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Successful NH_3 abatement policies and regulations in German agriculture

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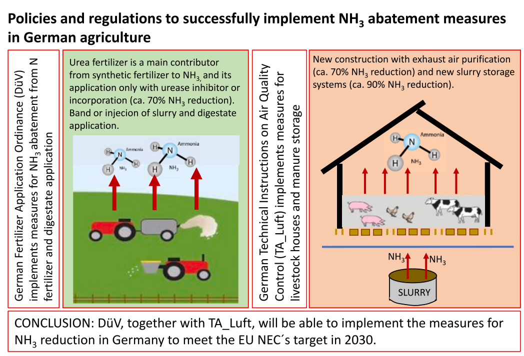
HIGHLIGHTS

- Anthropogenic ammonia emissions are about 95% are from agriculture
- The abatement policies and regulations in German agriculture have significantly reduced the emissions
- More than 80% of the agricultural ammonia emissions are from the manure and digesitate management chains
- The urgency of future mitigation measures focusing on livestock manure and digestates becomes clear

GRAPHICAL ABSTRACT



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ABSTRACT

Anthropogenic ammonia (NH_3) emissions, of which about 95 % are from agriculture, have led to environmental pollution, resulting in tremendous damage to human health and ecosystems. Thus, the NEC Directive 2016/2284/EU sets national reduction targets for NH_3 emissions in individual EU countries. To implement the NEC Directive for NH_3 emission targets, Germany amended the Fertilizer Application Ordinance in 2017 and 2020 (DüV_amended) and set the air pollution control regulation, Technical Instructions on Air Quality Control (TA_Luft). This study aimed to evaluate the impact of the DüV_amended on NH_3 mitigation from applying livestock manure, digestates, synthetic nitrogen (N) fertilizers, and TA_Luft on housing and storage. This study showed that Germany reached the first national NH_3 reduction target in 2020, as set by the NEC directive. The German DüV_amended, a significant policy change, has profoundly impacted NH_3 emission mitigation from agriculture after 2017 by implementing measures aimed directly at NH_3 reduction, reducing N surpluses, and improving N use efficiency. The reduction in NH_3 emissions from synthetic N fertilizers between 2016 and 2022 contributed about 51 % to the decrease from the agricultural sector over the same period. Among the synthetic fertilizers, NH_3 reduction from urea between 2016 and 2022 accounted for around 83 % of the total reduction from synthetic N, indicating that the NH_3 emissions from urea fertilizer by reducing urea application and mandating urea to be incorporated immediately or to be stabilized with urease inhibitors played a crucial role in the sharp decrease in NH_3 emissions over the last years in Germany. Achieving a high yield by lowering the synthetic N rate in this study strongly suggests that optimal reduction in N rate does not necessarily result in yield losses but rather in a pivotal relationship between the agronomic and environmental performance and indicates that the DüV_amended was an effective measure that can reduce the NH_3 emissions.

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Over 80 % of Germany's annual agricultural NH_3 emissions in 2021 and 2022 originated from livestock and digestates from energy crops. Mandatory close to the soil band application of slurry and digestates on cultivated cropland since 2020 reduced NH_3 emissions. In addition, banning of broadcast application of slurry to grassland and manure incorporation within one hour on uncultivated soils will become mandatory in 2025 to comply with NEC 2030's target of 29 % NH_3 reduction relative to 2005. The recent German air pollution control regulation (TA_Luft) enforces abatement measures such as air purifiers in large poultry and pig housings and covered storage of slurry and digestate storages of large farms. The results of the German NH_3 abatement strategy for synthetic N fertilizers may help reduce NH_3 emissions worldwide, especially for countries consuming high amounts of urea fertilizers.

1. Introduction

Anthropogenic ammonia (NH_3) emissions, with about 95 % from agriculture (Wyer et al., 2022), have led to air pollution, soil acidification, and surface water eutrophication, resulting in tremendous damage to human health and ecosystems (Pozzer et al., 2017; Giannadaki et al., 2018). The annual cost of harm to human health associated with NH_3 emissions was estimated at US$ 55–114 billion in the EU (van Grinsven et al., 2013) and US$ 69–180 billion in the United States (Goodkind et al., 2019). According to Stevens et al. (2004), a 23 % decline in plant species richness was attributable solely to NH_3 emissions in the EU. Thus, mitigating NH_3 emissions has received a high priority, and legislation in the EU has been established to implement mitigation strategies for NH_3 emissions.

In 2001, the EU adopted the first National Emission Ceilings (NEC) Directive (2001/81/EC) to control major air pollutants, including NH_3 (EEA, 2023). In Germany, the Fertilizer Application Ordinance (DüV) is a central instrument in the German National Air Pollution Control Program. It was first implemented in 1996 to focus on implementing the EU Nitrate Directive to protect surface and groundwater pollution by stipulating the proper use of all fertilizers. It includes regulations and measures for the best practices that limit the quantity of applied nutrients, i.e., application threshold and nutrient balance, and technical or management specifications (e.g., application techniques) in agriculture to mitigate NO_3^-, N_2O, NH_3, and P emissions arising from the application of fertilizers (DüV, 2017, 2020). Driven by policy regulations of the first EU NEC Directive, significant progress towards reducing primary air pollution emissions has been achieved in Europe over the past years. However, agriculture within the EU is still where air pollutant emissions, particularly NH_3 emissions, have decreased the least (Giannakis et al., 2019; EEA, 2023). Although NH_3 emissions from agriculture have decreased by a mere 5 % from 2005 to 2013 within the EU 28, they have slightly increased again from 2013 onwards (+3 % from 2013 to 2016) (Giannakis et al., 2019; EEA, 2023). The NEC Directive 2016/2284/EU sets national reduction targets for NH_3 emissions in the EU. Germany must reduce 5 % of national NH_3 emissions in 2005 by 2020 and by a further reduction to reach by 29 % of those in 2005 by 2030. National NH_3 emissions in Germany from 1996 to 2016 was increased by around 4 % in the agricultural sector (Häußermann et al., 2019). This was due to: i) the slow recovery of agriculture in East Germany starting in 1995, ii) the Intensification of agriculture, and an increasing proportion of urea in the mixture of synthetic fertilizers used, iii) the rapid increase in

Table 1
Measures adopted in Germany that directly or indirectly reduce the NH_3 emissions from agricultural policies (DüV, 2017, 2020; TA Luft, 2021).

DüV, 2017	Year of implementation
Measures that lead directly to a reduction in NH_3 emissions	
Urea application only with urease inhibitor or incorporation within 4 h	2020
Band application or injection of slurry and digestates to arable land with growing crops	2020
Band application or injection of slurry and digestates to grassland	2025
Incorporation of slurry, digestates, and poultry manure on uncultivated arable land within 4 h	2017
Measures that lead indirectly to a reduction in NH_3 emissions	
The upper limit for the application of organic nitrogen (N) fertilizer of 170 kg N ha^{-1} now also applies to digestates from energy crops	2017
No N application in autumn to cropland (exception: before cover crops, winter oilseed rape, or winter barley following cereals). This measure increases the band application of liquid manure to growing crops in spring.	2017
Uniform rules to determine fertilizer requirements for N in all federal states of Germany	2017

DüV, 2020	Year of implementation
Measures that lead directly to a reduction in NH_3 emissions	
Incorporation of slurry, digestates, and poultry manure on uncultivated arable land within 1 h	2025
Measures that lead indirectly to a reduction in NH_3 emissions	
In fertilizer requirement planning for croplands, the minimum effectiveness of slurry and digestates is increased by 10 %	2020
In fertilizer requirement planning for grasslands, the minimum effectiveness of slurry and digestates is increased by 10 %	2025
Expansion of protected areas along water courses without N fertilization	2020
Special requirements for nitrate-polluted areas (about 20 % of the total cropland): reduction of N fertilization by 20 %, no N fertilization in autumn	2020

TA-Luft (Technical Instructions on Air Quality Control)	Year of implementation
Measures that lead directly to a reduction in NH_3 emissions	
New construction of large housing facilities (G facilities) for pigs and poultry only with NH_3 exhaust air purification (70 % reduction in emissions); for medium-sized housing (V facilities), emission reduction has to be at least 40 %	2021
Retrofitting old barn facilities with appropriate NH_3 reduction technology by 2026 (G facilities) or 2029 (V facilities)	2026–2029
Protein-optimized feeding of pigs and poultry to reduce NH_3 emissions by 20 %	2024
Reduction of ammonia emissions from outdoor slurry storage tanks by 90 % (new systems) or 85 % (old systems, improvement until 2029) compared to an open storage tank	2029

biogas production from energy crops producing new NH_3 emissions, and iv) the first version DüV in 1996 that mainly focused on reducing the nitrate losses from agriculture with an emphasis on the aquifer and surface water caused, and the lack of specific regulations for NH_3 emission abatement in fertilizer application. In 2017 and 2020, Germany amended the DüV (DüV_amended) to reduce the environmental impact of agriculture – primarily to comply with the EU Nitrates Directive regarding the reduction of nitrate emissions and thereby also introduced regulations aiming at NH_3 abatement (DüV, 2017, 2020). The specific direct and indirect measures regarding NH_3 mitigation in the DüV_amended are summarized in Table 1. Briefly, they include the application of livestock manure and digestates from energy crops on cultivated croplands only near the ground, band application; incorporation of liquid manure and digestate on uncultivated fields within 4 h; incorporation of poultry manure on uncultivated fields; the band application of liquid manure and digestates on grassland only near the ground; 170 kg total N ha^{-1} as the upper limit for all organic fertilizers with large concentration of plant available N, e.g., digestates of production from energy plants (e.g., mainly maize) as well. Measures in Table 1 that lead indirectly to a reduction in NH_3 emission are primarily implemented to reduce nitrate leaching, e.g., the upper limit of organic fertilizer application, restricted N application in autumn, reduced N fertilization rates in nitrate polluted areas, and a higher proportion of liquid manure N and fermentation residue N in fertilization planning. The indirect effects on NH_3 emission are mainly related to the associated savings of synthetic N fertilizers. Urea fertilizer is applied either with additive urease inhibitors (UIs) or by incorporating urea into soils without delay or within four hours of spreading urea fertilizer. Urea is the most popular N fertilizer used by farmers because of its high N content (46 %), relatively low price per unit N, and relative safety and ease of handling in transportation, storage, and application (Cantarella et al., 2018; IFA 2023; Hu and Schmidhalter, 2024). However, urea causes NH_3 volatilization at high potential due to the rapid hydrolysis by soil ureases. To mitigate NH_3 emissions from urea fertilization, UIs have been used to couple urea fertilizers. The main working principle of UIs is to effectively reduce urease activity to decrease the urea hydrolysis rate for an increase in its dispersion into the soil (Schraml et al., 2016). The current UIs in the European market are NBPT (N-(n-butyl) thiophosphoric triamide), 2-NPT (N-(2-nitrophenyl) phosphoric triamide), and a mixture formulation containing NBPT and NPPT (N-(n-propyl) thiophosphoric triamide). Many studies from different regions (e.g., Schraml et al., 2016; Li et al., 2017; Silva et al., 2017; Cantarella et al., 2018) have shown that the UI available in the market can reduce NH_3 emissions from surface-applied urea fertilizer by 50–80 %. Therefore, adding UI to urea is an effective solution legally targeted by the revised German policy regulation.

Livestock slurry and manure, digestates, and mineral fertilizers are the primary sources of NH_3 emissions from agriculture (Amann et al., 2013). In the European Union, NH_3 emissions are approximately 80–90 % from livestock and digestates and 10–20 % from synthetic N fertilizers (Harrison and Webb, 2001; EEA, 2023). Hence, abatement measures for livestock housing and storage and the application of manure and digestates have been identified as having the most significant potential benefits (Cowell and ApSimon, 1998). The DüV_amended measures (DüV, 2017, 2020) have been based on cost-effective, practical, and widely applicable abatements for NH_3 emissions (Table 1). Furthermore, reductions of NH_3 emissions are possible in the whole manure management chain, including feeding, housing, manure storage, and manure application (Sajeev et al., 2018). Feeding reduced amounts of N directly reduces the emissions in the whole management chain; emission reduction technologies in housing and manure storage address the emissions in one step of the management chain, while transferring a greater amount of N to the next step in the chain. DüV implementation focuses on reducing emissions during and after spreading livestock manure and digestates (Table 1). For feeding, housing, and storage, the recent German air pollution control regulation, "Technical Instructions on Air Quality Control (TA-Luft)," enforces abatement measures such as air purifiers in large poultry and pig housings, covered storage of slurry and digestate storages of large farms, as well as N reduction feeding for pigs and poultry (Table 1).

Although the agricultural NH_3 inventory in Germany annually reports the emissions from livestock husbandry (housing, storage of livestock manure and digestates) and soils (application of manure and digestates and synthetic N fertilizers; grazing), there is little research on a comprehensive analysis of the impact of the DüV_amended in Germany. The potential of 40 measures to reduce NH_3 emissions from agriculture was analyzed by the German Environment Agency (Häußermann et al., 2019). Some of these measures were implemented in the DüV_amended and TA-Luft, while others were not but may become relevant if it becomes apparent that the NEC targets will not be achieved. Our study aimed to evaluate the absolute NH_3 reduction achieved after implementing regulations that affect NH_3 emissions. We analyzed the impact of the DüV_amended on NH_3 mitigation from livestock manure and digestates from energy crops and synthetic N fertilizers. Effects of TA-Luft on NH_3 emissions from livestock housing and the storage of manure and digestates were considered, and we discussed future NH_3 mitigation measures for complying with the NEC's NH_3 reduction target by 2030. In addition, knowledge of national policies tackling NH_3 emissions from livestock slurry and manure, digestates, and synthetic N fertilizers is particularly interesting to other countries. In particular, Germany is the first country to enforce UI implementation for urea fertilizer to the NH_3 emission abatement in the EU and worldwide. The results of the German NH_3 abatement strategy for synthetic N fertilizers may further help reduce NH_3 emissions worldwide, especially for countries consuming large amounts of urea fertilizers.

2. Materials and methods

2.1. Data collection

The methods in this study dealt with data collection and calculating agricultural NH_3 emissions in Germany. Data in Germany from 2005 to 2022, including the annual consumption of major synthetic N fertilizers, annual N input rate (kg N ha^{-1}), and major crop yield (t ha^{-1}), were collected from the database of the national NH_3 and GHG inventory (Thünen Institute, 2024). The fertilizer N input rates and crop yields in the national inventories are taken from the National Statistical Office (destatis). Details on the methodology of the NH_3 and GHG emission inventories were described by Rösemann et al. (2023). For the years 2020–2022, data on urea consumption in German agriculture were confidential. However, the statistical office provided information on the sum of urea-N plus UAN-N (urea ammonium nitrate) sold. We estimated the amounts of urea-N and UAN-N as follows for 2020–2022: it was assumed that the proportions of urea-N and UAN-N were the same as in the year 2019 (65 % urea-N, 35 % UAN-N). It was also unknown which proportion of urea was sold with UIs and which proportion was without UI. According to the expert estimate in the German national emission inventory, it was assumed that 75 % of the urea contained UIs and 25 % did not contain UIs, and, therefore, was incorporated into the soil (Thünen Institute, 2024). For the urea with UIs, the NH_3 emission factor was reduced by 70 % and for urea incorporated mechanically into the soil, the NH_3 emission factor was reduced by 60 % (Rösemann et al., 2023). Estimations of NH_3 emissions induced by N fertilizers are associated with considerable uncertainty. The main uncertainty of NH_3 emission estimations lies in the generalization of emission factors according to EMEP/EEA guidebook (EEA, 2023). The emission factor uncertainty in the German emission inventory is around 50 % for all types of synthetic nitrogen fertilizers (Thünen Institute, 2024).

The price of urea, urea with UIs (e.g., NBPT, 2-NPT, or mixture of NBPT and NPPT), and calcium ammonium nitrate (CAN) (2005–2023) (€ kg^{-1} N) in North Germany was from LWK Niedersachsen - Sachgebiet

Markt (2024).

2.2. Estimation of NH_3 emissions from different types of synthetic N fertilizers

The major synthetic N fertilizers currently being used in Germany are CAN, urea, N solutions (urea + ammonium nitrate) (UAN), NP- (N + Phosphorus) or NPK- (NP + Potassium) based compound or mixture fertilizers, and NK compounds or mixtures and other straight N. The calculation for ammonia emissions from different synthetic N fertilizers was based on the annual N consumption and the emission factors (EFs) proposed by the European Environment Agency (EEA) (2023):

$$NH_3 \text{ emissions } \left(\text{kt } NH_3 \text{ y}^{-1}\right) = \text{EF } (\text{g } NH_3 \text{ kg N applied}) \times \text{N consumption } \left(\text{t N y}^{-1}\right) \times 10^{-9}.$$

Under the national inventory, the emission factors for a cool climate and a pH value lower than 7 were chosen based on German common climatic and soil conditions. From the year 2020 onwards, the emission factor for urea was reduced by 70 % when it was used with a UI (Bittman et al., 2014) and 60 % when it was incorporated quickly (Rösemann et al., 2023), since DüV_amended (Table 1) made it mandatory to either incorporate urea immediately or apply it with a urease inhibitor (UI) in Germany starting from the year 2020.

2.3. NH_3 emission scenarios for livestock manure and digestates from energy plants

The NH_3 emissions from livestock were calculated as described in the Wiki of the German agricultural GHG and air pollutant inventory (Rösemann et al., 2023). The N flow through the agricultural system was followed by N-intake by the livestock, N-excretion, emissions in the livestock housings and manure storages, and emissions from spreading the livestock manures. NH_3 emissions were calculated based on the available ammoniacal N applied with manure (TAN) in each step of the N-flow chain. Livestock numbers, livestock performance, and typical feed components determine the N intake of livestock.

Average NH_3 emissions per kg N (for the mixture of synthetic N fertilizers applied) and per kg TAN were calculated to show specific changes per unit N applied. Energy crops are usually digested along with livestock manures. The emission calculations were done separately for the digestion of manure and energy crops so that emissions could be reported separately. The amounts of N contained in the energy crops fed into the digester are needed as times series, calculated from the amounts of substrates used for digestion following the estimation by KTBL (2021) for the most important energy crops.

Three different emission scenarios were calculated using the agricultural emission inventory model Py-GAS-EM to quantify the effects of some DüV regulations on the NH_3 emissions:

1. Effects of liquid manures applied only by band application on the soil surface in cultivated croplands: To test the effect of this measure, the spreading emissions with spreading techniques were compared to those before DüV amended, in which the proportion of broadcasting on cultivated cropland was set to 0. The proportions of this spreading technique were added to those of trailing hose on cropland. All other variables (e.g., livestock numbers and livestock performance) were kept constant.
2. Effects of the ban on spreading liquid manures via broadcasting on grasslands from 2025 onwards: the spreading emissions with spreading techniques as used after DüV amended were compared to spreading emissions when the proportion of broadcasting on grasslands was set to 0. The proportions of this spreading technique were added to the proportions of trailing shoes on grassland. All other variables (e.g., livestock numbers and livestock performance) were kept constant.
3. Additional effect of the reduced incorporation time for slurry, digestates, and poultry manure from 2025 onwards: The spreading techniques used in the second scenario were compared to a scenario in which the incorporation times of slurry, digestates, and poultry manure on uncultivated croplands was reduced to a maximum of one hour. This is mandatory from 2025 onwards.

3. Results

Annual NH_3 emissions in Germany between 2005 and 2021 are presented in Fig. 1. Between 2005 and 2021, total NH_3 emissions reached a maximum in 2014 and then slightly decreased until 2016, while a sharp decrease was found between 2016 and 2021. Compared to 2005, total NH_3 emissions in 2021, including agriculture and other sources, were reduced by 15.5 %. The NH_3 emissions from the agricultural sector significantly contributed to the total emissions, accounting for around 95 %. The pattern of NH_3 emissions from agriculture was similar to the total emissions in Germany between 2005 and 2021. Compared to 2005, the NH_3 emissions from agriculture in 2021 were reduced by 13.6 %, i.e., slightly less than those from other sectors. Furthermore, the reduction of NH_3 emissions in agriculture from 2014 to 2021 was approximately 126 kt NH_3, which accounted for about 20.7 % of the maximum in 2014.

The NH_3 emissions in the agricultural sector include those from synthetic N fertilizers and livestock manure and digestates produced from energy crops. Compared to the emissions from livestock manure and digestates, the NH_3 emissions from synthetic N fertilizers accounted for 7–16 % of those in agriculture (Fig. 1). Fig. 1 also shows that the maximum NH_3 emissions from synthetic N fertilizer were around 99.7 kt NH_3 in 2016. A rapid reduction in NH_3 emissions from synthetic N fertilizers was found from 2016 to 2021, accounting for 65 % of the maximum emissions from synthetic N and contributing about 55 % to the reduction from the agricultural sector during the same period. In contrast, a reduction in NH_3 emissions from livestock manure between 2016 and 2021 accounted for 10 % of their maximum emissions in 2015. It contributed about 45 % to the decrease from the agricultural sector during the same period.

Fig. 2 presents NH_3 emissions from the management chain (application and (housing + storage)) of livestock slurry and manure and digestates from energy crops in Germany between 2005 and 2021. Annual NH_3 emissions from all livestock and digestates ranged from 167 to 198 kt NH_3 year^{-1} from the application and 208–243 kt NH_3 year^{-1} from (livestock housing + the storage of livestock manure and digestates from energy crops). Annual NH_3 emissions (average over 2005–2021) from (livestock housing and the storage of livestock manure and digestates) were around 25 % higher than from the application. Compared to 2005, annual NH_3 emissions in 2021 were reduced by 14 % from (livestock housing and the storage of livestock manure and digestates) and 15 % from application, respectively.

Among the livestock and digestates from energy crops, the NH_3 emissions from their application were highest from dairy cattle, other cattle, and digestates, while those from (housing+storage) were highest from pigs, dairy cattle, and other cattle. Compared to 2005, annual NH_3 emissions from the application of livestock manure and digestates in 2021 were reduced by 14 % from dairy cattle, 21 % from other cattle, 24

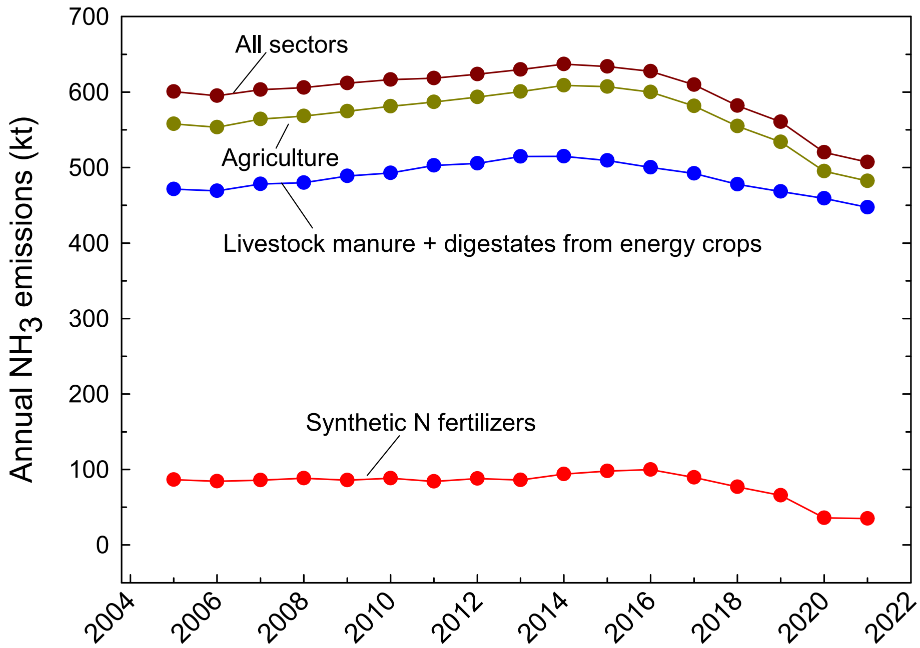

Fig. 1. Annual NH_3 emissions in Germany between 2005 and 2021 from different sources.

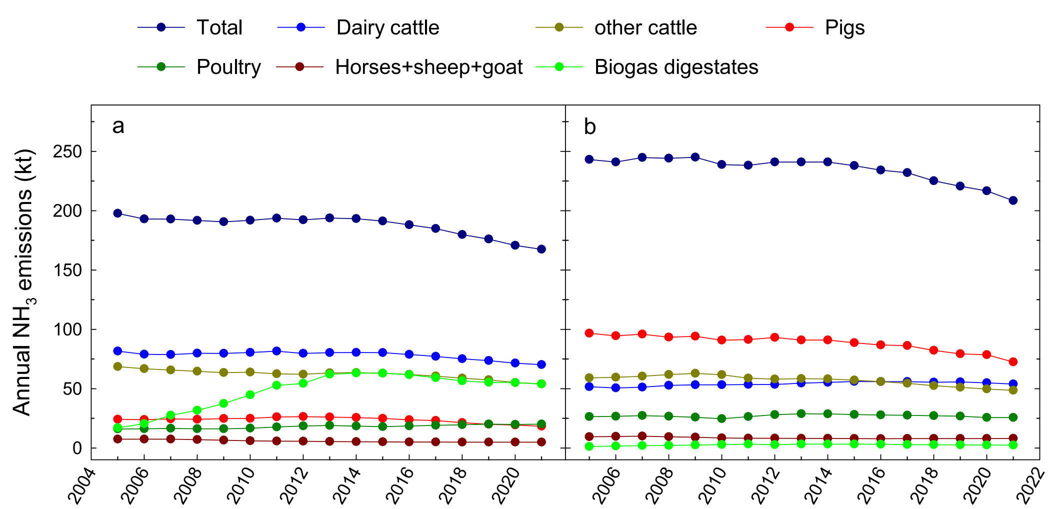

Fig. 2. NH_3 emissions from the application of livestock manure and digestates of energy crops (a) and from livestock housing and manure storage and the digestion of energy crops and digestate storage (b) between 2005 and 2021.

% from pigs, and 33 % from (horses+sheep+goat), respectively. In contrast, these were increased by 25 % from poultry and doubled from digestates of energy crops, respectively. Compared to 2005, annual NH_3 emissions from (livestock housing + the storage of livestock manure and digestates) in 2021 were reduced by 18 % from other cattle, 25 % from pigs, 2.7 % from poultry, and 15 % from (horses+sheep+goat), respectively. In contrast, these in 2021 were increased by 4 % from dairy cattle compared to 2005 and 23 % from digestates compared to 2009, respectively. Furthermore, Fig. 2 shows a significant increase in NH_3 emissions from digestates from 2005 to 2013.

Changes in NH_3 emissions from manure application (Fig. 2) are related to the amount of manure applied and/or improved application techniques. Fig. 3 shows the total ammoniacal N (TAN) and NH_3 EF (kg NH_3-N emission kg^{-1} TAN) from manure application in arable crops and grassland, arable crops alone and grassland alone between 2005 and 2022. After the early 2010s, the amounts of manure spread in croplands declined, while more was applied on grasslands (Fig. 3a). Generally, the EF declined over time, especially after the early 2010s due to the better-spreading techniques applied (Fig. 3b).

Fig. 4 shows the changes in the number of dairy cattle, other cattle, pigs, poultry, and (horses+sheep+goat) from 2005 to 2021. Compared to 2005, the number of livestock in 2021 was reduced by 9.5 % from dairy cattle, 18 % from other cattle, 13 % from pigs, and 27 % from (horses+sheep+goat), respectively; the poultry number increased from 2005 to 2013 and then remained almost unchanged.

Fig. 5 shows that NH_3 emissions from urea increased from 2005 to 2015 and rapidly decreased from 2016 to 2022, similar to the trends of the emissions from all synthetic N fertilizers with time. Among the synthetic fertilizers, urea accounted for 52–67 % of the total NH_3 emissions from synthetic N between 2005 and 2019 and around 31 % between 2020 and 2022. NH_3 reduction from urea accounted for 63 % of the total emission reduction from synthetic N fertilizers between 2005 and 2022. The emissions from UAN decreased slowly from 2005 to 2022, ranging from 23.1 to 10.3 kt NH_3 and accounting for 27–33 % of those from synthetic N. Emissions from other synthetic fertilizers (other straight N plus N compounds) decreased with time as well, accounting

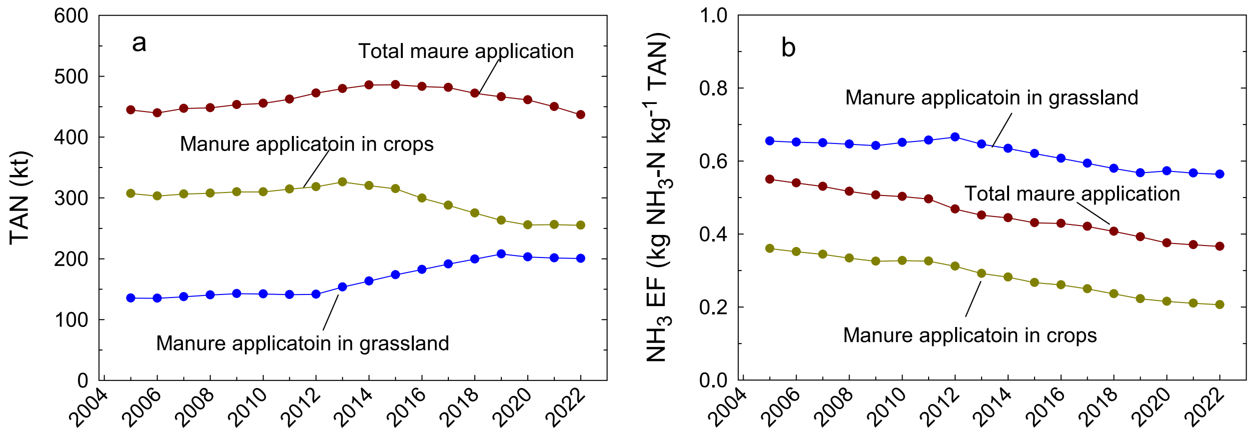

Fig. 3. The total ammoniacal N (TAN) applied (a) and NH_3 emission factor (EF) (b) for manure application in arable crops, grassland, and for total agricultural land between 2005 and 2022.

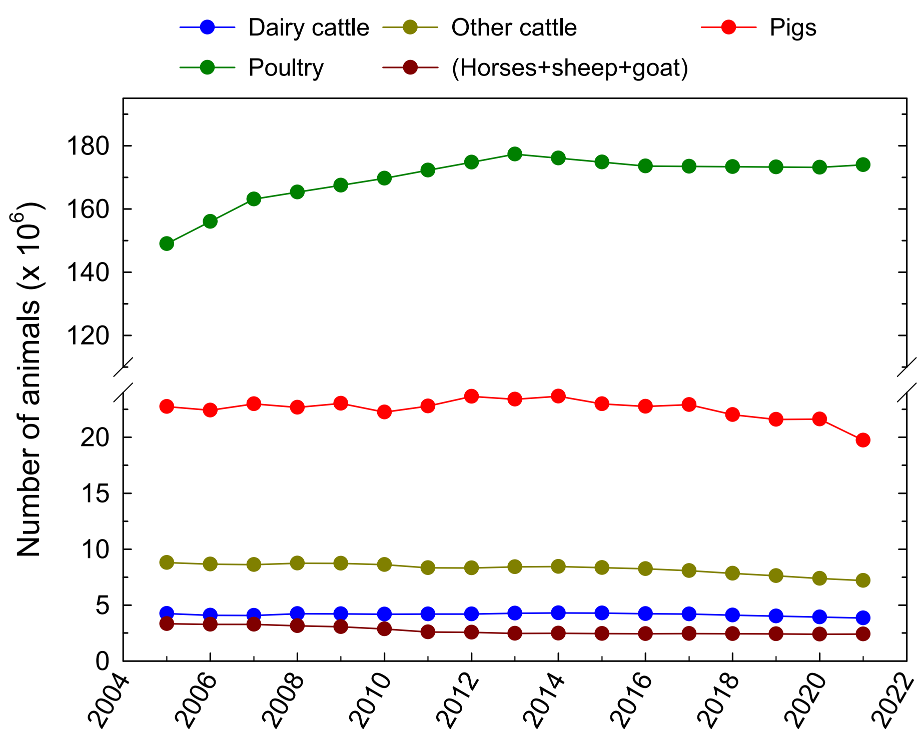

Fig. 4. The number of dairy cattle, other cattle, pigs, poultry, and (horses-sheep+goat) between 2005 and 2021.

for about 14–23 % of those from synthetic N over 17 years.

Fig. 6 shows the changes in annual consumption of different synthetic N fertilizers over time. The annual consumption of all synthetic N fertilizers tended to decrease from 2005 to 2008, and then be stable from 2008 to 2016. A rapid decrease was observed from 2016 to 2022. Compared to 2005, the annual consumption of synthetic N in 2022 decreased by 36 %. CAN is a major synthetic N fertilizer in Germany, accounting for 38–46 % of total synthetic N applied over the last 17 years. The annual CAN consumption decreased from 2005 to 2022, ranging from 824 to 441 kt N y^{-1}. In contrast to CAN, urea increased by 49 % from 2005 to 2016 and decreased by 55 % from 2016 to 2022. Annual urea-N consumption accounted for about 16 % over time, while UAN and N compounds accounted for 9–13 % and 7–10 %, respectively.

Based on the data presented in Figs. 5 and 6 we calculated the mean NH_3-N loss per kg synthetic N applied for the mixture of synthetic fertilizers. The mean NH_3-N loss kg^{-1} N applied was 4.0 % in 2005; it increased to 4.7 % in 2016 and then rapidly dropped to 2.3 % in 2020.

The price of urea (2005–2019), (urea+UI) (2020−2023), and CAN (€ kg^{-1} N) (2005–2023) in Lower Saxony of Germany is presented in Fig. 7. The price varied over time. The two highest peaks were found in 2008 and 2022. The lowest price was found in 2016 for urea and between 2016 and 2021 for CAN. The unit N price of CAN (mean values) was 26 % more than urea alone from 2005 to 2019) and 25 % more than (urea+UI) from 2020 to 2023.

Fig. 8 shows the mean annual N input rate per ha over time for synthetic fertilizers, livestock manure, digestates from energy crops, and the resulting total N input. After increasing between 2008 and 2016 (strongly influenced by increasing application of digestates produced from energy crops), total N inputs clearly decreased since 2016 (mainly due to decreasing application of synthetic N fertilizers). It sharply reduced by around 20 % from 2016 to 2021. The maximum N input rate in 2015 and 2016 was about 204 kg N ha^{-1}, whereas the minimum N rate was 164 kg N ha^{-1} in 2022. Synthetic N input rate accounted for 51–60 % of the total between 2005 and 2018 and $<$ 50 % starting from

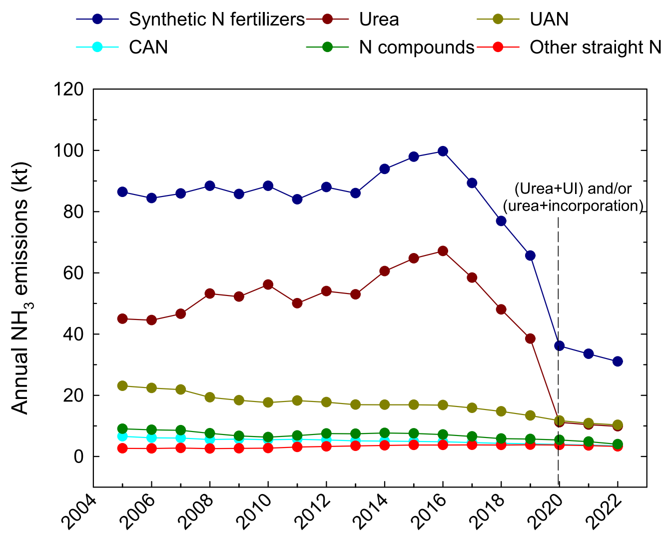

Fig. 5. Annual NH_3 emissions from synthetic N fertilizers in Germany between 2005 and 2022. DüV_amended made it mandatory for urea to be incorporated immediately or add UIs after 2020. NH_3 emissions from synthetic N fertilizers were calculated based on their annual consumption and emission factors.

2019, i.e., the first time below the N input rate of livestock manure plus digestates from energy crops. The N input with manure and digestates increased from 2005 to 2015 and remained almost unchanged after 2017.

Fig. 9 shows the yield of major crops over time. Over the last few years, grain maize, winter wheat, and potato yields remained almost unchanged, while winter barley and sugar beet yields have increased with time (Fig. 9).

4. Discussion

4.1. Impact of the DüV_amended on NH_3 abatement

Agriculture accounted for around 95 % of all NH_3 emissions over the last decades (Fig. 1). A sharp decrease in emissions between 2016 and 2021 (Fig. 1) coincided with the German DüV_amended, indicating that the new regulations of the improved fertilizer ordinance strongly influenced this emission reduction. To comply with the NEC emission reduction targets, the DüV_amended contains rules aiming directly at reducing NH_3 emissions (e.g., the application of urea and manure) and rules with indirect effects on NH_3 emissions by reducing N surplus and improving N use efficiency (e.g., more precise fertilization planning reducing N surplus and improving nitrogen use efficiency). In addition to the impact of policy or regulation, factors such as crop systems and management, climatic conditions, target crop yields, and prices of fertilizers and crops can influence fertilization and associated NH_3 emissions as well. For example, dry conditions in 2017 and the increase in fertilizer prices or changes in price differences between fertilizer types

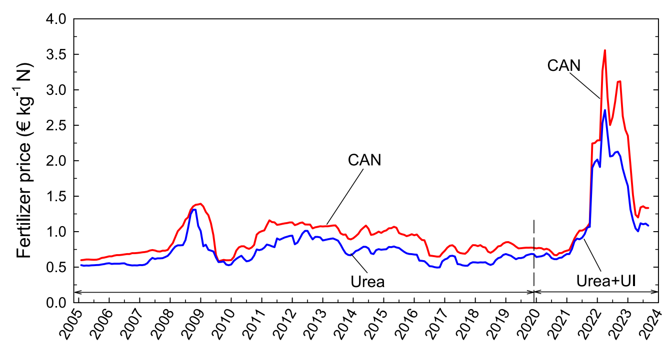

Fig. 7. The price of urea (Jan. 2005 - Nov. 2019), (urea+UIs) (Dec. 2020 - Nov. 2023), and calcium ammonium nitrate (CAN) (2005–2023) (€ kg^{-1} N) in Lower Saxony of Germany (data from LWK Niedersachsen - Sachgebiet Markt (2024)).

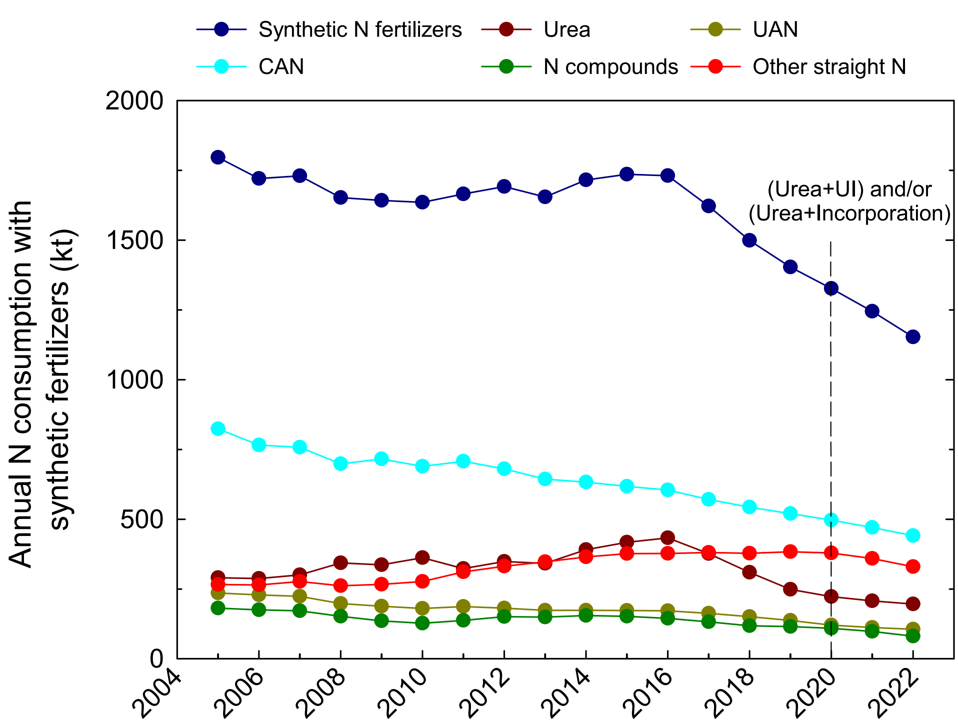

Fig. 6. Annual consumption of synthetic N fertilizers in Germany between 2005 and 2022. DüV_amended made it mandatory for urea to be incorporated immediately or add UIs after 2020.

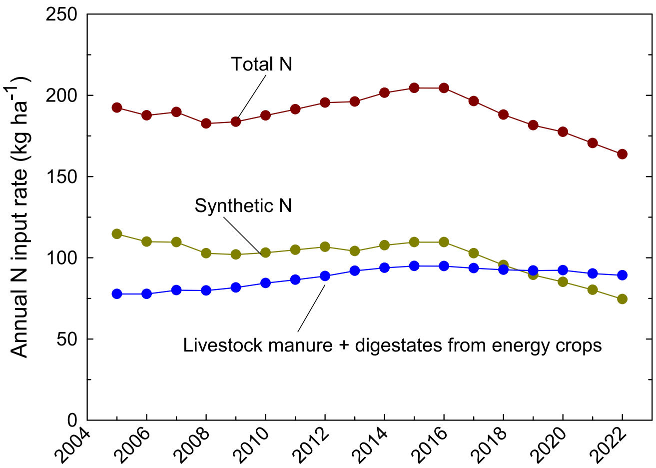

Fig. 8. Mean annual N input rate (kg N ha^{-1}) with synthetic N fertilizers and livestock manure plus digestates from energy crops in Germany between 2005 and 2022.

might have also contributed to the decline in the quantities of synthetic fertilizer consumption and related NH_3 emissions.

Interestingly, although the NH_3 emissions from synthetic N fertilizers accounted only for 7–16 % of those in agriculture, the reduction in NH_3 emissions from synthetic N fertilizers between 2016 and 2022 contributed about 51 % to the decrease from the agricultural sector over the same period. More importantly, among the synthetic fertilizers, NH_3 reduction from urea between 2016 and 2022 accounted for around 83 % of the total reduction from synthetic N, indicating that the mitigation strategies for NH_3 emissions from urea fertilizer played a crucial role in the sharp decrease in NH_3 emissions over the last years in Germany. NH_3 emissions from synthetic N fertilizers are associated with the annual consumption and emission factor under a given condition. Annual urea-N application ranking at the 2nd or 3rd position among all synthetic N fertilizers at the start of the time series. It accounted for about 16 % of the total annual consumption of synthetic N fertilizers (Fig. 6). Fig. 6 shows that although urea increased by 49 % from 2005 to 2016, it decreased by 55 % from 2016 to 2022. The emission factor was highest among other synthetic N fertilizers since urea can easily lead to NH_3 volatilization due to rapid hydrolysis by urease in soil. The reduction of the emission factor was based on the guidance document of the UNECE Task Force on reactive nitrogen (Bittman et al., 2014), which estimated the NH_3 reduction by UIs to be 70 % for solid urea fertilizers. From 2020, the emission factor for urea was reduced by 70 % when used with a UI, i.e., from 0.155 to 0.0465 kg NH_3 (kg N applied)$^{-1}$, since it is mandatory to either incorporate urea immediately or apply it with a urease inhibitor in Germany starting from 2020. However, incorporating UI into urea fertilizers may increase farmers' costs. According to DEFRA (2020) and DüV (2020) with industry sources, the addition of UIs to urea accounts for 10 % of the urea unit price, i.e., ca.0.08 € kg^{-1} urea-N in 2017 or 2018 (Hu and Schmidhalter, 2021). CAN fertilizers with low EF values (e.g., 0.008 g NH_3 per kg N applied) in temperate climate zones and at normal pH compared to 0.159 for urea alone, which have been suggested to replace urea, are more expensive than urea and (urea+UI) fertilizers (Hu and Schmidhalter, 2021, 2024). However, the unit N price of CAN (mean values) was 26 % higher than urea alone between 2005 and 2019 and 25 % higher than (urea+UI) from 2020 to 2023 (Fig. 7).

Fertilizers resulting from livestock husbandry and conversion of organic materials, such as livestock manure, digestates from energy crops, composted waste, and sewage sludge, are responsible for >80 % of the NH_3 emissions in agriculture (Fig. 1), even for up to 93 % in 2021. For housing and storage, the recent German air pollution control regulation, "Technical Instructions on Air Quality Control (TA-Luft)," enforces abatement measures such as air purifiers in large poultry and pig housings, covered storage of slurry and digestate storages of large farms (Table 1). Fig. 2 shows that, compared to 2005, annual NH_3 emissions in 2021 were reduced by 15 % from the application of livestock manure and digestates. The DüV_amended measures have been based on practical and widely applicable abatements for NH_3 emissions. The NH_3 emissions from managing the application of manure and digestate in the field are related to wind, air temperature, area of manure, and duration exposed to atmosphere, which are the keys for managing the manure application. Thus, Germany's low-emission application of slurry and digestates has been mandatory in arable farming since 2020 and is further required in grassland from 2025 (Table 1). DüV_amended enforces manure and digestate application using band application starting in 2020, which means an application in which at least 50 % of the area is without manure or digestates, and the band width with manure is a maximum of 25 cm. Incorporation should be as close to the soil as possible or into the soil. The most effective band application approach is to use the injection technique (Huf et al., 2023). The uncertainties of calculated NH3 emissions were 36–41 % for application of animal manure depending on animal category (Thünen Institute, 2024). The application techniques and management highly impact the amount of NH_3 volatilization (Rösemann et al., 2023; Webb et al., 2010). Wulf et al. (2017) reported that low-emission applications would cover almost 60 % of the total technical NH_3 abatement potential in German agriculture (Wulf et al., 2017). Under DüV_amended (Table 1), broadcast spreaders are banned for their application in crops. Only techniques ensuring the band application or directly on or in the soil, such as drag shoe or injection, are compulsory on arable land in 2020 and grassland in 2025.

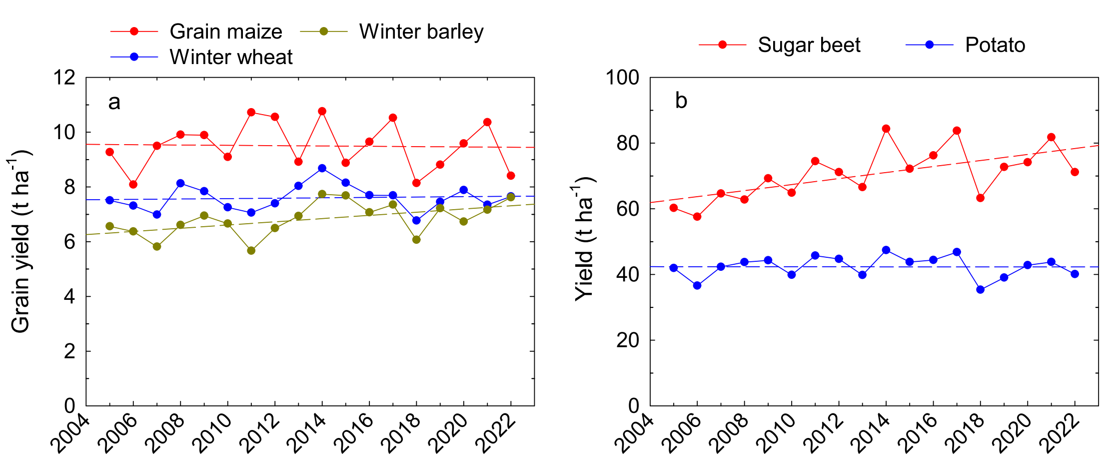

Fig. 9. Yield of major field crops (grain maize, winter wheat, winter barley, rape, silage maize) (a) and (sugar beet, potato) (b) (t ha^{-1}) in Germany between 2005 and 2022.

NH_3 emissions from manure application are associated with the amount of manure applied and/or improved application techniques. Fig. 3b shows the positive effects of DüV_amended related to application techniques on the EF for manure spreading in cropland and grassland. The scenario calculations aimed at quantifying the impact of single measures of the DüV_amended show clear emission reductions due to the changes in spreading techniques. The results of the first scenario calculation (liquid manures applied only by band application close to the soil on cultivated croplands) show that the NH_3 emission factors for manure spreading in the "no broadcasting on cultivated croplands-scenario" were 4.7 % lower compared to the scenario in which broadcasting on cultivated croplands was allowed. For the second scenario, concerning manure application on grassland, the NH_3 emission factors for manure spreading in the "no broadcasting of liquid manures on grasslands-scenario" were 12.4 % (equal to about 21 kt NH_3 calculated for 2020) lower than those in the scenario were broadcasting of liquid manures on grasslands was allowed.

NH_3 emissions from livestock housing and the storage of livestock manure and digestates were around 25 % higher than from the application of livestock manure and digestates (Fig. 2). According to TA-Luft, there are requirements for the new construction of large housing facilities for pigs and poultry only with NH_3 exhaust air purification (70 % reduction in emissions) starting from 2021; for medium-sized housings, emission reduction has to be at least 40 %. These measures are essential, will have an impact in the longer term as they affect new livestock housing systems. For the 2030 reduction target, reducing emissions from existing housings and manure storage systems is essential. Using NH_3 reduction techniques such as protein-optimized feeding, covering outdoor slurry tanks, and a more precise automated cleaning of barn floors may help to reduce emissions from existing systems. It has to be taken into account that the requirements of housing systems are increasing in terms of livestock welfare. The barn area per livestock will increase, especially when open-air areas are integrated for pigs and poultry. These livestock welfare measures restrict the effectiveness and implementation of air purification systems. Livestock welfare and air pollution control requirements must be planned and implemented together. Accordingly, the research work and politics are called upon to develop and implement NH_3 mitigation concepts for livestock welfare housing.

To reach the NEC's reduction target by 2030 (i.e., −29 % compared to 2005), the annual NH_3 emissions are not allowed to exceed 445 kt in 2030 (IIR, 2024), i.e., the required further reduction must be at least around 11 % relative to the levels in 2005 (equal to about 67 kt NH_3, based on the reporting in 2024) since the annual NH_3 emissions in Germany already decreased about 18 % in 2022 compared to 2005. Among the synthetic N fertilizers, there may still be a potential to reduce the NH_3 emissions from UAN fertilizer. Given the success of making UIs mandatory with urea, they should also be used with urea/AN mixtures.

However, even if this measure is implemented, there will be only a relatively small contribution of the NH_3 emission abatements from synthetic N fertilizers in the following years (Figs. 1 and 5), and future mitigation measures have to focus mainly on lowering NH_3 emissions from livestock manure. Starting in 2025, DüV_amended will force the band application or injection of slurry and digestates to grassland (2025). This will reduce NH_3 emissions from grassland by about 21 kt (assuming data of 2022); Incorporation of slurry, digestates, and poultry manure on uncultivated arable land within 1 h (2025) (Table 1) will contribute around 6 kt reduction additionally. As described above, there are still considerable challenges in reducing emissions from existing housing and manure storage systems. Some of the measures described (Table 1) are not very specific, and there are many exceptions (e.g., for smaller farms) and unclear restrictions (e.g., the reliability of the measure). In addition, there is the described challenge to combine livestock welfare and NH_3 mitigation. This makes it all the more important to take a regular critical look at the development of emissions to be able to adjust regulations.

The NH_3 reduction target for 2030 in Germany appears to be feasible with a strict implementation of measures listed in Table 1. However, some measures must be concreted, and specific measures for open livestock welfare housing should be added. In contrast, Häußermann et al. (2019) even suggested that the targets for 2030 can be achieved without costly measures, such as the further expansion of exhaust air purification and far-reaching cuts in the agricultural sector, such as the reduction in livestock numbers. However, efforts to keep the air clean will not end in 2030. Ultimately, there are two major levers for reducing ammonia emissions from agriculture: implementing all management and technical options to reduce emissions and/or reducing livestock numbers.

4.2. *DüV's fertilization planning and optimized N input*

Figs. 8 and 9 show that, in contrast to the decrease in mean N input rate (kg N ha^{-1}) over the last years (e.g., by ca. 20 % between 2016 and 2022), the yield of major crops in Germany either increased or remained unchanged, indicating an increase in agronomic N use efficiency (kg yield per kg N input). The results in Fig. 8 also demonstrated that the decrease in the N rate was mainly due to the reduction in synthetic N input from 2016 to 2022. Generally, policy or regulation associated with N emissions or loss may bring trade-offs such as reducing crop yield, increasing farmers' costs, and affecting food security. Achieving a high yield by reducing the N rate in this study strongly suggests that optimal reduction in N rate does not necessarily result in yield losses but rather in a pivotal relationship between the agronomic and environmental performance and indicates that the DüV_amended was an effective measure that can reduce the NH_3 emissions.

Over the last few years, DüV_amended has forced farmers to make better decisions about fertilization by considering fertilization planning. Although the German action program has never included total nutrient application thresholds for mineral and organic fertilizer as the implementation of the Directive in the Netherlands or Denmark (Schröder and Neeteson, 2008; Kronvang et al., 2008), the DüV_amended introduces a compulsory and clearly defined fertilizer planning. Estimation of N demand for different crops is based on their target yields. The target yield derives from the average yield over the last three years. The allowed synthetic N fertilizer application is determined by considering mineral N from the soil and the mineral fertilizer equivalents (MFE) from organic fertilizers. Organic N sources, including livestock manure and digestates, are central to fertilizer planning. Although synthetic fertilizers can be replaced with organic fertilizers (Gutser et al., 2005), the N use efficiency decreases with higher proportions of organic N, while the risk of NO_3- leaching rises (Osterburg and Techen, 2012; Gutser et al., 2010). Thus, DüV_amended defined the N application limit: the N application of manure up to 170 kg ha^{-1}, and DüV_amended further extended this limit, including digestates from energy crops (Table 1). DüV_amended especially requires nitrate-polluted areas (about 20 % of the total cropland) to reduce the N fertilization by 20 % and no N fertilizer application in autumn starting from 2020 (Table 1). Consequently, this will reduce NH_3 emissions depending on the fertilizer types applied. However, there is a controversial discussion of whether and to what extent this regulation will reduce crop yield and yield quality. In addition, fertilization planning forced farmers to optimize N input by considering better management technologies, such as precision N management using sensing technology and better fertilizer spreader equipment.

5. Conclusions

To implement the NEC Directive 2016/2284/EU for NH_3 emission targets in 2030, Germany amended the Fertilizer Application Ordinance in 2017 and 2020 and set the air pollution control regulation. Enforcing UI incorporated for urea by DüV_amended can reduce NH_3 emissions by around 70 %. Germany is the first country to set UI implementation for urea in the EU and even worldwide. Urea, which accounts for >50 % of the synthetic N fertilizers worldwide, is a primary contributor to NH_3 emissions; thus, such regulation will inspire other countries, and be essential for the global NH_3 emission abatements. Current agricultural NH_3 emissions from Germany's livestock manure and digestates management chains still account for >80 % of the total from agriculture. The DüV_amended enforces band or injection application of manure and digestates to cropland and grassland as measures for NH_3 emission abatement. The German TA-Luft further sets measures such as air purifiers in large poultry and pig housings (ca. 70 % NH_3 reduction) starting in 2021 and new storage systems of slurry and digestate storages in large farms (ca. 90 % NH_3 reduction) starting in 2029. However, specific mitigation options for livestock welfare housing still need to be tested. We further suggest that the effects of regulations on emission reduction progress should be assessed at the national scale. Germany has already reached the first national NH3 reduction target in 2020, as set by the NEC directive, and will meet the NH_3 reduction target in 2030 by implementing NH_3 abatement measures from DüV and TA_Luft.

CRediT authorship contribution statement

Yuncai Hu: Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Conceptualization. **Heinz Flessa:** Writing – review & editing, Visualization, Validation, Formal analysis, Conceptualization. **Cora Vos:** Writing – review & editing, Validation, Investigation, Data curation, Conceptualization, Formal analysis, Methodology. **Roland Fuß:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **Urs Schmidhalter:** Writing – review & editing, Validation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors are unable or have chosen not to specify which data has been used.

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