Strategies to reduce ammonia emissions from livestock and their cost-benefit analysis: A case study of Sheyang county

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Highlights:

- Huge gaps exist between laboratory/pilot-scale studies and on-farm implementation.
- Government support and subsidies are major factors in encouraging technology use.
- Traditional livestock farms will remain as key sources of future emissions.
- Integrating crop and livestock system is central to efficient manure utilization.

Abstract

Ammonia (NH_3) emissions, the majority of which arise from livestock production, are linked to high concentration of $PM_{2.5}$ and lower air quality in China. NH_3 mitigation options were well studied at the small-scale (laboratory or pilot), however, they lack of a large-scale test in China. This study fills this crucial gap by evaluating the cost-benefit of pioneering NH_3 mitigation projects carried out for a whole county – Sheyang, Jiangsu province, China. Measures were implemented in 2019 following two distinct strategies, improved manure treatment for industrial livestock farms, and collection and central treatment for traditional livestock farms. Emission reductions of 16% were achieved in a short time. While this is remarkable, it falls short of expectations from small-scale studies. If measures were fully implemented according to purpose and meet expectations from the small scale, higher emission reductions of 42% would be possible. The cost benefit analysis presented in this study demonstrated advantages of central manure treatment over in-farm facilities. With improved implementation of mitigation

strategies in industrial livestock farms, traditional livestock farms may play an increasing role in total NH_3 emissions, which means such farms either need to be included in future NH_3 mitigation policies or gradually replaced by industrial livestock farms.

The study found an agricultural NH_3 reduction technology route suitable for China's national conditions (such as the "Sheyang Model").

Keywords: Ammonia emission; Mitigation technologies; NUFER model; Livestock manure; Cost-benefit

1. Introduction

Ammonia (NH_3) as the most basic alkaline gas in the atmosphere, triggers the formation of secondary inorganic aerosol and hence contributes to the formation of $PM_{2.5}$ (Huang et al., 2015; Lelieveld et al., 2015; Liu et al., 2020; Wu et al., 2016). China's annual NH_3 emissions are 12-15 million tons, the emission intensity is 4-5 times that of the European Union and the United States, and 90% comes from agricultural sources, with livestock accounting for more than half (Kong et al., 2019; Wang et al., 2018; Zhang et al., 2017). NH_3 emissions from agriculture mainly occur as a result of volatilization from livestock excreta, as the consequence of microbial decay of urea or mineralization of organic N compounds (Bouwman et al., 2013). Release may occur at different stages in the manure management chain: from livestock housing, manure storage, urine and dung deposition in grazed pastures, or following manure spreading on agricultural land.

Strategies for reducing NH_3 emissions have been demonstrated in a large number of scientific studies globally. Many small-scale (laboratory or pilot) studies throughout the livestock manure management chain demonstrate that a high rate of NH_3 mitigation is possible also under Chinese conditions (Burchill et al., 2019; Cao et al., 2019, 2020; Hou et al., 2015; Pereira et al., 2012; Sha et al., 2020; Ti et al., 2019). No analysis, however, is available on the effect of a large scale implementation of such technology, especially at regional or county scale. Understanding the actual mitigation potentials at the large scale is important, as national scale policies on manure treatment have been implemented at the county level in China. e.g., the program “Promote recycling of waste from livestock production" aims to increase the manure recycling rate above >90% in the 500 selected pioneer counties, through using new technologies and facilities. The county level NH_3 mitigation pioneer projects have been implemented in several counties, however quantitative analyses of the actual benefits and costs are lacking.

Velthof et al. (2009) introduced an assessment model applicable for all of Europe, based on extensive data on emission reduction measures in the Netherlands for each of the emitting stages. Winiwarter and Klimont (2011) coupled mitigation costs for NH_3 as well as other compounds with the respective emission reductions to derive cost-optimized approaches. As the European situation does not necessarily reflect practices in China, Zhang et al. (2016) quantified the potential and costs of mitigation measures for relevant Chinese situations, specifically for dairy cattle. Impacts of NH_3 emission reductions on atmospheric quality of the North China Plain have been modeled by Zhao et al. (2017).

Such studies still lack information about localized implementation rates, acceptance of new technologies as well as emission parameters. The need to extend from individual measures to integrative consideration of bundles of measures also has been described (Oenema et al., 2014). Hence, this study considered a county-wide approach, where emission reductions were quantified based on questionnaires and interviews with local stakeholders regarding practical aspects of implementation. Such interviews also allowed us to estimate relevant costs specifically for the situation of Sheyang county, Jiangsu province, China. The analysis not only allowed us to assess the emission reductions for the county, but also to obtain the cost effectiveness of mitigation measures. This study also aims to elucidate the economic viability of implementing abatement measures in similar situations, and hence discusses future pathways for NH_3 emission abatement from livestock production in China. Consideration of the overall effects of measures, including practicability of their implementation, may be relevant for any region globally attempting to limit ammonia release from agriculture.

2. Material and Methods

2.1 Study area and collection of data

Sheyang county is under the administration of Yancheng, Jiangsu Province, and borders the Yellow Sea coast. The total land area is 2.6×10^3 km^2 located in a typical maritime climate zone. This agriculturally dominated area is inhabited by 0.88 million permanent population. In this study, we collected detailed information about operating conditions and locations of industrial livestock farms – industrial farms were identified by size (Table S1). We also collected information from major traditional livestock farms in Sheyang county in 2012, 2018 and 2019 through government annual reports and in-situ survey. Collected data included livestock numbers as well as information on all aspects of manure management in livestock housing, manure storage, manure treatment and manure application. In this study, a total of 70 industrial farms and 113 traditional farms were investigated, the principle of farm research is: the number of industrial farms research is not less than 20%, and the number of traditional farms research is not less than 5%. See the Supplementary Information for detailed information about the surveys.

Sheyang is an ideal place to test NH_3 emission reduction strategies. Livestock production is an important element of agriculture, dominated by pigs and poultry (Table S2). Traditional farms have been supplemented with more modern industrial systems, with manure management of both contributing to NH_3 emissions. In 2018, the total stock number was 0.4 million head for pigs and 10 million head for poultry (SYY., 2019), respectively.

2.2 System boundary

In this study, we focus on the impact of NH_3 emission reduction technologies and strategies on the full chain of livestock manure management in Sheyang county. We used NUFER (NUtrient flows in Food chains, Environment and Resources) model which was developed to simulate N flows throughout the food chain (Ma et al., 2010). The NUFER model allows to simulate the mass flow of N in its compounds along the manure management chain. The spatial boundaries cover the Sheyang county. Within these boundaries, pigs, poultry, dairy cattle, sheep and goats are considered separately. At each stage (housing, storage, treatment, and application of manure), losses to atmosphere, as direct discharge or to the surface and ground water are subtracted and the remainder moved to the next stage of manure treatment. Loss factors differ by technology used or management practice. Activity data (animal numbers as well as management measure) are from farm survey data for each livestock farm. Manure excretion rates (in terms of nitrogen contents) and NH_3 emission factors are from NUFER model which considered more detailed manure management practice (Bai et al., 2016; Ma et al., 2010; Zhao et al., 2017). The major parameters of the ammonia emission factors are shown in Table 1.

2.3 Livestock production in Sheyang county

Sheyang has more than 2400 farms (both traditional livestock farms and industrial livestock farms). We use livestock units (LUs), to compare production, costs and environmental impacts between very different animal sizes (chicken to cattle). In this metric, industrial livestock farms accounted for 59% of animals in Sheyang. Livestock farms were unevenly distributed in Sheyang county, which is reflected by the large difference of livestock density between different towns (Fig. 1).

2.4 Two strategies for NH_3 mitigation

Sheyang county was selected as the demonstration county to carry out the whole county recycling of the wastes from livestock production. Sheyang county adopted a policy of combining government promotion and market operation to build and operate a town-level manure treatment center. There are 14 towns in Sheyang county in total. The manure treatment center was located in each town according to the local density of traditional farms and availability of land for construction of the treatment center (Fig.

S1). Different manure treatment centers were designed for different treatment capacity as livestock density differed between regions.

Starting from 2018, the county government issued a county-level emission reduction policy that required each farm to follow one out of two strategies: farms either had to transport manure to the town-level central treatment facilities, or they had to prove capacities to treat manure at their own site. For each of the 2439 farms studied, either strategy was chosen and mandated to the farm operators by the county government. At present, 14 town-level manure treatment centers were constructed, with the operation principle of 'government subsidizes the basic construction-enterprise while farms are responsible for the operation cost'. Due to the impact of African swine fever, it is difficult to install related facilities and perform related measurements on pig farms, as a pilot project, in-situ treatment facilities were installed in 35 poultry farms of different scales.

1) Strategy 1: Livestock manure 'Decentralized collection and centralized treatment' strategy (Fig. 2). Decentralized collection and centralized treatment has been defined as collection from each farm and treatment at the point of manure treatment center. The manure treatment center arranges vehicles to collect manure from each farmer who has signed the contract, according to their physical distance to the center and type of manure production. After transportation to the manure treatment center, manure is separated into a solid and a liquid fraction, and the solid part is composted by a compost reactor.

The remaining liquid is transferred to closed tank and treatment. The final products of both solid and liquid manure are sold as organic fertilizer at different prices. Due to the advanced operating conditions of storage and treatment in the manure treatment center, NH_3 emission can be reduced in all subsequent stages (except for the housing stage).

2) Strategy 2: A farm uses a set of advanced facilities to treat manure in situ. Emission reductions performed on the farm in principle may affect each of the stages. In total, four individual technologies were applied in Sheyang county (Fig. S2).

T1: NH_3 emission reduction technology of manure acidification in animal house. A liquid tank containing an aqueous solution of lactic acid (concentration 0.01 mol L^{-1}) is arranged outside of an animal house. An acid spraying pipe is fixed at the lower part of the animal house, and a spray head (nozzle) is installed on the pipe and operated via an automatic control system (Fig. S2). The pilot scale experiment is carried out in one of the commercial livestock farms (40,000 head of poultry farm) at the large operational scale, which is a different situation compared to previous small scale laboratory-type experiments. The acidic solution is sprayed to the surface of feces and urine at a rate of 250 g m^{-2}, three times each day at 8:00, 16:00 and 24:00. The manure surface acidification technology has a significant effect on reducing the NH_3 concentration in the animal house, and can achieve a 45-60% reduction in NH_3 emissions (Liu et al., 2019). This technology has the technical advantages of accurately controlling the amount of acid spraying and the interval of acid spraying to achieve technical automation; acidifying the surface of feces and urine allows minimizing acid content and costs while being highly universal, suitable for a variety of breeding types such as sheep, pigs, and chickens.

T2: NH_3 recovery in the exhaust air. This technology establishes an NH_3 recovery technology system outside of animal house. This technology combines the NH_3 emission reduction and NH_3-N recycling. It sprays aqueous solution of a weak acid to absorb the dust and NH_3, and operates as a washer of the exhaust air. The technology is able to collect NH_3 and degrade microorganisms, reduce dust, NH_3 and other odors in the exhaust air. This technology could also achieve emission standards for livestock and poultry houses, and recover ammonium salts for resource utilization. In the exhaust air, an acid atomizing spray system is used to achieve 80% reduction in NH_3 emissions through automated pH online control and a two-stage water curtain circulating system. This technology has been implemented at one of the medium poultry farms at in Sheyang county.

T3 and T4 (combined): Continuous-closed composting technology (T3) combined with NH_3 recovery technology (T4). The continuous-closed composting reactor combines the storage and treatment of manure, through the regulation of oxygen and temperature, in the use of a microbial metabolism to convert livestock manure into organic fertilizer (Liu et al., 2020; Wang et al., 2018). This can significantly reduce the N losses during storage and treatment in the existing system. The newly developed system collects the NH_3 emission in the exhaust gas generated in the process through a multi-stage circulating water/acid spray scrubbing system. The NH_3-N is trapped in the liquid phase and potentially can be used as liquid fertilizer. Compared with standard composting, the reactor composting technology mitigates the NH_3 emission by 54% (Liu et al., 2020). In addition, combined technology may further increase NH_3 mitigation rate to 82% (Liu et al., 2020). The emission factor and mitigation rate is derived from the large scale operational composting tank, (40 m^3) with a treatment capacity of 4.5 m^3 per day (Liu et al., 2020).

Different combinations of technologies were applied for different type of farms (Table S8). For example, all four technologies were applied for large poultry farms, however, only T2+T3+T4 combined technologies were used at the pig farm. The sheep farm adopted the T1+T3+T4 combined technology and dairy farm applied T3+T4 combined technology. In the town level manure treatment center, T3+T4 technology combination was used.

2.5 Cost-benefit estimation of different abatement options

The cost for the implementation of abatement options was divided into investment cost, fixed operation cost, and variable operation cost (Klimont and Winiwarter, 2011). The investment cost estimation for technical implementation was based on the price of the equipment and installation costs for the abatement options, considering the lifetime of the equipment. Estimation of the fixed operation cost was based on the cost of equipment at an annual rate of 4% of the total investment. The fixed operation cost reflected the cost of maintenance, insurance, and administrative overhead. Variable operation costs covered costs of labour, energy, and materials used for the abatement options, considering the usage amount and price of the materials.

As the investment cost varied with farm size and farm type, the calculation was based on the assumption that an in-situ farm had 40,000 head of laying hens, which is equipped with a full chain of NH_3 reduction management measures (Table S5). The manure treatment center would annually process 8,000 tons of manure, collected from poultry farms, pig farms, cattle farms and sheep farms (Table S4).

3. Results

3.1 NH_3 emission under different scenarios

We used the NUFER model to calculate NH_3 emission in Sheyang county in different situations: 1) 2012, without environmental protection policy control conditions; 2) 2018, with the manure discharge (directly into watercourses) abolished (SCPRC., 2015) but before manure management policy started; 3) 2019, manure management in place (30% of the manure was treated); 4) ideal situation, based on 2018 animal numbers assuming full implementation of NH_3 mitigation strategies (87% of the manure is treated). We noted that NH_3 emissions from the livestock manure chain were 8.1 kt NH_3 yr^{-1} in 2012, and increased by 8.6% to 8.8 kt NH_3 yr^{-1} in 2018 without significant changes of environmental management practices (Fig. 3a).

After the implementation of the manure recycling and NH_3 mitigation policy in 2018, we found the direct effect was not as obvious as that achieved in the small-scale studies. The direct NH_3 emission decreased by 16% between 2018 and 2019. The smaller actual mitigation rate in 2019 mainly was due to: 1) only 4 of the 14 (about 29%) manure treatment centers were under regular operation, 2) only 9 of 35 in-situ poultry farms have operated continuous-closed composting reactors. 3) <30% of the manure was transported to the manure treatment centers, and most of the remaining manure was directly returned to the field.

By analysing the situation of farms using either of the two strategies in 2019, we note that the choice between strategies is mainly related to the farm size (also related to the amount of manure produced). Cost and benefit are also different. Part of the manure produced is sold as shrimp and crab feed, and part is returned to the field nearby. The in-situ treatment strategy of the farm requires considering facility supplements and operating costs. If the amount of manure generated is not sufficient to support the operation of the in-situ treatment equipment, this is unreasonable.

Following the survey results, we distinguished the selection of a manure treatment strategy for the farm under ideal conditions according to the wishes of farmers and the best cost-effectiveness. Criteria were farm sizes (number of animals) as listed in Table S3. Farms smaller than these thresholds were requested to have their manure treated centrally (Strategy 1), while larger scale farms had to treat manure in situ (Strategy 2). If all the technologies had been implemented in such ideal situation, the total NH_3 emission could have been reduced by as much as 42% when compared with 2018.

3.2 Changes of contributions to NH_3 emission

The pig industry(2012, 47%; 2018, 73%; 2019, 70%; ideal, 71%) is the largest source of NH_3 emission followed by poultry farming(2012, 44%; 2018, 23%; 2019, 26%; ideal, 25%) in Sheyang county in all scenarios (Fig. 3(b)), mainly due to the larger stock number in recent years. In different scenarios, NH_3 emission at the housing stage(2012, 81%; 2018, 69%; 2019, 69%; ideal, 82%) accounts for the largest amount (Fig. 3(a)). From year 2012, the NH_3 emission in the storage and application were less than the year 2018 and 2019, mainly due to the direct discharge (about 54% of total N according to the NUFER model) of a large amount of livestock manure, which was abolished in an effort to improve the water quality of rivers and canals (SCPRC., 2015). However, the NH_3 emission in the housing stage is higher than the 2018 scenario and 2019, mainly due to the lack of strict manure management measures in 2012 and the inadequate manure management. In an ideal situation, the contribution from housing, storage & treatment and application stages accounted for 82%, 10% and 8% (Fig. 3 (a)), respectively. Bai et al. (2016) quantified the nitrogen flows through the manure management chain in China in 2010, and found the greatest losses occurred from housing and storage stages through NH_3 emissions (39% of total nitrogen losses). Therefore, focussing attention to the reduction of NH_3 in the housing stage seems justified. As measures outlined in the abatement strategies above affect the housing stage of industrial farms, but not that of traditional farms, emissions from industrial livestock farms decrease much more strongly than those of traditional farms (Fig. 3 (c)). Traditional livestock farms account for an increasing proportion of NH_3 emissions, which means that if traditional livestock farms are gradually replaced by industrial livestock farms, higher NH_3 emissions reduction effects will be achieved.

3.3 Spatial distribution of NH_3 emission

Prior to 2012 and the introduction of strict manure management measures in China, the utilization of manure resources was not considered. A major part of the manure was discharged into water bodies and stored near the residential areas, causing serious atmospheric pollution and water pollution. Bai et al. (2016) quantified the nitrogen flows through the manure management chain in China in 2010, they found the greatest losses occurred from housing and storage stages through direct discharge of manure into water bodies or landfill (30-73% of total nutrient losses). Bai et al. (2014) quantified the pig production in China and found in 2010 the discharge nitrogen loss of pig industry accounted for more than 30% of the total nitrogen loss. In 2018, manure management measures were issued, and manure was prohibited from being discharged into water bodies. It can be seen that the areas with high NH_3 emissions (Fig. 4(a)) would show overlap with livestock density (Fig. 1).

After the application of NH_3 emission reduction technology, NH_3 emission decreased significantly (Fig. 4(b)). The reduction in NH_3 emissions was mainly concentrated around industrial livestock farms. Scenario analysis (Fig. 4(c)) showed that if the entire county of Sheyang county fully uses two strategies of NH_3 reduction, the NH_3 emission will be lower, especially in the northern part of Sheyang county, the area of highest emissions.

3.4 Cost-benefit analysis of the two NH_3 reduction strategies

Sheyang county has 14 town-level manure treatment centers, covering all traditional livestock farms. We conducted a cost survey of NH_3 reduction technology in all the manure treatment centers(Supplemental information Questionnaire). We can see that the total investment in manure treatment center is 1.13 million Yuan year^{-1}(Table S4). The NH_3 emission reduction with the technology in all animal type farms included in this manure treatment center (Xingqiao manure treatment center) was 27 tons per year, the cost of NH_3 reduction technology in the manure treatment center strategy is 42 Yuan kg^{-1} NH_3 or 5.1 Euro kg^{-1} NH_3 (Table S7).

Sheyang county has 35 in-situ treatment farms, covering laying hens farms and poultry farms. We conducted a cost survey of NH_3 reduction technology in one of the in-situ treatment farms (40,000 head of laying hens with annual manure processing of 1,500 tons). This poultry farm was chosen due to more complete availability of data. The total annualized investment in manure treatment technologies is 0.43 million Yuan year^{-}

$^{-1}$ (Table S5). The NH_3 emission reduction with the technology was 5.6 tons per year, the cost of NH_3 reduction technology in the in-situ treatment strategy is 80 Yuan kg^{-1} NH_3 or 9.7 Euro kg^{-1} NH_3 (Table S7). Among them, the cost of NH_3 emission reduction technology in the housing stage is 37 Yuan kg^{-1} NH_3, while it is 280 Yuan kg^{-1} NH_3 for the treatment stage.

The income of the manure treatment center mainly comes from the sales of organic fertilizer and the collection fee of manure collected from farmers. The total income of the manure treatment center is 1.6 million Yuan per year, which means this strategy is economically possible (Table S6). The income of the in-situ treatment farm also comes mainly from the sales of organic fertilizer. The estimated total income of the in-situ treatment farm is 350 thousand Yuan per year. However, equipment costs are covered by the government in the current situation, which means the actual benefit will be lower or even negative if the farmers need to purchase the equipment on their own. Comparing the two strategies, the NH_3 reduction cost of the manure treatment center is 5.1 Euro kg^{-1} NH_3, while the NH_3 reduction cost of the in-situ treatment strategy is 9.7 Euro kg^{-1} NH_3 (Fig. 5). The manure treatment center strategy has better cost efficiency.

4. Discussion

4.1 Implementing NH_3 emission mitigation strategies in practice

While NH_3 emission reductions achieved on small-scale is high, we note that the practical application in Sheyang county was not able to reach these targets. Through the implementation of the NH_3 reduction strategies at the county level, we found that there are many obstacles in the actual implementation process. While an emission reduction of 16% within a year clearly is notable, we also find that there is a need to identify the gap between what has been achieved already, and what the measures implemented could bring in a more ideal situation. For that purpose, it is important to understand the reasons of this gap. It seems it takes a process for farmers to accept the policy and also requires the government to promote the implementation of the policy (Liu et al., 2020).

4.2 Obstacles to fully implement the mitigation options at the county level

In 14 town-level manure treatment centers, only 4 town-level treatment centers are operating as required, and only 30% of livestock manure in Sheyang has been treated. The main reason is that: 1) There is no local discharge of treated sewage: the location of the manure treatment centers does not consider the issue of sewage discharge, the treated sewage cannot be directly connected to the irrigation canal and has nowhere to be discharged. 2) The manure collection income is less: most of the manure from farms are returned to the field or sold before ever reaching the treatment center. 3) Animal epidemic prevention is a big problem: as the manure transporter go to the relevant farms to collect manure, it brings great pressure to the animal epidemic prevention work, especially during the African Swine Fever.

Sheyang actively promotes the combination of crop farming and livestock breeding. Industrial livestock farms use rented land or transfer the surrounding land to treat the manure. At present, the government has invested in only 35 industrial livestock farms for manure treatment facilities. As mentioned, only 9 of these farms with more than 50,000 laying hens had treatment facilities in operation, and even these did not always run full time. The main reason is that: 1) the amount of manure that can be used for composting does not match the capacity of the reactor, so it is not enough to make the reactor operate normally, the investment is large, and the benefit is low. 2) Due to the small amount of organic fertilizer produced, the sales channels are limited. 3) The policy is not compulsory.

The main reason why the manure treatment center cannot operate normally is that the cost of sewage treatment is high, and there is no place to discharge the treated sewage. The main reasons for the failure of the in-situ manure treatment farms to operate normally are the large power consumption for manure disposal, the high cost of manual input, and the limited sales channels for organic fertilizer. At present, although the requirements for industrial livestock farms' manure treatment facilities are relatively high, industrial livestock farms create pressure to the environment. Although manure treatment devices exist, due to lack of environmental awareness, these devices are not used and untreated manure is piled up aboveground (Zhang et al., 2020).

At present, the policy of resource utilization of livestock manure in Sheyang has not been well implemented, and the annual NH_3 emissions are still very high. The current NH_3 emissions are 7420 t NH_3 yr^{-1}, the reduction rate is only 16%. Since Sheyang was the first pilot county to implement a policy on the utilization of livestock manure resources to reduce environmental pollution, there is no previous experience to learn from. As a consequence, some difficulties have arisen in the implementation of the policy. Due to constraints such as inconvenience in use of organic fertilizer, large input and slow fertilizer effect, farmers are reluctant to use organic fertilizer, except for organic vegetable production operators and forest contractors. This led to fewer sales channels for organic fertilizer. In such a situation, economic pressure can make it difficult for industrial livestock farms to properly operate manure treatment facilities. Increased government support for industrial livestock farms and improved central collection for other farms may increase application rate of otherwise useful measures (Ju et al., 2016; Wu et al., 2018; Zhang et al., 2020). Moreover, integrating animal and crop production into one harmonized agricultural system that makes use of available resources can redirect the focus of farmers towards optimizing agricultural as well as environmental targets (Guo et al., 2020; Jin et al., 2021; Zhang et al., 2019).

4.3 Cost-benefit analysis of two mitigation strategies

A cost analysis of NH_3 reduction technology showed that NH_3 reduction in the manure treatment center strategy costs 5.1 EUR kg^{-1} NH_3, while the cost of NH_3 reduction technology in the in situ farms is 9.7 EUR kg^{-1} NH_3. Among them, the cost of NH_3

emission reduction technology in the housing stage is 4.5 EUR kg^{-1} NH_3, while the cost of NH_3 emission reduction technology in the storage & treatment stage is 33.9 EUR kg^{-1} NH_3. Measures have not been developed as cost-efficient strategies for NH_3 mitigation: compared to numbers developed for Europe, where reported abatement ranges are well below 5.0 EUR kg^{-1} (about 4.1 EUR kg^{-1} NH_3)(Klimont and Winiwarter, 2011). For most measures on pig farms (liquid manure system) there seems to be considerable room for optimization.

However, we found that in the in-situ treatment strategy, the cost of abatement at the housing stage is 4.5 EUR kg^{-1} NH_3. Previous analyses of the NH_3 marginal abatement cost curve (MACC) for Europe showed that the average acidification abatement cost in housing stage is between 2.1 Euro kg^{-1} N (about 1.7 EUR kg^{-1} NH_3) and 4.0 Euro kg^{-1} N (about 3.3 EUR kg^{-1} NH_3) (Buckley et al., 2020; Reis et al., 2015), but the NH_3 reduction in the housing stage is the largest. Therefore, in the future research, the NH_3 reduction technology at the housing stage is particularly important.

Comparing the two strategies, the manure treatment center strategy has greater advantages in terms of NH_3 emission reduction costs, but it is not able to remove housing emissions and therefore remaining emissions are still high. In the in-situ treatment strategy, the cost of NH_3 emission reduction technology in the housing stage is lower and the cost of NH_3 emission reduction in the treatment stage is higher, mainly because the cost of compost reactors in the manure treatment stage is higher, and it consumes more Energy.

5. Conclusions

NH_3 emissions from agriculture can cause non-point source pollution and are an important contributor to PM pollution, which seriously harms human health. Implementing measures that are known to work in the small-scale or in specific test farms still can be challenging. Through the combination of "unified collection and centralized treatment" and "one field, one tank, in-situ treatment" in Sheyang County, the measures implemented achieved to reduce NH_3 emission by 16% in the livestock industry. Through the cost-benefit analysis of the two strategies, limited cost data available indicate that the centralized manure treatment center strategy has lower cost of reducing NH_3 emission than the in-situ poultry treatment of manure, but also emission reductions are smaller. Still, considerable further efforts are needed to unlock the full potential of the measures in practice, which should allow emission reductions of as much as 42%. The mitigation measures (e.g. housing adaptation and manure handling systems) are expensive due to the higher requirements of the investments in technologies and infrastructures. Increased government support (e.g. technical guidance and training) and subsidies (e.g. agricultural machinery, manure treatment facilities) is expected to encourage farmers to adopt these mitigation measures.

The study found an agricultural NH_3 reduction technology route suitable for China's national conditions (such as the "Sheyang Model"), which is in line with the majority of traditional livestock farms, and also provides environmental protection solutions for industrial livestock farms. It is of great significance to support the healthy development of China's agricultural industry.

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.

Author statement

Lin Ma, Chunsheng Hu and **Xuan Wang** devised the project, the main conceptual ideas and proof outline. **Zhaohai Bai** and **Wilfried Winiwarter** supervised the project and developed the theoretical framework. **Haodan Wang** and **Zhanqing Zhao** worked out almost all of the model simulation and data analysis. **Haodan Wang**, **Zhanqing Zhao**, **Zhaohai Bai**, **Wilfried Winiwarter**, **Lin Ma**, **Xuan Wang**, **Xiangwen Fan**, **Zhiping Zhu** and **Chunsheng Hu** contributed to the interpretation of the results. **Haodan Wang** and **Zhanqing Zhao** took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research and manuscript.

Acknowledgements

We thankfully acknowledge the financial support from the National Key R&D Program of China (2018YFC0213300); National Natural Science Foundation of China (71961137011, 31801941, 32002138); President's International Fellowship Initiative (PIFI) of CAS (2019VCA0017); Hebei Key R&D Program (20327305D); Hebei Dairy Cattle Innovation Team of Modern Agro-industry Technology Research System (HBCT2018120206); Outstanding Young Scientists Project of Natural Science Foundation of Hebei (C2019503054); Youth Innovation Promotion Association, CAS (2019101); "Towards the International Nitrogen Management System" project funded by the Global Environment Facility through the United Nations Environment Programme; This publication contributes to UNCNET, a project funded under the JPI Urban Europe/China collaboration, project numbers 71961137011 (NSFC, China).

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Table 1. NH_3 Emissions (in % of N available at each point released as NH_3) at each stage of the manure management chain.

Livestock Type	Stage	Treatment Type	NH_3 emitted [%]
Dairy	Housing	Ganqingfen*	18.0
Dairy	Storage & treatment	Aboveground without cover	17.0
Dairy	Storage & treatment	Underground with cover	14.0
Dairy	Storage & treatment	Fixed	7.8
Pig	Housing	Ganqingfen	37.0
Pig	Housing	Soaked excrement	22.0
Pig	Storage & treatment	Aboveground without cover	30.0
Pig	Storage & treatment	Underground with cover	10.0
Pig	Storage & treatment	Industrial biogas	2.7
Pig	Storage & treatment	Fixed	14.0
Laying Hen	Housing	Ganqingfen	20.0
Laying Hen	Storage & treatment	Aboveground without cover	29.0
Laying Hen	Storage & treatment	Underground with cover	8.3
Laying Hen	Storage & treatment	Fixed	14.0
Other Poultry	Housing	Ganqingfen	20.0
Other Poultry	Storage & treatment	Aboveground without cover	29.0
Other Poultry	Storage & treatment	Underground with cover	8.3
Other Poultry	Storage & treatment	Fixed	14.0
Sheep &Goat	Housing	Ganqingfen	23.0
Sheep&Goat	Storage & treatment	Aboveground without cover	17.0
Sheep&Goat	Storage & treatment	Fixed	7.8
All type	Application	Fresh manure	19.0
All type	Application	Compost products	2.5

*) *The method of manure collection from the animal house in China is the ‘ganqingfen-干清粪’ system* (Huaitalla et al., 2010; Schuchardt et al., 2011)*, literally translated as ‘clear manure dryly’, which separates the solid and liquid manure fractions in-house* (Wei et al., 2018).

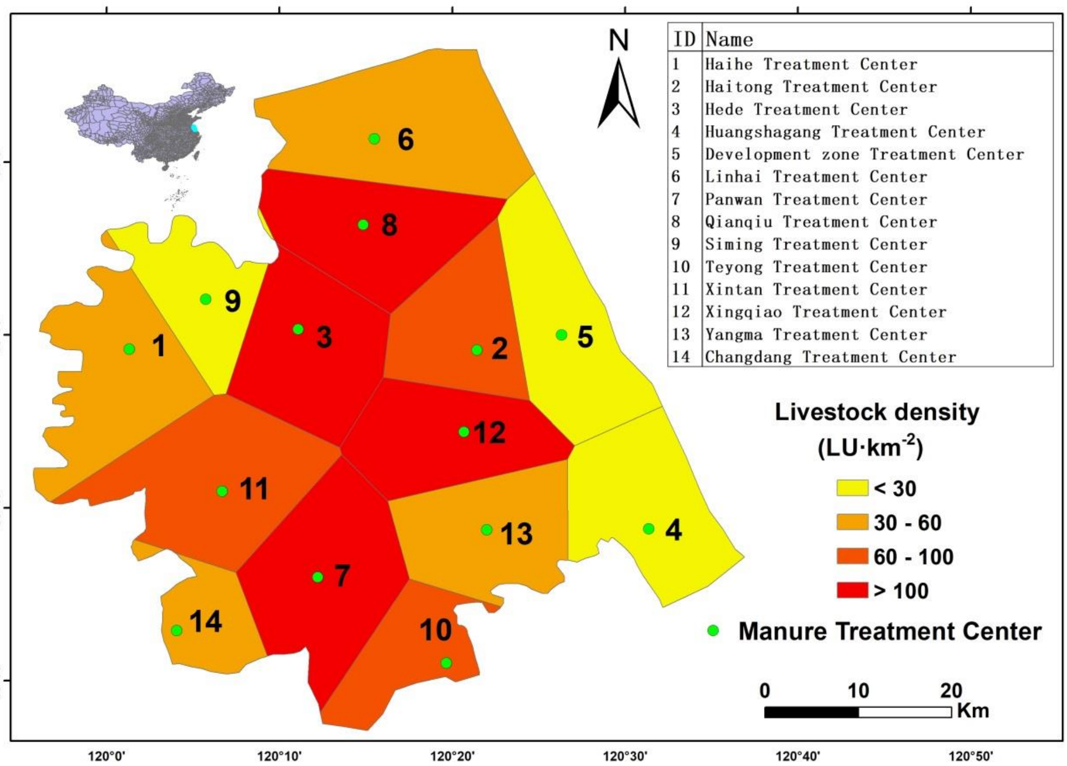

Fig. 1. Livestock densities and location of the treatment center in Sheyang county in 2018.

Polygons designate all area of closest distance to a given treatment center.

Fig. 2. Schematic diagram of manure treatment center strategy

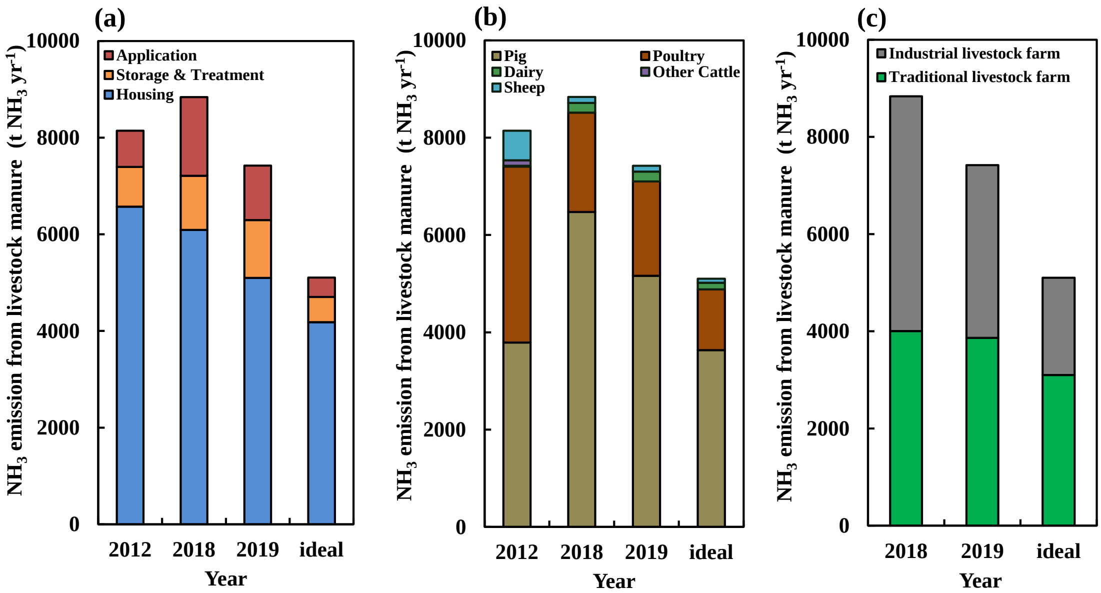

Fig. 3. NH_3 emissions from livestock manure management and from different sources

(a) NH_3 emissions from different livestock manure management chain; (b) NH_3 emissions from different animal categories; (c) NH_3 emissions from different livestock farm system.

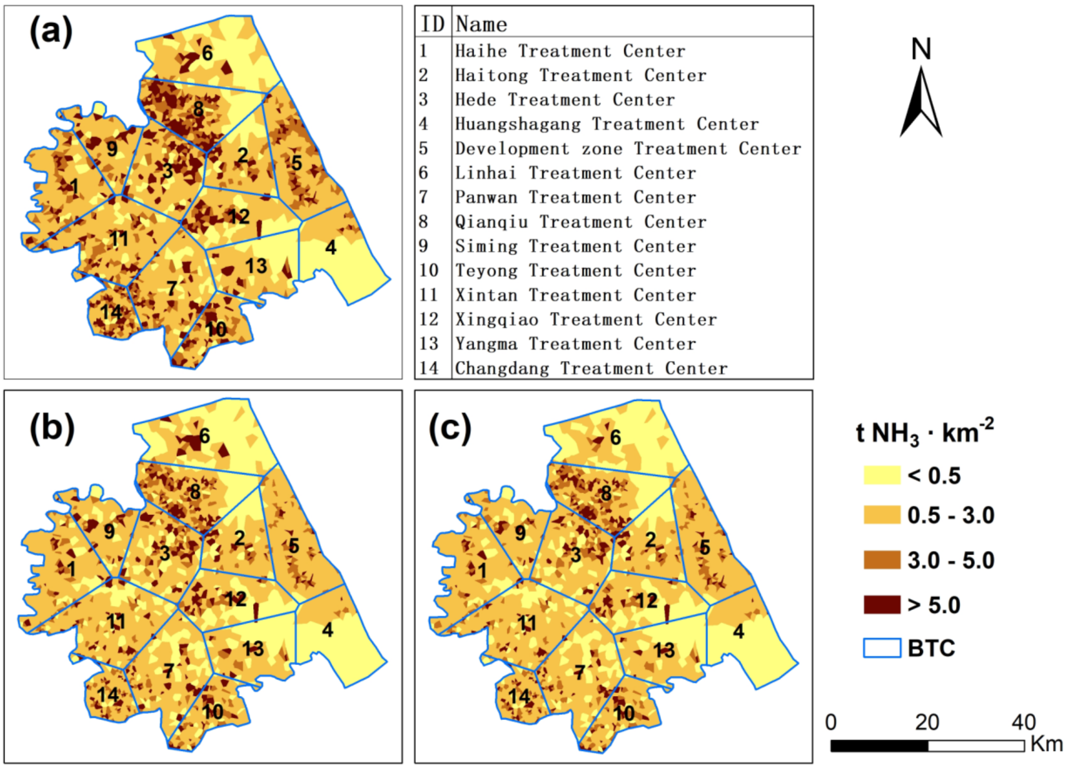

Fig. 4. Spatial distribution of NH_3 emission from livestock manure management in different scenarios

(a) 2018; (b) 2019; (c) Ideal situation. BTC stands for "Boundary of Treatment Center".

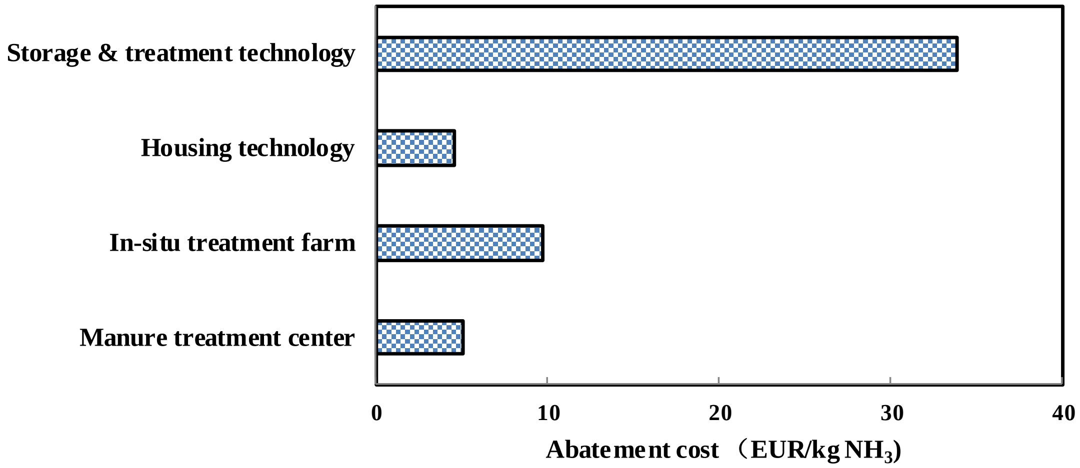

Fig. 5. Economic costs of different emission reduction models（EUR/kg NH_3）