pig slurry
Acid Added	Sulfuric acid to achieve pH 6.5 or 6.0 (depending on trial)
pH Before / After Acidification	~7.2 → 6.5 or 6.0
Application Techniques – Broadcast – Trailing hose (with/without acid) – Shallow injection (17.5 cm / 35 cm row spacing)	
NH_3 Emission Reduction – Broadcast: high NH_3 loss – Trailing hose (untreated): moderate loss – **Acidification (pH 6.0)**: NH_3 loss reduced by ~50% – Injection (35 cm): **lowest NH_3 loss** (~5–10 kg N/ha)	
Yield Effect – No significant differences across methods (280 kg NH_4-N/ha) – Slight yield advantage for **acidification pH 6.0 and injection 35 cm**	
N2O Emissions	No increase from acidified slurry; injection had similar emissions
Soil Impact – Injection on sandy soil increased sward damage – Acidification was gentler on grassland surfaces	
Conclusion – Acidification (pH 6.0) is a reliable mitigation tool – Best NH_3 reduction with **injection**, but **acidification is more flexible** in practice	

This trial showed how acidification offers **significant emission reductions** while preserving surface spreading's simplicity, especially useful where injection may damage grass swards.

Experiment Summary: Field Trials with Acidified Cattle and Pig Slurry – Sweden (2013)

Source: Kjell Gustafsson et al., Agroväst / SLU / HS Sjuhärad

Parameter	Details
Experiment Title	Acidification of slurry and digestate in grassland and winter wheat
Year	2013
Slurry Types – Cattle slurry (raw and digested) – Pig slurry (raw and digested)	
Acid Added	Sulfuric acid (96%), manually added during spreading to reach **pH ~6.0**
pH Before / After Acidification – Cattle slurry: ~7.0–7.2 → ~6.0 – Biogas slurry: ~7.5–8.0 → ~6.0	
Application Rates	~450–570 kg N/ha (based on NH_4-N content), 45–57 tons/ha slurry
NH_3 Emission Reduction	Not directly measured – inferred from pH control and weather conditions
Yield Effect – Grassland – **Acidified slurry increased dry matter yield by 400–1100 kg/ha** (1st cut) – +250–750 kg/ha (2nd cut) – Especially strong effect for **acidified biogas slurry**	
Yield Effect – Winter Wheat – **No benefit** from acidification – Slight yield depression observed in some acidified slurry treatments	
Nitrogen Use Efficiency (Wheat) – Biogas slurry had higher fertilizer value than raw slurry – Acidification **increased mineral fertilizer equivalence from ~30% to 70%**	
Observations – Late fertilization may have reduced effect in wheat – Possible delay in nitrification from low pH – Skimming and foaming during acid addition caused practical issues	
Conclusion	

– Acidification is **clearly beneficial on grassland**

– Results mixed for winter wheat due to weather, crop stage, and timing

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This was the **first Swedish field trial on slurry acidification**, inspired by Danish SyreN technology. It highlights a strong case for using acidified digestate in grassland systems, but shows the importance of **timing and technique** in cereals like winter wheat.

Experiment Summary: Acidification vs Injection on Grassland – Germany & Denmark (2012–2013)

Source: Seidel et al., Abstract from Kiel University & Aarhus University

Parameter	Details
Experiment Title	Ammonia loss reduction from cattle slurry by acidification and injection
Years	2012 and 2013
Slurry Type	Cattle slurry
Acid Added – pH 6.5: ~2.7 L/t – pH 6.0: ~4.4 L/t (Acid used: 96% H_2SO_4)	
pH Before / After – Untreated: ~7.2 – Acidified: 6.5 or 6.0	
Application Methods – Band spreading – Injection (17.5 cm and 35 cm slot distance) – Trailing hose with acidified slurry	
NH_3 Emission Reduction Relative to **band spreading (14.0% of NH_4-N lost)**: – Injection 17.5 cm: **–31.4%** – Injection 35 cm: **–60.6%** – Acidification to pH 6.5: **–42.2%** – Acidification to pH 6.0: **–68.9%** (lowest NH_3 loss: 4.4%)	
Measurement Method	Passive flux samplers, multi-site replicated field trials
Yield Effect	Not reported

Key Conclusion:

- **Acidification to pH 6.0 is more effective** than most injection techniques in reducing ammonia emissions.
- Results were **statistically significant**, with standard deviation <1%.
- Study shows acidification can be a practical and highly efficient mitigation option for cattle slurry on grassland.

Study Summary: National Scenario – Acidifying 50% of Danish Slurry

Source: Henning Lyngsø Foged et al., Organe Institute (2017, Baltic Slurry Acidification project)

Parameter	Details
Scenario Type	**National-scale projection** – not field trials
Slurry Types	Pig slurry, cattle slurry, digested slurry
Acid Added	Sulfuric acid, typical rates:
– Pig: 2.6–3.5 L/ton	
– Cattle: 3.0–4.5 L/ton	
– Digested: 7.9–9.0 L/ton	
pH Target	pH 5.5–6.4 depending on method
NH_3 Emission Reduction (modelled)	
– ~40–60% reduction across all technologies	
– Markforsuring (in-field) estimated at ~45%	
– Staldforsuring (in-stable): higher total system impact (~60%)	
GHG Emissions	
– Methane reduction up to **67–87%** (storage-related)	
– Slight N_2O reduction (uncertain)	
Health & Environment Benefits	
– Healthcare savings: **DKK 429 million/year**	
– Reduced airborne N deposition: **~4,600–6,900 tons N/year**	
– GHG reduction: **23,598 tons CO_2e/year** (~2.6% of DK target for 2030)	
Economic Cost (Farmer)	
– Average: **DKK 5.70/ton** (~€0.77/ton) for 14 million tons slurry	
– Most expensive: **acidified digested cattle slurry** (~DKK 17–20/ton)	
Break-even N Benefit	No longer attractive post-2016 due to relaxed fertilization norms
Investment Need	~DKK 400 million to triple current acidification capacity
Policy Note	EU recognized slurry acidification as **Best Available Technique (BAT)** in 2017

Key Insights:

- Acidifying half of Danish slurry **could nearly achieve** the 2020 NH_3 reduction target.

- The environmental **benefits outweigh costs** at national level, especially for health and air quality.
- **For farmers**, the direct profit is **negative** unless supported by incentives or stricter regulations.

Technology Summary: SyreN Acidification System – VERA Certified (2010 Test)

Source: VERA Verification Statement 001, BioCover A/S, tested by Aarhus University & AgroTech A/S

Technology Name	SyreN (manufactured by BioCover A/S)
Test Year / Location	2010 – Foulum, Denmark (grassland and winter wheat)
Slurry Types Tested	Cattle slurry and pig slurry
Acid Used	Sulfuric acid (96%)
– Cattle slurry: 2.3–2.9 L/ton	
– Pig slurry: 1.9–2.9 L/ton	
Target pH After Acidification	Cattle: ~6.4–6.5
Pig: ~6.1–6.7	
Application System	Trailing hoses (30 cm spacing), acid added during spreading (on-the-go)
NH_3 Emission Reduction	
– Cattle slurry: **49% reduction** (avg; range 34–61%; SD = 11%)	
– Pig slurry: **37% reduction** (avg; range 18–52%; SD = 12%)	
Odor Reduction	No significant change in odor emissions (measured for cattle slurry only)
Operational Stability	Verified as **satisfactory** – includes real-time pH and acid dosing control
Other Features	
– Online data logging: pH (in/out), acid consumption, slurry volume	
– System maintains target pH via automatic acid adjustment	
Side Effects Observed	**None** during test

Key Takeaways:

- SyreN demonstrated **reliable ammonia reduction** (49% for cattle slurry, 37% for pig slurry) under controlled field conditions.
- The **system is VERA certified** for environmental and operational performance.
- No odor or unintended side effects were found, and acid use was well-managed via real-time controls.

Experiment Summary: Cost Efficiency of Acidified Cattle Slurry – Germany (2019 Field Trials)

Source: Jorissen & Recke (2021), Hochschule Osnabrück, presented at DHF 2021

Parameter	Details
Experiment Title	Cost analysis of ammonia mitigation via acidified cattle slurry
Year	2019
Crops	Winter wheat
Slurry Type	Cattle slurry
Application Method	Trailing hose (with and without sulfuric acid)
Acid Added	
– 6.5 L/m³ in Kiel/Langenburg	
– 8.5 L/m³ in Hohenheim	
→ Target: pH 6.0	
NH_3 Emission Reduction	
– Kiel: **–11.7 kg NH_3/ha**	
– Hohenheim: **–4.1 kg NH_3/ha**	
Grain Yield Effect	
– Kiel: from 6.4 to 7.0 t/ha (+600 kg)	
– Hohenheim: from 11.4 to 10.7 t/ha (–700 kg)	
Straw Yield Effect	
– Kiel: +400 kg/ha	
– Hohenheim: +800 kg/ha	
Cost Analysis Method	NH_3 mitigation cost = change in margin (DAk) per kg NH_3 avoided
Economic Result	
– **Acidification increased costs per hectare**	
– NH_3 mitigation cost ranged up to **€1,200–2,400/ha**, depending on site	
Conclusion	Acidification **effective for NH_3 reduction**, but **economically unfavorable** unless supported by policy or high N efficiency need

Key Insight:

Although acidification reduced NH_3 emissions effectively and increased straw yield, its **profitability varied sharply** between sites, with one location (Hohenheim) even showing **lower grain yield** after acidification.

Experiment Summary: Measuring Ammonia Loss from Treated Slurries – Germany (2019, Published 2024)

Source: Urs Schmidhalter, *J. Plant Nutr. Soil Sci.* (2024)

Parameter	Details
Experiment Title	^{15}N mass balance to measure NH_3 losses from additive-treated slurries
Years	2019 (results published 2024)
Slurry Types	Biogas slurry, cattle slurry, pig slurry
Additives Tested	18 total, incl.
– Sulfuric acid (5 levels)	
– Adsorbents (e.g., charcoal, bentonite)	
– Molasses ± microorganisms	
– Water dilution (1:1, 1:0.5)	
pH Before / After Acidification	Biogas: 7.9 → 5.6
Cattle: 7.2 → 5.2	
Pig: 7.7 → 5.8–6.1	
NH_3 Loss in Untreated Controls	
– Biogas: **54.4%** of NH_4-N	
– Cattle: **33.9%**	
– Pig: **11.0%**	
NH_3 Emission Reduction	
– **Sulfuric acid (pH ~5.2–5.9)**:	
• Biogas: –69% to ~99%	
• Cattle: –53% to 80%	
• Pig: –48% to ~99%	
– **1:1 water dilution**:	
• Biogas: –39%	
• Cattle: –50%	
• Pig: –58%	
– **Molasses (with or without microbes)**:	
• Biogas: ~40–43%	
• Cattle: ~44–50%	
• Pig: 5–34%	
– **Adsorbents**: mostly **ineffective** or slightly increased emissions	
Yield Effect	Not measured – container study
Key Methodology	Precise ^{15}N isotope technique with small containers and controlled environment

Key Takeaways:

- **Sulfuric acid acidification** is confirmed as the most **reliable and potent NH_3 mitigation** method across slurry types.
- **Molasses and water dilution** are promising alternatives, especially where acid use is restricted.
- **Adsorbents were ineffective** under these conditions.
- The ^{15}N method offers a **new reference standard** for evaluating additive-based NH_3 mitigation.

This study contributes robust quantitative data under semi-field conditions and supports prioritizing acidification strategies.

Experiment Summary: Danish SyreN Winter Wheat Yield Trials (2010–2017)

Source: Martin Nørregaard Hansen, SEGES PlanteInnovation

Parameter	Details
Years Covered	2010–2017
Number of Trials	30 total trials across 8 years
Slurry Types	Animal slurry (likely pig and/or cattle)
Acid Used	Sulfuric acid (SyreN system)
Average Acid Dose	**2.1 L/m³** (range: 1.7–3.3 L/m³)
Average Target pH	**6.1** (range: 5.8–6.3)
Yield Response – Weighted mean across all years: **+2.2 hkg/ha** (**= +220 kg/ha**)	
Yearly Results – 2010: +4.0 hkg/ha – 2011: +5.0 – 2013: +3.2 – 2014: +0.3 – 2015: –0.4 – 2016: +0.7 – 2017: +6.3 (highest recorded)	

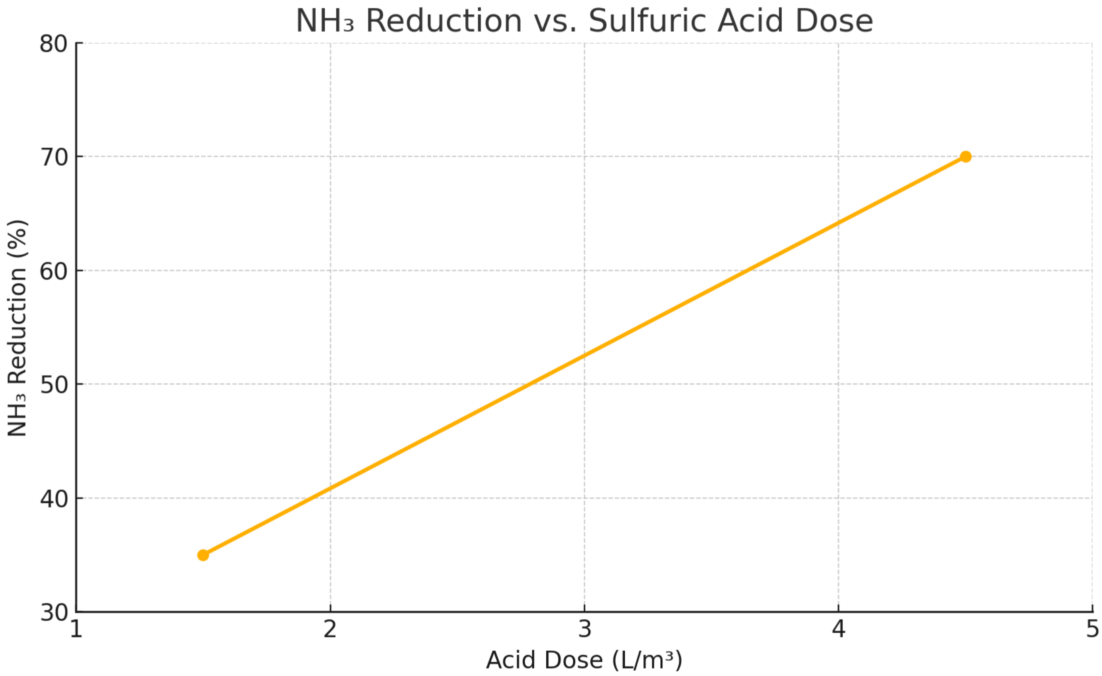
Key Takeaways:

- Acidification with SyreN shows a **consistent, though modest, positive yield effect** in winter wheat.
- The **largest benefit** was seen in 2017 at **pH 5.8**, supporting the conclusion that **lower pH enhances effectiveness**.
- These data confirm the earlier SEGES summary and validate long-term performance of the SyreN system.

Enclosure: Summary of trails

Summary of Graph: NH_3 Reduction vs Sulfuric Acid Dose

A simplified chart illustrates the relationship between sulfuric acid dose (L/m³) and NH_3 emission reduction (%). The graph connects two key data points: at 1.5 L/m³ acid dose, NH_3 reduction is approximately 35%, while at 4.5 L/m³, the reduction reaches 70%. This linear trend visually confirms that higher acid application leads to greater emission control. It also illustrates that moderate doses (e.g., ≤2.5 L/m³) can deliver meaningful reductions (up to ~50%), while doses above 4.0 L/m³ offer the strongest results—though they may exceed sulfate limits without careful management



Summary of Graphical Analysis: NH_3 Reduction vs Acid Dose (with pH)

A scatter plot was produced using 60+ trials, showing the relationship between **acid dose (L/m³)** and **ammonia (NH_3) reduction**, with **target pH** represented by color shading.

Key Observations:

- **NH_3 reduction increases with higher acid doses**, particularly above **2.5 L/m³**.
- Trials achieving a **target pH ≤ 6.0** consistently delivered **>60% NH_3 reduction**.
- **Lower pH values (darker dots)** clustered in the **upper-right corner**, confirming strong correlation between **low pH and high NH_3 mitigation**.
- Doses in the **1.7–2.5 L/m³ range** typically resulted in **30–50% NH_3 reduction**, which aligns with moderate sulfur use thresholds (40–50 kg SO_4-S/ha).
- Variability increases at low doses and higher pH, likely due to slurry type, application method, and environmental factors.

Conclusion from the Graph:

Acidification is most effective when the dose is ≥2.5 L/m³ and target pH is ≤6.0. These settings provide high NH_3 reduction with acceptable sulfur loads under common regulatory limits. However, substantial reductions can still be achieved at lower doses if carefully managed.

SyreN System: 12 Acidification Awards

- Agromek prisen 2008
- Agromek prisen 2010
- Miljøministeriets CSR Award 2012
- Baltic Manure Award 2012
- EU CSR Award environment 2013
- EU Award program Scale-up finalist 2018
- Solar Impulse Efficient solution SyreN 2019
- Solar Impulse Efficient solution Changes 2020
- Energy Globe Award 2020
- Energy Globe International Award 2021
- Solar Impulse Efficient solution e-missioN 2021
- Agromek prisen 2022