Austrian Journal of Agricultural Economics and Rural Studies, Vol. 33.6
https://oega.boku.ac.at/de/journal/journal-informationen.html
DOI 10.15203/OEGA_33.6, ISSN 1815-8129 I E-ISSN 1815-1027

Trade-offs associated with on-farm ammonia emission abatement practices in specialised pig farms

Zielkonflikte von betrieblichen Maßnahmen zur Ammoniakminderung in der Mastschweinehaltung

René Méité[1,2*], Astrid Artner-Nehls[1,2] and Sandra Uthes[1]

[1] Leibniz Centre for Agricultural Landscape Research (ZALF e.V.), Müncheberg, Deutschland
[2] Albrecht Daniel Thaer-Institute of Agricultural and Horticultural Sciences, Department of Agricultural Economics, Humboldt University Berlin, Berlin, DE

[*] *Correspondence to:* meite@zalf.de

Received: 25 Oktober 2023 – Revised: 15 Mai 2024 – Accepted: 22 Juni 2024 – Published: 10 Februar 2025

Summary

The livestock sector accounts for a large proportion of ammonia emissions from agriculture. Livestock farms can adopt various practices to reduce on-farm ammonia emissions, however, the available literature often neglects on-farm costs and other environmental impacts of these practices, and thus potential trade-offs. To fill this gap, we developed a multi-criteria assessment system with 35 indicators to analyse trade-offs between ammonia reduction, on-farm costs and further environmental impacts of on-farm ammonia emission abatement practices in specialised pig farms. Our analysis showed that all considered practices were beneficial for the environmental category "air", while for the other categories mixed effects occurred. High-cost practices were usually more effective in reducing ammonia emissions and other environmental impacts, while low-cost practices tended to cause different trade-offs. Thus, on-farm costs can often serve as a rough orientation for the environmental effectiveness of abatement practices.

Keywords: manure management, ammonia emission abatement, environmental impacts, on-farm costs, multi-criteria assessment

Zusammenfassung

Der Tierhaltungssektor ist einer der größten Verursacher von Ammoniakemissionen in der Landwirtschaft. Tierhaltende Betriebe können verschiedene Maßnahmen zur Ammoniakminderung auf der Betriebsebene verwenden. In der verfügbaren Literatur wird jedoch häufig ausschließlich das Ammoniakreduktionspotenzial dieser Verfahren bewertet, während betriebliche Kosten und Umweltwirkungen selten einbezogen werden. Um diese Lücke zu schließen, wurde für diesen Beitrag ein multikriterielles Bewertungssystem mit 35 Indikatoren entwickelt, um Zielkonflikte zwischen der Ammoniakreduktion, den entstehenden betrieblichen Kosten und verschiedenen Umweltkategorien von Minderungsmaßnahmen in spezialisierten Schweinemastbetrieben zu analysieren. Unsere Analyse zeigte, dass sich alle Maßnahmen positiv auf die Umweltkategorie "Luft" auswirkten, während für andere Umweltkategorien gemischte Wirkungen auftraten. Kostengünstige Maßnahmen verursachten diverse Zielkonflikte mit Umweltkategorien, während kostenintensivere Maßnahmen Ammoniakemissionen und Zielkonflikte mit Umweltkategorien effektiver verringerten. Daher können die Kosten der Maßnahmen als grober Orientierungswert für die Umwelteffektivität der Minderungsmaßnahmen dienen.

Schlagworte: Wirtschaftsdüngermanagement, Ammoniakminderung, Umweltwirkungen, Betriebskosten, multikriterielle Bewertung

1 Introduction

The agricultural sector, particularly livestock production, is responsible for 95% of the ammonia emissions in Germany. Ammonia emissions have various negative impacts on the environment, including eutrophication, biodiversity loss or climate change (Leip et al., 2011). The European Union (EU) has implemented different policies, for example the National Emissions reduction Commitments (NEC) Directive to reduce ammonia emissions from livestock production (NEC Directive (EU) 2016/2284, 2016). Several studies identified a variety of practices for reducing on-farm ammonia emissions (for an overview, see Santonja et al. 2017). However, most studies assess the environmental effectiveness of these practices only in terms of their ammonia reduction potential (UNECE, 2014; Santonja et al., 2017), while on-farm costs and impacts on other environmental categories are usually not assessed.

The objective of this article is to analyse trade-offs between ammonia reduction, on-farm costs, and further environmental impact categories of ammonia emission abatement practices, with a focus on specialised pig farms. Ammonia emission reduction may have indirect farm benefits through increased resource efficiency, yet provides no additional market income. Farmers therefore tend to adopt low-cost practices when adapting to environmental regulations (Méité et al., 2024). However, low-cost practices might be less effective in reducing ammonia emissions and more likely to cause trade-offs with other environmental impact categories than more costly practices. Studies show that simpler low-cost ammonia emission abatement practices can cause pollution swapping, for example the use of a trailing hose reduces ammonia emission while increasing nitrous oxide emissions (Hou et al., 2015), and the pressure on other environmental categories such as biodiversity, soil or water (Bergfeld et al., 2017).

2 Material and methods

Based on an integrative literature review (Snyder, 2019), including scientific articles, research reports and articles published by the farm press (total n=445), we developed an inventory of ammonia emission abatement practices. The search terms were the name of each adaptation option AND ‘emission’ AND ‘abatement’ OR ‘reduction’ OR ‘mitigation’ (Méité et al., 2024). In this paper, we analysed these articles regarding environmental assessments of these practices.

Using an inductive-deductive approach, we developed a multi-criteria assessment (MCA) system building on existing environmental impact assessment frameworks (e.g. Zapf et al., 2009; Schießl et al., 2015), covering nine assessment categories with a total of 35 indicators (Figure 1). The categories “on-farm costs” and “ammonia reduction” referred to single indicators and were quantitatively assessed. The indicators of the assessment categories “water”, “biodiversity”, “soil”, “air”, “resources”, “climate” and “animal welfare” were qualitatively assessed and their values were aggregated into a composite indicator for each category (Figure 1).

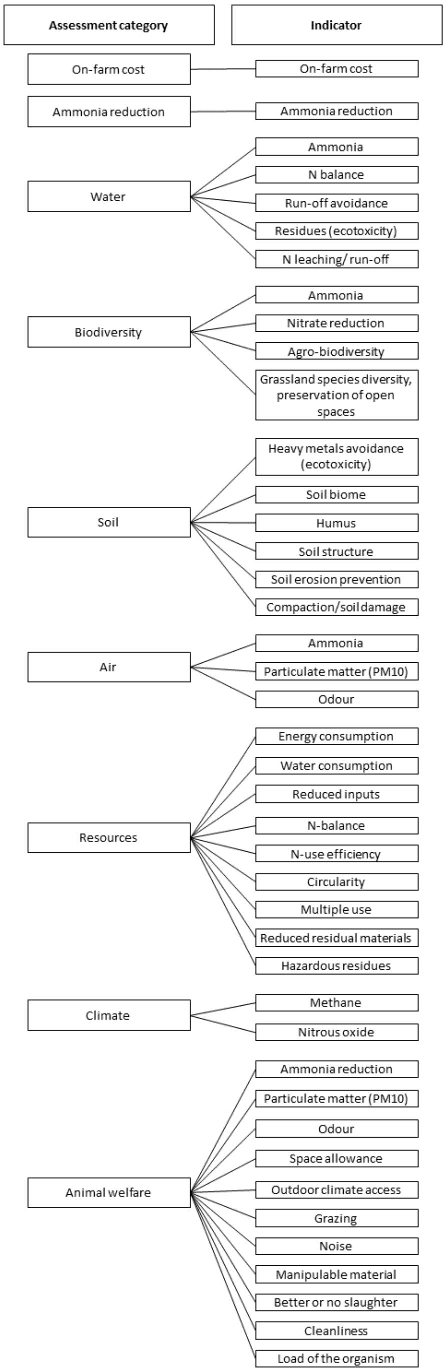
As reference scenario, we assumed a typical pig finishing farm in northern Germany with a dietary crude protein content of 18%, slatted floors, uncovered slurry storage, manure stored in heaps, and slurry application with a baffle plate.

For the indicator “ammonia reduction”, we calculated the absolute ammonia loss in each stage of the manure management chain (e.g. housing, storage or field) of the reference practices, as described in Vos et al. (2022), and subtracted the absolute ammonia reduction of each practice in the respective stage using reduction potentials as obtained from our literature survey.

On-farm costs of the reference and abatement practices were derived from scientific articles, reports, or the farm press. The costs included investment costs, fixed and variable costs of a practice. To account for the additional on-farm costs caused by the abatement practices, we calculated the cost difference between the reference practice and the abatement practice. Revenues from the sale of extracted materials (e.g. recovered nitrogen, biogas) or savings on inputs (e.g. mineral fertilisers) could not be included due to lack of data, incomplete data, price fluctuations or recent lack of markets of most of the practices in question. The practices were classified into low (0 to < 10 €/place), medium (10 to < 20 €/place) and high (≥ 20 €/place) on-farm cost practices.

Regarding the environmental assessment categories, we considered following nitrogen (N) flow indicators: ammonia (NH_3), nitrogen balance, nitrogen use efficiency, runoff, leaching as well as nitrate reduction that we assigned to the different categories (Figure 1). In the category „water“, we also included an indicator to depict toxic residues. The “biodiversity” category additionally comprises the indicators agro-biodiversity and grassland species diversity to incorporate the impact of practices on the diversity of plants and animals in agricultural systems or adjacent systems. Regarding the category “soil”, we used a variety of indicators to cover impacts on, e.g. the humus content and soil structure, the compaction of the soil, the input of heavy metal components into the soil, and effects on the soil biome. In the “air” category we took into account the formation of airborne particulate matter (PM10) and odour. The “resources” category included indicators that cover the consumption of water and electricity (including fossil energy) of a practice, circularity aspects of produced outputs, the possible multiple use of slurry in a cascading or in a circular manner, the possibility to reduce inputs in the farm system, and remaining hazardous residues on fields. Under “climate” we included the effects of the two most climate-relevant gases nitrous oxide and methane emissions, according to the assessment schemes available in literature (e.g. Zapf et al., 2009; Schießl et al., 2015), to depict pollution swapping effects. For the category “animal welfare”, we included indicators that measure the impact on the welfare, comfort and health status of animals, such as space allowance, the presence of manipulable material in the stable, noise and air quality, and the potential health risk for the animal through, such as a high dietary protein intake.

Figure 1: Overview of the assessment categories and indicators utilised in the multi-criteria assessment system



Source: own illustration, 2024.

The direction of impact on the indicators in these categories was qualitatively assessed, based on the literature reviewed, differentiating the options “deterioration” (-1), “positive and negative effects” (0) and “improvement” (+1). The results of the individual indicator values were summed up per assessment category and transformed into a scale ranging from “+++” to “---”. Results are shown in Table 1.

The aggregated environmental impact of the practices was calculated through summation of all environmental impact category values. Results are depicted in Figure 2.

3 Results

3.1 Ammonia emission reduction

Selected ammonia emission abatement practices are assessed in Table 1 in terms of their absolute ammonia reduction and environmental impact, ordered by cost groups. The *N/P-reduced diet* reduces the intake of nitrogen and phosphorus by the animals, resulting in lower nutrient concentrations in excreta and emissions while reducing feed costs. *Composting* is the biological, aerated decomposition process of organic material into a nutrient-rich soil amendment and reduces ammonia emission compared to manure stored in a heap. The *trailing hose* is the legal minimum standard technique for applying slurry to the soil in bands reducing the aeration of slurry, thus ammonia formation. *Permanent storage cover* closes the tank ceilings to mechanically prevent emissions to be released. *Stable flushing* with water applied by a hose ensures cleaner surfaces and a faster removal of slurry from the stable. *Slurry injection* into the soil decreases the contact of slurry with the air, improves the absorption by the soil, and reduces ammonia emissions. *Slurry acidification* uses acids, e.g. sulfuric acid added to lower the pH of slurry to lower ammonia formation during fertilisation. *Slurry cooling* in livestock buildings aims to reduce the temperature of slurry, and thereby reducing ammonia emissions. The *pig toilet* is designed to collect urine and faeces separately to prevent the formation of ammonia. *Slurry channel flushing* uses water to support faster removal of slurry from the stable in the slurry tank. *Nutrient recovery* techniques involve a variety of complex processing systems designed to recover nutrients from slurry while treating the emissions. *Biogas production* aims to release methane from organic materials during decomposition in an anaerobic fermentation process, producing biogas and digestate, contributing to lower ammonia emissions. The *exhaust air treatment* involves a chemical treatment of ammonia-containing air from the stable using, e.g. sulfuric acid, before being released to the environment. *Nitrification-denitrification* is a biological process to remove nitrogen from slurry released as non-hazardous dinitrogen (N_2) to the atmosphere. *Destocking* refers to reducing the number of animals on a farm.

3.2 Low-cost practices

Low-cost practices (< 10 €/place/year) achieved a comparatively lower ammonia reduction in the range of 0.5 to 1.5 kg NH_3/place/year, while impacts on other assessment categories were mixed (Table 1).

Positive impacts for the categories „air“, “biodiversity” and “animal welfare” may arise, due to improved indoor air quality and overall reduced emissions (Bergfeld et al., 2017). *Composting* benefits the “soil” category through an improved soil structure and soil organic matter balance (Bernal et al., 2015), while *N/P-reduced diet* and *slurry injection* reduce inputs in the farm system and increase the nitrogen use efficiency (Ndegwa et al., 2008; Hou et al., 2015) and can therefore have a positive effect on the "resources" category. *N/P-reduced diets* achieved the best overall result due to cost savings, a moderate ammonia reduction and improvement in all other impact categories (Table 1).

The assessment categories „water" and „climate" can be negatively affected by low-cost practices (Table 1). For example, practices such as *slurry cooling* in the stable retain more N in the manure and increase the risk of higher losses in a subsequent manure management step, e.g. during field application through run-off or leaching (Loyon et al., 2016). In the category „climate" *composting* and *slurry injection* may have negative impacts resulting from shifted emissions from ammonia to nitrous oxide (Wang et al., 2017; Hou et al., 2015). *Slurry acidification* can cause a deterioration in the assessment category „soil" due the negative impact on soil biome of potentially toxic residues, e.g. sulphuric acid (Kupper, 2017). *Surface flushing* may have negative impacts in the category „resources" due to an increasing amount of slurry (Ogink and Kroodsma, 1996). *Composting* can cause multiple trade-offs with other assessment categories including „water", „resources" and „climate", causing a higher risk of leaching and shifting emissions, a lower nitrogen use efficiency, and a higher energy demand (Peigné and Girardin, 2004; Flotats et al., 2011), compared to applied manure on fields (Table 1).

3.3 Medium-cost practices

Medium-cost practices (10 to 20 €/place/year) achieved an ammonia reduction in the range of 0.2 to 2.1 kg NH_3/place/year, and caused fewer trade-offs with other impact categories than low-cost practices (Table 1).

Positive effects may result for the assessment categories "biodiversity", "air", "resources", "climate" and "animal welfare". Practices that separate the liquid and solid phases of manure (i.e. pig toilet) effectively reduce ammonia and can potentially contribute to a fertilisation strategy that is better adapted to needs of the crops, and thereby save mineral fertiliser (Wang et al., 2017). For *nutrient recovery plants* on-farm costs could be considered, while ammonia reduction could not be calculated due to missing data in literature (Table 1).

Indoor medium-cost practices (e.g. *pig toilet* or *slurry channel flushing*) caused similar trade-offs with the assessment category „water" as low-cost practices, if the subsequent management, e.g. the fertilisation, is not appropriately adapted (Table 1). *Biogas production* may negatively affect the "soil" category, due to a higher risk of heavy metal accumulation and a lower potential for humus formation from digestate (Schießl et al., 2015; Flotats et al., 2011), compared to the manure application (Table 1).

3.4 High-cost practices

High-cost practices (> 20 €/place/year) achieved the highest possible ammonia reduction between 1.4 to 4.8 kg NH_3/place/year) and had in most cases positive effects on the environmental categories (Table 1).

Potential trade-offs are possible with the categories "water" and „resources", as these practices often require additional external input, causing e.g. a higher energy or water consumption (Flotats et al., 2011; Santonja et al., 2017). The *exhaust air treatment* also increases resource consumption since acidic filter materials are needed, which end up as hazardous residues (DLG, 2016). *Nitrification-denitrification* improved most environmental assessment categories (e.g. "water", "soil" and "climate"), since nitrogen is released in the environmentally-harmless form N_2, but increased the consumption of "resources" (Schießl et al., 2015; Flotats et al., 2011). *Reducing livestock* numbers achieved the highest ammonia reduction (equal to the ammonia emission factor of one animal), while also improving all other assessment categories, yet at the highest on-farm costs due to the resulting income loss (Table 1).

3.5 On-farm costs vs. aggregated environmental impact

On-farm costs and the aggregated environmental impacts generally had a positive relationship, as more costly practices tended to have a higher aggregated environmental impact than less costly practices. Exceptions were *N/P-reduced diets*, *nutrient recovery* and *livestock destocking*, which caused no trade-offs with environmental categories; however, the first practice resulted in cost savings, while the latter caused the highest on-farm costs. Figure 2 visualises the aggregated composite assessment categories in relation to the calculated on-farm costs.

4 Discussion

4.1 Interpretation of results

Our results show that less costly abatement practices tend to cause more diverse trade-offs with environmental impacts than more costly practices (Table 1). Practices that can be implemented in the barn, during storage or field management (often low-cost practices) are often affected by various abiotic and biotic factors and are influenced in terms of, e.g. their reduction or pollution swapping potential (Hou et al., 2015) and thus potentially create diverse trade-offs with different environmental categories.

For example, *slurry injection* (field stage) mitigates ammonia emissions through injecting slurry into the soil and reducing the contact with air, yet thereby supports pollution swapping effects (e.g. nitrous oxide formation) resulting in a trade-off with the category "climate". Further practices create a trade-off with the category „water" (Table 1), since the nitrogen content in the slurry may remain high and increase the farm N balance (Bach et al., 2016).

In contrast, slurry treatment practices in the medium and high-cost range, such as *nutrient recovery* and *nitrification-denitrification,* are less influenced by abiotic or biotic

Table 1: Results of the multi-criteria assessment of selected ammonia abatement practices (selection)

Abatement practices	**on-farm costs**[x]	**ammonia reduction**[*]	**water**	**biodiversity**	**soil**	**air**	**resources**	**climate**	**animal welfare**
low-cost practices									
N/P-reduced diet	-18,7	1,1	+++	++	+	++	++	++	+
composting	1,5	0,5	-	+/-	++	+/-	-	---	+/-
trailing hose	1,9	0,5	-	+/-	+/-	+	+	-	+/-
permanent storage cover	3,4	1	-	+/-	+/-	++	+	++	+/-
stable flushing	3,9	1,3	+/-	+	-	+++	-	+	+
slurry injection	4,3	0,9	+/-	+/-	+/-	++	+	--	+/-
slurry acidification	5,4	0,8	+	+/-	-	++	+/-	+++	+/-
slurry cooling	5,7	1,5	-	+/-	+/-	++	+/-	++	+
medium-cost practices									
pig toilet	10	2,1	-	+/-	+	++	+/-	+/-	+
slurry channel flushing	17,5	1,8	-	+/-	+/-	++	+/-	++	+
nutrient recovery	>18	unknown[#]	+++	+++	++	+++	+	++	+/-
biogas production	18,5	0,2	+	++	-	+++	+	++	+/-
high-cost practices									
exhaust air treatment	20,8	2,4	-	+/-	+/-	+++	-	+/-	+
nitrification- denitrification	27,4	unknown[#]	++	++	+/-	++	--	+++	+/-
destocking LSU/ha	54	4,8	+++	+++	+	+++	++	+++	++

[#] unknown: results of the achieved ammonia reduction is not yet reported

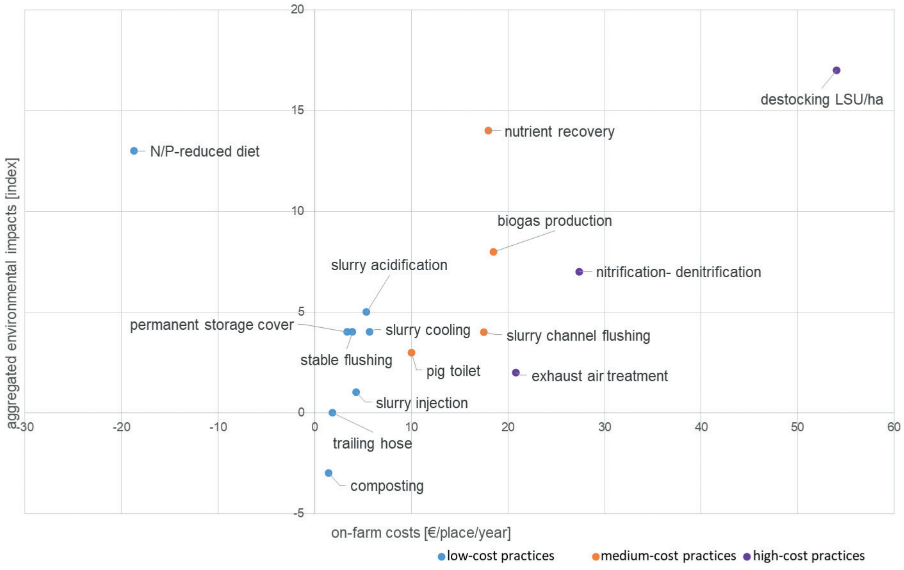
+ improvement, - deterioration, +/- positive as well as negative effects; N/P: nitrogen/phosphorus; LSU: livestock units

* [kg NH_3/place/year]

[x] [€/place/year]

Source: own compilation, 2024.

Figure 2: Relationship between on-farm costs [€/place/year] and aggregated environmental impact [index] (positive values indicate improvement, negative values indicate deterioration, compared to the reference)



Source: own illustration, 2024.

factors. For instance, the recycling of slurry in a *nutrient recovery plant* is conducted in a closed systems resulting in low emissions to the air, without negatively affecting the categories "water" and "climate" (Table 1). The *nitrification-denitrification* releases the nitrogen in form of harmless N_2 to the atmosphere (Flotats et al., 2011), which also relieves the burden in several assessment categories, e.g. "water", "soil" and "climate" and thus creates less diverse trade-offs (Table 1). However, slurry treatment practices require a higher water and energy consumption (Bernal et al., 2015) and therefore mainly negatively affect the „resources" category (Table 1).

In this context, two outstanding practices are the *N/P-reduced diet*, which positively affects the entire management chain by reducing the N input to the system (Sajeev et al., 2018), and *livestock reduction*, which prevents emissions from the animal and the manure, avoiding negative effects on the environment (Scheffler and Wiegmann, 2019). However, the determination of the optimal stocking density requires the consideration of, e.g. societal preferences such as national emission reduction targets, the farms' economic viability, and the identification of the most environmentally friendly production system, which vary according to regional conditions.

In each cost group, we found examples of practices with positive effects for all considered assessment categories (Table 1), which consequently achieved the highest aggregated environmental impact (Figure 2). These high impact practices can be distinguished according to the following principles: i. reducing the N input to the farm system and thus the total emission potential (*N/P-reduced diet*), ii. recycling and recirculating manure (*nutrient recovery*) and iii. lowering direct emissions by reducing the animal number (*livestock destocking*; Figure 2).

Our study confirms that all abatement practices improve the category "air" (Table 1), yet only measures that process manure (e.g. *biogas production*) as well as *livestock destocking* improved the category "biodiversity" (Table 1). Practices that reduce ammonia emissions at the barn, storage and field level increased the farm N balance and thereby potentially negatively affect the category "water" (Table 1) through leaching and run-off, while an *N/P-reduced diet* decreased the farm N balance (Bach et al., 2016). The assessment category "animal welfare" showed to be a relevant assessment category for practices for feeding and in the barn, where basically the indoor air quality or the cleanliness were improved (Bergfeld et al., 2017).

4.2 Methodological reflections

The focus of our study was on trade-offs between on-farm costs, ammonia reduction and other environmental impacts categories. Therefore, we excluded assessment categories that address, e.g. "human" (Schießl et al., 2015) or indicators of social sustainability (Zapf et al., 2009; Schießl et al., 2015). Depending on the focus of the study, the MCA system can be expanded with other assessment categories.

Although other studies served as input, our multi-criteria assessment produced some deviating results. This is due to the fact that other studies have not systematically assessed the effects (cf. Schießl et al., 2015; Bergfeld et al., 2017). Furthermore, the results, conclusions and comparability between studies may be influenced when using varying indicator sets or assuming different system boundaries (e.g. farm or regional level). A critical aspect is that a clear separation of the system boundaries is difficult due to the interconnectedness of processes, nutrient cycles and in some cases the environmental effects on farms as well as on the agricultural system. Depending on how the different levels (e.g. farm or regional level) are taken into account results may vary.

4.3 Outlook and implications

Current German policies focus mainly on reducing ammonia emissions (e.g. the implementation of the NEC Directive (EU) 2016/2284, 2016) and implementing low-cost practices. For example, the low-cost practices *trailing hose* and *slurry cover* are mandatory (DüV, 2020), while the high-cost practice *exhaust air treatment* is only required for large pig farms (TA Luft, 2021). However, in order to meet the climate targets by 2030, practices that cause fewer trade-offs with the "climate" category should be prioritised and funded.

Future MCA studies should include revenues as a separate aspect of the cost calculation to assess the entire economic viability of abatement practices. Examples of possible revenues are an increase in the fertiliser value of slurry, produced outputs (e.g. struvite and recycling fertiliser), or saved mineral fertiliser.

5 Conclusions

Our study shows that on-farm costs often provide a fairly good orientation for the environmental effectiveness of ammonia emission abatement practices in specialised pig farms. Overall, low-cost practices tended to have a comparatively narrow focus on direct emission reduction in a single manure management stage, which can create trade-offs with various environmental categories, e.g. „water", „climate" or „resources". High-cost practices tended to be more effective in reducing emissions and caused fewer trade-offs. However, in all three cost groups there were also examples of practices (*N/P-reduced diet*, *nutrient recovery plants* and *livestock destocking)* that cause no trade-offs.

We conclude that an integrated consideration of the environmental impacts and costs along the entire manure management chain is required to determine appropriate emission reduction strategies to avoid unintended environmental impacts and new undesirable path dependencies. Farming guidelines and financial support schemes should encourage and promote the adoption of abatement practices that cause fewer trade-offs.

Acknowledgements

This article was made possible through funding by the German Federal Ministry of Education and Research (BMBF) for the junior research group BioKum (031B0751).

References

Bach, M., Klement, L. and Häußermann, U. (2016) Bewertung von Maßnahmen zur Verminderung von Nitrateinträgen in die Gewässer auf Basis regionalisierter Stickstoffüberschüsse - Teil I: Beitrag zur Entwicklung einer ressortübergreifenden Stickstoffstrategie. Zwischenbericht. Dessau-Roßlau. Umweltbundesamt.

Bergfeld, U., Böcker, H., Büscher, W., Flessa, H., Lasar, A., Reinsch, T., Roth, U., Schmid, H., Südekum, K.-H. and Wulf, S. (2017) Klimaschutz in der Landwirtschaft. Emissionsminderung in der Praxis. Heft 119. Darmstadt; Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL).

Bernal, M., Bescós, B., Bonmatí, A., Burgos, L., Bustamante, M. Á., Clemente, R., Claudio, F., Xavier, F., García-González, M. C., Herrero, E., Mattachini, G., Moscatelli, G. and Noguerol, J. (2015) Evaluation of manure management systems in Europe. URL: https://core.ac.uk/download/pdf/46606176.pdf (20.11.2022).

DLG (Deutsche Landwirtschaftsgesellschaft) (2016) Hinweise zum Betrieb von Abluftreinigungsanlagen für die Schweinehaltung, 2016 (403). URL: https://www.rimu.de/files/contentdata/DLG_Merkblatt_403_Hinweise%20zum%20Betrieb%20von%20Abluftreinigungsanlagen%20fuer%20die%20Schweinehaltung.pdf (13.07.2021).

DüV (Düngeverordnung) (2020) Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Düngen (Düngeverordnung - DüV). Bundesministeriums der Justiz und für Verbraucherschutz sowie des Bundesamts für Justiz. Berlin.

Flotats, X., Foged, H. L., Bonmati, A. and Palatsi, J. (2011) Manure Processing Technologies. Technical Report No. II to the European Commission, Directorate-General Environment, Manure Processing Activities in Europe. URL: https://www.researchgate.net/profile/Xavier-Flotats/publication/267028110_Manure_Processing_Technologies/links/54450f0a0cf2d86e9a642fd6/Manure-Processing-Technologies.pdf?origin=publication_detail (27.07.2022).

Hou, Y., Velthof, G. L. and Oenema, O. (2015) Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. Global Change Biology. https://doi.org/10.1111/gcb.12767.

Kupper, T. (2017) Evaluation of slurry acidification for mitigating ammonia emissions in Switzerland, Evaluation of slurry acidification for mitigating ammonia emissions in Switzerland. URL: https://www.agrammon.webtest.oetiker.ch/assets/Documents/Bericht-Ansaeuerung-Guelle-20170123v.pdf (23.07.2022).

Leip, A., Achermann, B., Billen, G., Bleeker, A., Bouwman, A. F., de Vries, W., Dragosits, U., Döring, U., Fernall, D., Geupel, M., Herolstab, J., Johnes, P., Le Gall, A. C., Monni, S., Neveceral, R., Orlandini, L., Prud'homme, M., Reuter, H. I., Simpson, D., Seufert, G., Spranger, T., Sutton, M. A., van Aardenne, J., Voß, M. and Winiwarter, W. (2011) Integrating nitrogen fluxes at the European scale. In: Sutton MA (ed) The European nitrogen assessment. Sources, effects, and policy perspectives. Cambridge: Cambridge University Press, 345–376.

Loyon, L., Burton, C. H., Misselbrook, T., Webb, J., Philippe, F. X., Aguilar, M., Dorequ, M., Hassouna, M., Veldkamp, T., Dourmad, J. Y., Bonmati, A., Grimm, E. and Sommer S. G. (2016) Best available technology for European livestock farms: Availability, effectiveness and uptake. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2015.09.046.

Méité, R., Artner-Nehls, A. and Uthes, S. (2024) Farm adaptation to stricter nutrient management legislation and the implications for future livestock production: a review. Nutrient Cycling in Agroecosystems. https://doi.org/10.1007/s10705-024-10341-0.

Ndegwa, P. M., Hristov, A. N., Arogo, J. and Sheffield, R. E. (2008) A review of ammonia emission mitigation techniques for concentrated animal feeding operations. Biosystems Engineering. https://doi.org/10.1016/j.biosystemseng.2008.05.010.

NEC Directive (EU) 2016/2284 (2016) DIRECTIVE (EU) 2016/2284 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the reduction of national emissions of certain atmospheric pollutants. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016L2284&from=EN (04.01.2023).

Ogink, N. and Kroodsma, W. (1996) Reduction of Ammonia Emission from a Cow Cubicle House by Flushing with Water or a Formalin Solution. Journal of Agricultural Engineering Research. https://doi.org/10.1006/jaer.1996.0021.

Peigné, J. and Girardin, P. (2004) Environmental Impacts of Farm-Scale Composting Practices. Water, Air, & Soil Pollution. https://doi.org/10.1023/B:WATE.0000019932.04020.b6.

Sajeev, E. P. M., Amon, B., Ammon, C., Zollitsch, W. and Winiwarter, W. (2018) Evaluating the potential of dietary crude protein manipulation in reducing ammonia emissions from cattle and pig manure: A meta-analysis. Nutrient Cycling in Agroecosystems. https://doi.org/10.1007/s10705-017-9893-3.

Santonja, G. G., Georgitzikis, K., Scalet, B. M., Montobbio, P., Roudier, S. and Delgado Sancho, L. (2017) Best Available Techniques (BAT) Reference Document for the Intensive Rearing of Poultry or Pigs. Industrial Emissions Directive 2010/75/EU Integrated Pollution Prevention and control. URL: https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/JRC107189_IRPP_Bref_2017_published.pdf 01.06.22.

Scheffler, M. and Wiegmann, K. (2019) Quantifizierung von Maßnahmenvorschlägen der deutschen Zivilgesellschaft zu THG - Minderungspotenzialen in der Landwirtschaft bis 2030. Berlin: Öko-Institut e.V. URL: https://www.oeko.de/fileadmin/oekodoc/Quantifizierung-von-Massnahmenvorschlaegen-der_Klima-Allianz_Landwirtschaft.pdf 01.06.22.

Schießl, P., Krämer, C. and Heißenhuber, A. (2015) Aufbereitung und Transport von Wirtschaftsdüngern. Dessau-Roßlau. Berlin. URL: https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_80_2015_aufbereitung_und_transport_von_wirtschaftsduengern_0.pdf (01.06.22).

Snyder, H. (2019) Literature review as a research methodology: An overview and guidelines. Journal of Business Research. https://doi.org/10.1016/j.jbusres.2019.07.039.

TA Luft (2021) Technische Anleitung zur Reinhaltung der Luft – TA Luft. URL: https://www.verwaltungsvorschriften-im-internet.de/bsvwvbund_18082021_IGI25025005.htm (24.05.2022).

UNECE (2014) Guidance document on preventing and abating ammonia emissions from agricultural sources. URL: https://unece.org/DAM/env/documents/2012/EB/ECE_EB.AIR_120_ENG.pdf (14.04.2021).

Vos, C., Rösemann, C., Haenel, H.-D., Dämmgen, U., Döring, U., Wulf, S., Eurich-Menden, B., Freibauer, A., Döhler, H., Schreiner, C., Osterburg, B. and Fuß, R. (2022) Calculations of gaseous and particulate emissions from German agriculture. Braunschweig, Germany. URL: https://d-nb.info/1253489017/ (20.05.2023).

Wang, Y., Dong, H., Zhu, Z., Gerber, P. J., Xin, H., Smith, P., Opio, C., Steinfeld, H. and Chadwick, D. (2017) Mitigating Greenhouse Gas and Ammonia Emissions from Swine Manure Management: A System Analysis. Environmental science & technology. https://doi.org/10.1021/acs.est.6b06430.

Zapf, R., Schultheiss, U., Dolutschitz, R., Oppermann, R. and Döhler, H. (2009) Nachhaltigkeitsbewertungssysteme – Allgemeine Anforderungen und vergleichende Beurteilung der Systeme RISE, KSNL und DLG-Zertifizierungssystem für nachhaltige Landwirtschaft. In: Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (ed) Berichte über Landwirtschaft, 87 (3). Stuttgart.Tabelle A1: Tabellarische Übersicht über die im Modellverbund verwendeten Modelle