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Reducing Ammonia Emissions from Dairy Cattle Production via Cost-Effective Manure Management Techniques in China

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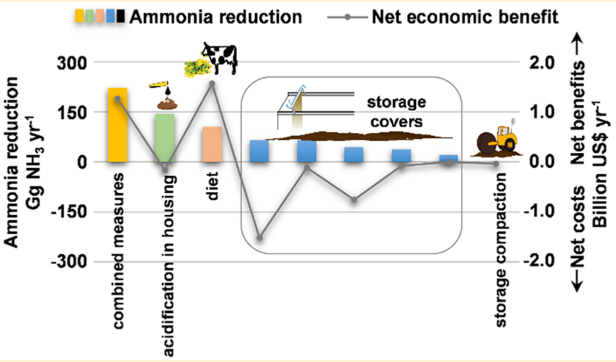
Ⓢ *Supporting Information*

ABSTRACT: This study analyzed ammonia reduction potential and related costs and benefits of several ammonia emission reduction technologies applicable for dairy production from cattle in China. Specifically, these included diet manipulation, manure acidification, manure/slurry covers, and solid manure compaction. Ammonia emissions for China were estimated using the GAINS and NUFER models, while mitigation potentials of technologies were determined from laboratory studies. Ammonia reduction potentials from dairy production in China ranged from 0.8 to 222 Gg NH_3 year^{-1} for the selected technologies. Implementation costs ranged from a savings of US \$15 kg^{-1} NH_3 abated to an expenditure of US\$45 kg^{-1} NH_3 abated, while the total implementation costs varied from a savings of US\$1.5 billion in 2015 to an expenditure of a similar size. The best NH_3 reduction technology was manure acidification, while the most cost-effective option was diet optimization with lower crude protein input. For most abatement options, material costs were the critical element of overall costs. The fertilizer value of manure could partly offset the implementation cost of the options tested. Furthermore, benefits due to avoided health damage, as a result of reducing NH_3 emissions, could make all abatement options (except for manure compaction) profitable on the scale of a national economy.



1. INTRODUCTION

Over 50% of ammonia (NH_3) emission in China was caused by livestock manure during 2000−2008,[1] which was ~4.1−5.1 Tg N year^{-1} and was much higher than that for the United States or the European Union (1.7−3.2 Tg N year^{-1} during 2000−2008).[2−4] An important source of NH_3 emissions in China is dairy production from cattle at nearly 8.9% of the total in 2009.[5] On the basis of predicted changes, the contribution of dairy production to the total NH_3 emission in China will increase to 15% by 2030.[5] Ammonia in the atmosphere not only is a pollutant itself but also contributes to many other environmental problems. As a precursor compound to inorganic aerosols, atmospheric NH_3 contributes to the formation of particulate matter with diameter less than 2.5 μm ($PM_{2.5}$) due to its reaction with nitric and sulfuric acids, causing severe haze pollution and adverse effects on human health in China.[6−11] Furthermore, NH_3 deposition to soil and water and subsequent conversions contribute to acidification of lakes, eutrophication of natural ecosystems, and formation of the greenhouse gas N_2O.[9,12−14] Because of the high emission rate and negative effects on the environment, NH_3 emission mitigation is urgently required in China. At the same time, emissions of NH_3 represent the loss of a valuable resource of nitrogen (N) for agriculture.

In manure, hydrolysis of urea or decomposition of organic N produces NH_3, which diffuses to the surface and is released to ambient air. This process of NH_3 emission is influenced by many factors, including the equilibrium between NH_4^+ and NH_3 in aqueous environments, pH, temperature, wind speed, and turbulence over the manure surface.[15] Hou et al.[16] summarized previous studies exploring NH_3 emission abate-

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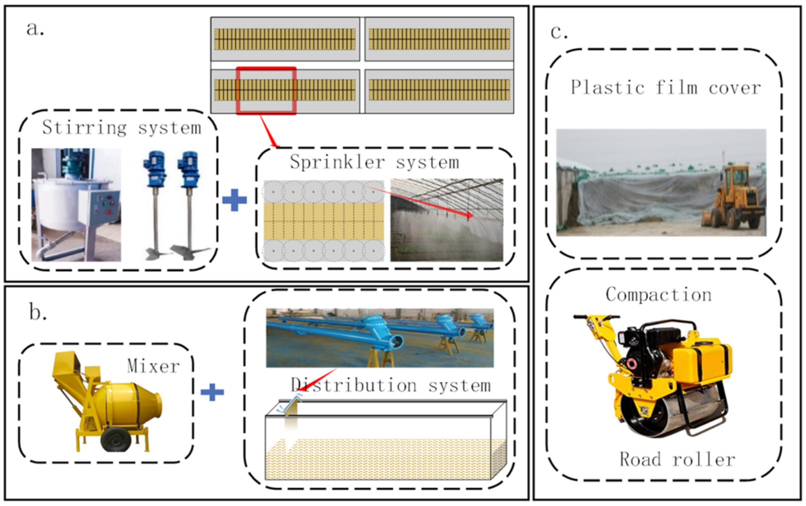

Figure 1. Schematic diagram of technical implementation of the acidification system in housing (a), the covered system over the surface of manure (b), and the plastic film cover and compaction system (c).

ment options, including dietary manipulation, reducing volatile NH_3 in manure, urine−faeces segregation, and binding ammonium-N with chemical additives. The most effective NH_3 emission reduction options were reducing N excretion, addition of acids to manure, or covering manure during storage. However, most of the underlying studies were conducted in Europe, and there is a large difference between manure management systems in dairy farms in China and Europe, including in dairy housing, manure collection, and storage practices.[17−20] Moreover, the cost of the mitigation options could limit their implementation and application in dairy farms. However, current practices of manure treatment in China are inefficient and offer many opportunities for greater recycling of manure and nutrient utilization.[17,21] This illustrates that it is important to get local data both on the NH_3 reduction potential from relevant mitigation options for dairy production in China and on their related costs or benefits. In this study, we aimed to (1) assess the NH_3 reduction potential of several abatement options from dairy production in China, (2) explore implementation of the abatement measures and estimate the related economic costs, and (3) discuss future pathways for NH_3 emission abatement from dairy production in China.

2. MATERIALS AND METHODS

Ammonia reduction potential of several selected ammonia abatement techniques and their costs and benefits were analyzed using the GAINS (greenhouse gas−air pollution interactions and synergies) model[22,23] coupled with parameters derived from the NUFER[24] model and laboratory trials. On the basis of the data for individual measures, the implications for cost-effective ammonia emission mitigation exploration in the future were determined.

2.1. Estimation of Ammonia Emission and Reduction from Dairy Production Based on GAINS Model. In the present study, estimation of NH_3 emissions and reduction potential from dairy production in China were considered along the whole manure management chain including grazing, housing, storage, treatment, and application. Total NH_3 emissions from dairy production were the sum of NH_3 emissions from all stages of the manure management chain, coupled with NH_3 reduction efficiencies of the abatement options under different mitigation scenarios, using the GAINS model.[22,23] The calculations used the following equation,[25]

$$E_{NH_3} = \sum_{r} L_{r,y} \sum_{m} \sum_{s=1}^{5} [\mathrm{ef}_{y,r,s}(1 - \eta_{r,m,s,y})] \tag{1}$$

where E_{NH3} represents the total ammonia emission from dairy production; r is the specific province; y is the specific year; m is the mitigation technique; s is the emission stage (five stages including grazing, housing, storage, treatment, and application); L is the animal population; ef is the ammonia emission factor; and η is the reduction efficiency of the specific mitigation technique. Ammonia emission factors were calculated using N excretion and volatilization rates at distinct stages, accounting for N-losses involving NH_3, N_2O, N_2, and NO_3^- emissions at previous stages. Provincial data for N excretion and volatilization rates were derived from the GAINS[22,23] and NUFER[24] models, while NH_3 reduction efficiency was derived from the laboratory trials described in the Supporting Information (optimized reduction potential are shown in Table S1), which is considered to be a reliable source of information about reduction efficiencies for application to Chinese dairy production systems as there is a lack of data from previous studies.[16]

2.2. NH_3 Mitigation Scenarios. Because there was a shortage of local research on NH_3 emission mitigation from dairy production in China, 12 scenarios of mitigation measures for manure management in a dairy farm were considered, including current practice (control), low protein feed, acidification, cover and acid (slurry), cover (slurry), manure cover and acid (liquid), cover (liquid), plastic film cover, manure compaction, compaction and cover (liquid), manure compaction and cover and acid (liquid), and combined measures, based on surveys and experts' knowledge. "Slurry" was a mixture of urine and faeces without bedding materials. "Liquid" and "solid" were liquid and solid fractions separated from slurry using a screw-press separator. The details of the scenarios are shown below.

Scenario 0: Control. This scenario assumes a dairy production system in China with no mitigation technique implemented. NH_3 emission under this scenario was used as a baseline value.

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Scenario 1: Low Protein Feed. To achieve higher milk production with better quality, dairy cows are fed with extra crude protein (CP) resulting in increased N excretion and posing a high risk for NH_3 emission. Common practice is for 17% of the cow's diet to be crude protein, based on experts' knowledge. For this low protein feed scenario, it was assumed that the diet was reduced to 15% crude protein and this reduction in feed protein would not affect milk production. As no extra equipment was needed to use lower protein diets, there was no extra cost considered for its implementation.

Scenario 2: Acidification. Acidification is an effective measure to reduce NH_3 emission from manure management systems. For this scenario it was assumed that the dairy building was equipped with a slatted floor and diluted sulfuric acid (H_2SO_4 1:100) was sprayed to form a 3 mm layer on top of the manure surface under the slatted floor. To estimate the cost involved in acidification, the following general assumptions were made about dairy houses, acidification systems, and application based on experts' knowledge: (1) Each dairy building was equipped with two stirring systems, which were used to dilute the H_2SO_4, and four sprinkler systems, which were used to apply the diluted H_2SO_4 to the surface of the slurry under the slatted floor. (2) Each sprinkler system included 50 nozzles, 110 m of pipe, and one pump. (3) Three liters of tap water per square meter of manure was used to clean the spraying system after each operation (see Figure 1a). Acidification of the manure surface was expected to have little influence on the quality of the slurry and bioavailability of N in the manure as the amount of acid was small (3 mm surface layer) compared to the slurry volume.

Scenario 3: Cover (Slurry). During storage, slurry was covered with a vermiculite cover to a depth of 6 cm. It was assumed that a system would consist of a U-spiral conveyor with mesh on the bottom to be moved on tracks installed on the edge of the lagoon. Moving the conveyor along the tracks at a certain speed would distribute covering materials through the mesh. As the size of the tank influenced the costs of the equipment and operation, it was assumed that the lagoon used for storage was 10 m wide with a maximum depth for stored slurry and liquid manure of 4.5 m, based on general dairy farm practice (Figure 1b).

Scenario 4: Cover and Acid (Slurry). During storage, slurry was covered with a 6-cm thick mixture of vermiculite and lactic acid at a volume ratio of 1:5. The equipment used for this measure was the same as that for scenario 3, plus a mixer for mixing lactic acid with vermiculite.

Scenario 5: Cover (Liquid). This scenario was similar to scenario 3, replacing the slurry in scenario 3 with liquid manure.

Scenario 6: Cover and Acid (Liquid). This scenario was similar to scenario 4, replacing the slurry in scenario 4 with liquid manure.

Scenario 7: Plastic Film Cover. Solid manure was covered with plastic film during storage, and the implementation of the plastic film cover was mainly through manual operation (Figure 1c). The lifetime of the plastic film was assumed to be 1 year.

Scenario 8: Manure Compaction. This scenario assumed that solid manure was compacted until the volume of the manure halved. Implementation was via a road roller. To estimate the cost of technical implementation, we assumed that the depth of stored solid manure was 1.5 m, with 0.15 m solid manure being added per day.

Scenario 9: Manure Compaction and Cover (Liquid). To account for additional emissions of compaction due to leaking liquid manure, this scenario was a combined measure with manure compaction and cover (liquid).

Scenario 10: Manure Compaction and Cover and Acid (Liquid). This scenario was the same as scenario 9 but combined with application of acid (liquid).

Scenario 11: Combined Measures. Considering the mitigation options from the perspective of the manure management chain, this scenario was a combination of the diet manipulation, acidification, and cover (slurry) scenarios.

2.3. Cost Estimation for Technical Implementation of Abatement Options. The cost for the implementation of abatement options was divided into investment cost, fixed operation cost, and variable operation cost.[26] 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 and an interest rate of 4%. Estimation of the fixed operation cost was based on the fixed operation cost at a 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 labor, energy, and materials used for the abatement options, considering the usage amount and price of the materials. As the investment cost varied with herd size, the calculation was based on the assumption that a dairy farm had 500 cows, a representative herd size for a dairy farm in China. The parameters used in the calculation can be seen in Tables S2 and S3.

2.4. Benefit Estimation. *2.4.1. Benefit from Mineral Fertilizer Saving.* In addition to the cost of technical implementation of these abatement options, we also estimated the costs saved when manure (and N retained) was used as fertilizer. Cost saving from N abated from selected measures was calculated from the price of mineral fertilizer, the amount of N retained in manure, and a use factor to describe the potential efficiency of manure N as a substitute for mineral fertilizer, which was assumed to be 75%.

2.4.2. Benefit from Reduced Health Damage and Mortality. Quantification of health-related costs and attributing such costs to a single cause (air pollution) is inherently difficult. Hence, data are sparse and very uncertain. With increased mortality being the most significant impact, it seems useful to integrate a value judgment of human life. For Europe, Desaigues et al.[27] have provided a framework from Willingness-To-Pay studies but have also taken national GDP and life expectancy as well as information from medical practice into consideration. They have developed the concept of "Value of a Life Year" (VOLY), which, for Europe, is calculated at 40 000 EUR (25 000 EUR to 100 000 EUR). The application to air pollution and related premature deaths was the explicit aim of the study. The value of 40 000 EUR has been further used in the European Nitrogen Assessment[28] (and also related to other relevant parameters, like the Value of a Statistical Life) for a cost−benefit analysis. Using the relationship between emissions and atmospheric PM concentrations on the one hand and population density on the other hand, these authors quantify the resulting benefit in health-related costs of reducing one mass unit of reactive nitrogen in countries of the European Union (EU27).

Here we assume that the relationship between emissions and impacts (in terms of PM formation as well as impact of incremental PM on health) also holds for the conditions in

China, except that the observed concentrations need to be weighted by population density. To account for a possibly different perception of VOLY, an approach was followed that had been used for China previously, allowing for a VOLY of 10% as "decreased health damage costs".[3] Calculation of health damage then can be performed according to eq 2,[3,28,29]

$$\mathrm{cost}_{\mathrm{HD}} = \frac{\mathrm{VOLY}_{\mathrm{China}}}{\mathrm{VOLY}_{\mathrm{EU27}}} \times \sum_{i=1}^{31} \mathrm{emission}_i \times f_{\mathrm{EU27}}(\mathrm{PD}_i) \qquad (2)$$

where $\mathrm{cost}_{\mathrm{HD}}$ is the health damage cost of life year loss in US\$ million year^{-1}; $\mathrm{VOLY}_{\mathrm{China}}$ is the value of a life year of air pollution mortality in China; $\mathrm{VOLY}_{\mathrm{EU27}}$ is the value of a life year of air pollution mortality in EU27; $\frac{\mathrm{VOLY}_{\mathrm{China}}}{\mathrm{VOLY}_{\mathrm{EU27}}}$ is an adjustment factor for the VOLY of 100% (using European health data cost set)[3,28,29] and 10% (decreased health damage cost set);[3,29] i is a province in mainland China; $\mathrm{emission}_i$ is the total NH_3 emission from the respective province in Gg year^{-1}; $f_{\mathrm{EU27}}(\mathrm{PD}_i)$ is the equation for health damage cost per reactive nitrogen emission related to population density in Europe in US\$ kg^{-1} NH_3–N;[28,29] and PD_i is the population density of the respective province in capita km^{-2}. Population density was estimated from population and land area.[30,31]

2.5. Uncertainty and Sensitivity Analysis. To estimate the uncertainty of NH_3 mitigation potential and economic benefits of the options tested, we performed Monte Carlo simulations using @RISK software (Palisade Corporation) by varying the parameters for NH_3 emission estimation and cost–benefit analysis. Data for the variability of the input parameters were obtained from this study, literature review, and a survey and are presented in Table S4. Careful differentiation was done between statistically dependent and independent elements, due to potential differing impacts on resulting probability parameters. Individual parameters that were derived separately were regarded as statistically independent, whereas if an identical parameter was applied to different statistical data, it was considered as statistically dependent, e.g., each element of Table S4 was considered statistically independent. We ran 1000 iterations to find the probability distributions of the baseline NH_3 emissions in 2015, predicting NH_3 reduction and net economic benefit from the selected mitigation measures in the present study. Output distributions of 1000 simulated data of each Monte Carlo result were approximated using the software's built-in functionality to apply the Akaike information criterion for an idealized representation. The resulting distribution is termed the "best fit" distribution. This approach also allows derivation of the standard deviation of such idealized output distributions. Results are presented as ±2 standard deviations, with the uncertainty range covering 95% of the statistical outcomes. In addition, we analyzed the sensitivity of net economic benefit to the variation of health damage cost saving, total technical implementation cost, and mineral fertilizer savings using @RISK software. The Monte Carlo simulations did not account for the variation in accounting of health damage—instead, the two discrete values developed earlier were maintained.

3. RESULTS AND DISCUSSION

3.1. Ammonia Emission from Dairy Production under Abatement Options in China. In the present study, it was assumed that selected options were fully adopted (100%) to the respective stage of all dairy systems in China, which obviously was an optimal assumption to achievable NH_3 reductions. Unabated NH_3 emissions ("control") were derived from data from dairy production systems in China to estimate total emission of 458 Gg NH_3 in 2015, of which 186, 93, 76, 85, and 19 Gg were from housing, storage, treatment, application, and grazing, respectively (Figure 2). The annual NH_3 emission estimated in the present study was lower than the 578 Gg NH_3 in 2010 estimated by Zhang et al.[21] The difference might be due to the different system boundaries of the two studies and data from different years, and Zhang et al.[21] also accounted for NH_3 emission from animal feed production. Results from all the scenarios, excluding compaction, showed a reduction efficiency in the range of 4–49% from the whole chain of dairy production in China (Figures 2 and S1). A Monte Carlo simulation with the uncertainty of input parameters showed that the baseline NH_3 emission in 2015 was in the range of 375–680 Gg NH_3 (95% confidence interval) with a standard deviation of 84 Gg NH_3 (Figure 3). The potential distribution of the simulated results of baseline NH_3 emission ("control") in 2015 based on Monte Carlo analysis is presented in Figure S2.

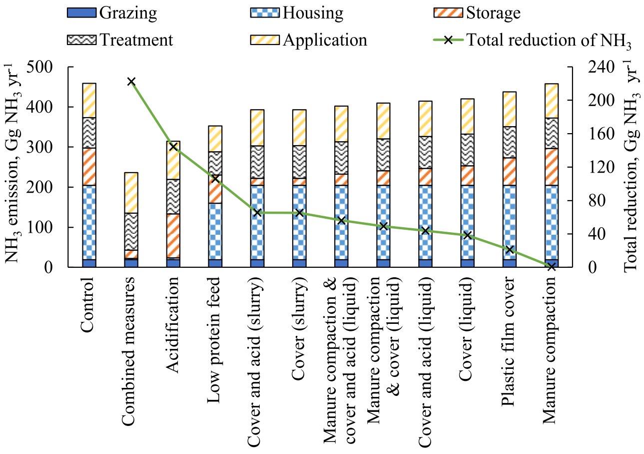

Figure 2. Ammonia emission from selected abatement options for dairy production in China in 2015. The respective scenarios are described in section 2.2.

Taking diet manipulation, acidification during housing, vermiculite cover on slurry, and combined measures as examples, hotspots (Hebei, Henan, Shandong, Heilongjiang, Inner-Mongolia, and Xinjiang) of NH_3 emission have been identified that provide the greatest mitigation potentials (Figure S3). Uncertainty analysis, using the Monte Carlo simulation of the variation of input parameters, showed no large variation in reduction of NH_3 emission from the tested options, excluding low protein feed. Details of the uncertainty range for NH_3 emission reduction are presented in Figures 3 and S2.

In practice, not all of the abatement options will be operating at full scale all the time. To account for possible malfunctions of equipment, inadequate upscaling from lab to farm scale, or specific situations where a given technology is just not applicable, we ran a sensitivity case with 80% of implementation achieved.[32] Results of this sensitivity case are presented in the Supporting Information (Figure S4). This showed that annual NH_3 reduction potentials under selected options ranged from −2 to 115 Gg NH_3 in 2015, which was equivalent to −0.10 to 8.79 kg NH_3 cow^{-1} year^{-1} (Figure S4),

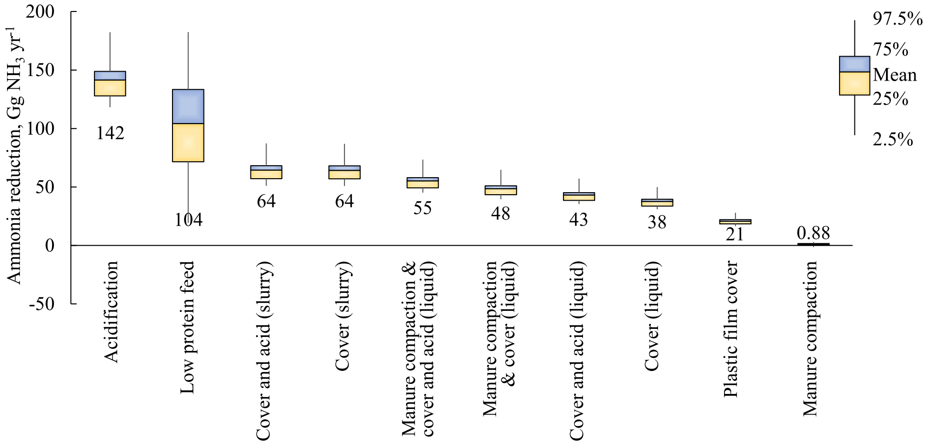

Figure 3. Uncertainty of NH_3 reduction potential of emission abatement options. The respective measures are described in more detail in section 2.2.

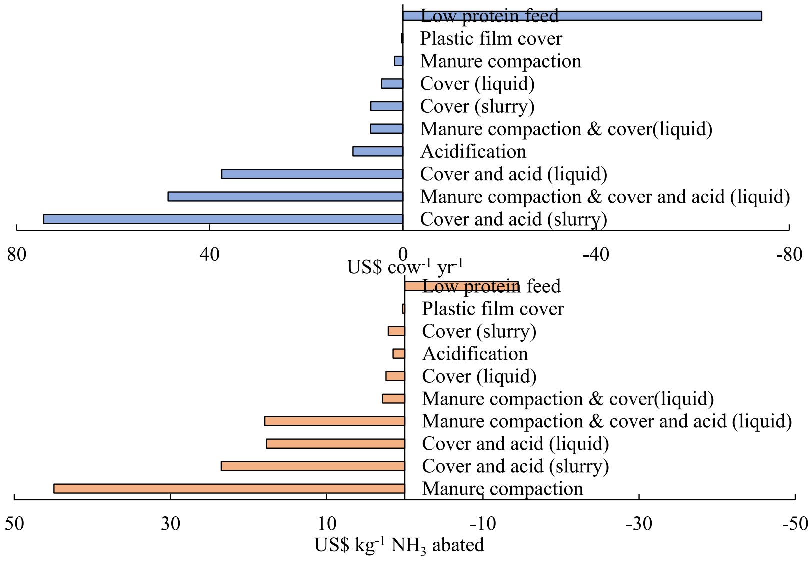

Figure 4. Cost of technical implementation of NH_3 emission abatement options. Blue and orange bars are the cost values "on an individual cow basis" and "on a kilogram NH_3 abated basis", respectively. The respective measures are described in more detail in section 2.2. A negative cost value refers to cost saving from the selected abatement measures.

and the combined measure with diet manipulation, acidification of manure under slatted floors, and vermiculite cover on slurry during storage could remove 182 Gg of NH_3 emission from dairy production in the case year.

The present study on the estimation of NH_3 emission from the following manure management stages only accounted for the influence on N retained in manure and not the potential effect of changes in physical and chemical characteristics of manure.[33] Consideration of effects of physical and chemical properties on manure and emission factors for abatement options is necessary in the future.

3.2. Cost of the Abatement Options.

3.2.1. Technical Implementation of the Abatement Options.

On the basis of the technical implementation assumption and results of any economic data survey in the present study, the cost of the selected NH_3 emission abatement options ranged from a saving of US\$15 kg^{-1} NH_3 abated to a cost of US\$45 kg^{-1} NH_3 abated, which was equivalent to a savings of US\$74 cow^{-1} $year^{-1}$ to a cost of US\$74 cow^{-1} $year^{-1}$ (Figure 4). The different ratios on kg NH_3 abated and an animal basis were due to the difference of reduction potential per animal under the selected options.

For the diet manipulation option, adjusting diet protein would not need any extra technical equipment, labor, or energy input. Therefore, there was no additional implementation cost for the diet manipulation option. However, a lower crude protein diet may change the cost of feed due to different ingredients. According to the diets used in the present study, a lower crude protein diet would be cheaper and the net economic benefit estimated from the diet manipulation was calculated at US\$15 kg^{-1} NH_3 abated, equivalent to US\$74 cow^{-1} $year^{-1}$ (Figure 4), which is similar to the cost savings estimated in a study by VanderZaag et al.[34] The cost of diet manipulation was determined by the composition of the feed, the price of the ingredients, and the variability of feed costs based on market fluctuations rather than change of local conditions.[26] Cost saving from lower crude protein in the diet is due to a greater choice of low-protein ingredients with lower prices. Moreover, the feeding experiment used to provide manure for testing effects of the lower CP feed also showed that milk productions of cows with the low-protein diet and

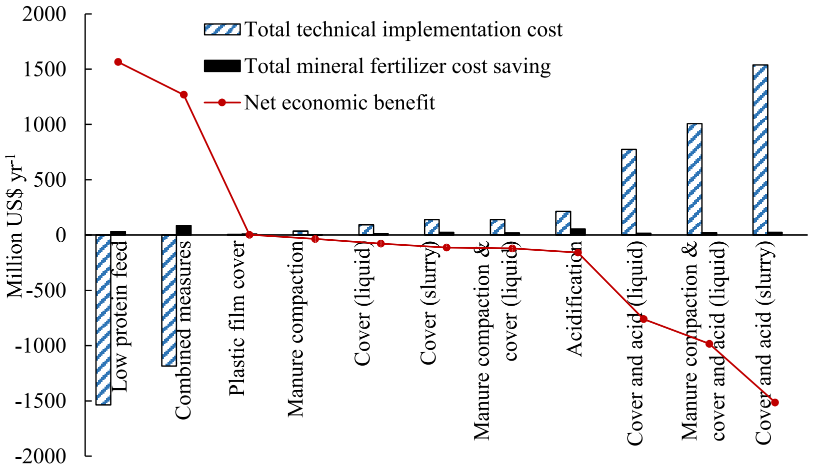

Figure 5. Costs and benefits of NH_3 emission abatement options for dairy production in China in 2015. The respective measures are described in more detail in section 2.2. A negative value for "Total technical implementation cost" refers to cost saving from the implementation. A positive value for "Net economic benefit" refers to net benefit from the combined costs for technical implementation and cost saving from replacement of mineral fertilizer, while a negative value refers to a net cost from the cost for technical implementation and cost saving from replacement of mineral fertilizer.

standard diet were similar, with both ~30 kg day^{-1}, and that there were no significant differences in the protein content and milk yield between the two diet treatments.[35] However, future studies of long-term effects on milk yield and the related indirect impacts on farm benefits still need to be confirmed.

Acidification of the manure surface under the housing was a highly efficient measure for NH_3 abatement, with a cost of US $1.5 kg^{-1} NH_3 abated, equivalent to US$10 cow^{-1} $year^{-1}$ (Figure 4). The difference in the cost of abating the same amount of NH_3, using the vermiculite or acidified vermiculite cover options between slurry and liquid manure storage, was due to differences in both the total amounts of slurry and liquid manure produced and the NH_3 reduction efficiencies for stored slurry and liquid manure. A previous study summarized annual costs for a number of cover types, including natural crust, straw, floating permeable coverage (e.g., hexacover), floating impermeable coverage such as clay balls, wood, a tent, concrete, and a storage bag,[34] and the results showed a range in costs from US$2.2 to US$9.8 kg^{-1} NH_3 abated. The price of the cover materials and the amount of coverage used were the main reasons for the difference in costs.

The plastic film cover was the cheapest NH_3 abatement option, at only US$0.3 kg^{-1} NH_3 abated due to the low price of plastic film, low labor requirement, and little investment input. The abatement cost of compaction of solid manure was highest among the options investigated at US$45 kg^{-1} NH_3 abated. The costs per kg NH_3 abated for compaction with the vermiculite cover or acidified vermiculite cover were much lower.

The highest cost of the selected NH_3 abatement options was US$74 cow^{-1} $year^{-1}$ for the acidified vermiculite cover for the slurry store, which corresponded to ~16% of the profit for dairy production in China.[21,36] In the present study, the total cost for technical implementation of the NH_3 abatement options was divided into three parts including investment, fixed operation, and variable operation costs. The variable operation cost of the selected NH_3 abatement options accounted for the largest share of the total cost, ranging from 46 to 100% (Figure S5). In absolute number, the variable operation costs ranged from US$0.3 to US$72 cow^{-1} $year^{-1}$. The investment cost for the acidification option in animal housing was very high at US $4.8 cow^{-1} $year^{-1}$, equivalent to 47% of the total cost. Also the variable operation costs, including materials, labor, and energy, were high for the acidification option. Replacement of materials with similar chemical and physical properties with lower prices (e.g., using H_2SO_4 instead of lactic acid for acidifying the vermiculite cover) could be an option for consideration.

Costs for technical implementation of the selected mitigation options were based on assumptions about the technical implementation and related economic parameters. As the equipment and materials were available locally or could be bought online at similar prices varying only slightly in shipping costs, variation in the cost for technical implementation on an animal basis could be negligible. For 2015 in China, the technical implementation of diet manipulation was estimated to directly save US$1536 million, while the cost under other scenarios ranged from US$6 to US$1538 million (Figure 5).

3.2.2. Benefit from Ammonia Emission Abatement Options.

Ammonia abatement options help retain more N in manure, and N retained in manure could replace mineral N fertilizers applied to crop systems. Considering cost saving as a result of reduction in mineral N fertilizers by using manure, the NH_3 abatement options could potentially generate a profit. Cost saving from fertilizer benefit derived from the use of extra N retained in manure was estimated at US$0.3−54 million in 2015 in China (Figure 5). The largest fertilizer cost saving for a single mitigation was with acidification in housing, and the least cost saving was with manure compaction. The large variance in the cost saving from mineral fertilizer was a direct result of the NH_3 mitigation potential of the different reduction options.

In addition to the costs and benefits of implementing the selected mitigation options, we also analyzed the balance. On the basis of technical implementation costs and total mineral fertilizer cost saving for the manure management options, only the cost for plastic film cover on solid manure during storage was so low that the saving in mineral fertilizer cost would produce an economic benefit (US$2.0 million $year^{-1}$) (Figure 5). Using the Monte Carlo simulation, uncertainties for net economic benefit of the selected abatement options were assessed and are shown in Figure S6 in the Supporting

Information. Taking diet manipulation, acidification during housing, vermiculite cover on slurry, and combined measures as examples, the balance between technical implementation and total mineral fertilizer cost saving showed a large regional variation across China (Figure S7). Under the diet manipulation scenario, the net economic benefit was higher in the hotspots of NH_3 emission (e.g., Hebei, Henan, Shandong, Heilongjiang, Inner-Mongolia, Xinjiang, Figures S3 and S7). The "combined measures" scenario showed the same pattern as diet manipulation, because cost saving from diet manipulation dominated the balance. Nevertheless, acidification of manure under slatted floors in housing and vermiculite cover on slurry during storage showed an opposite pattern with considerable net costs for the balance.

Quantification of benefits due to avoided health damage costs has been dealt with separately and has not been analyzed in the uncertainty assessment, as critical additional assumptions need to be considered. Specifically, the "adjustment factor" describing potential different perceptions of human life values (expressed as VOLY) is critical. Using an adjustment factor of 10%, avoided damage costs ranged from US\$0.4 to US\$27 kg^{-1} NH_3 emission in the different provinces (Figure S8), with an average of US\$3.5 kg^{-1} NH_3 emission for all of China in 2015. Using the same cost set as used for Europe,[28,29] the health damage costs would be much higher at US\$3.9−268 kg^{-1} NH_3 emission in the different provinces. Taking diet manipulation, acidification during housing, vermiculite cover on slurry, and combined measures as examples, higher health damage costs occurred in eastern China, which coincided with higher population densities, reflecting a larger population exposure and a more developed economy with a potentially greater willingness to pay for health.[37]

Taking health damage cost (VOLY from the European data set) into consideration, all the abatement options investigated in this study, except for solid manure compaction, would be profitable (Table S5). However, large regional variation in the balance between technical implementation cost, mineral fertilizer cost saving, and health damage cost saving can be seen in Figures S9 and S10. Except for Inner-Mongolia and Xinjiang, the balance for all regions showed a net economic benefit, which was highest in regions with the greatest population and large NH_3 reduction potential. With health damage costs reduced to 10%, rewards were much smaller and only some of the emission abatement options resulted in net economic benefit (Table S5 and Figure S10), i.e., the cover for liquid manure or slurry, plastic film cover, acidification, and low protein feed. Acidified coverage of stored slurry and liquid manure showed no net economic benefit due to the high implementation costs of these options.

Potential economic benefits of the abatement options presented in this study depend on many factors that are also uncertain. Specifically, the costs of the options, animal numbers, NH_3 emission rate, and parameters determining that emission rate affect the overall economic valuation. Hence, the underlying uncertainties also affect the net economic benefit of the respective mitigation options. The Monte Carlo simulation and associated sensitivity tests, which are detailed in Supporting Information, help to understand these effects. It becomes evident that the conclusions remain robust under most conditions. Their impact is small compared to the assumptions about health damage cost saving based on NH_3 reduction. As already noted, choosing the more health-conscious cost range with the European data set may shift the overall cost balance toward selecting almost any of the mitigation options.

3.3. Implications.

Dairy production is projected to contribute 15% of total NH_3 emission in China by 2030,[5] which might lead to a great environmental and health risk. Previous studies have been conducted in Europe, mainly focusing on NH_3 reduction, related cost, and benefit for dairy production.[16,24,28,29] In this study we have made a comprehensive analysis of ammonia mitigation potentials, technical implementation costs of the selected technologies, and their related potential benefits based on the models of NUFER and GAINS and the data from experimental trials and local surveys. This is the first study for this kind of comprehensive analysis for dairy cattle production in China, which provides consolidate support for controlling the air pollution from dairy farm manure management practices and contributes important knowledge for further developing cost-effective mitigation measures for NH_3 emissions. Our results showed that diet manipulation, acidification of the manure surface, and vermiculite coverage on slurry during storage could reduce 144, 106, and 65 Gg NH_3, respectively, with economic benefits of US\$4.4, US\$1.1, and US\$0.6 billion, respectively, from Chinese dairy production in 2015. However, our estimation of the benefits remains conservative and incomplete.

Atmospheric NH_3 is not just a precursor to particulate matter (PM), which negatively affects human health—an issue that has been considered in this analysis; it is also a precursor for tropospheric ozone and can decrease plant productivity.[38] Nitrous oxide (N_2O), the third most important greenhouse gas, can be produced as a result of NH_3 being deposited on soils.[39] Also global warming effects on ecosystems are contributed to by ammonia emissions.[39] These effects and the potential benefits of avoiding them have not been integrated in this study. Reducing protein levels in animal diets could directly lower the cost of animal production, while a change in diet ingredients also poses an opportunity to reduce potential environmental damage from the fodder production, processing, and transportation sectors.[40,41] Considering all the elements mentioned, benefits further increase over costs; consequently, the mitigation measures might be even more profitable (population benefit rather than profit to farmers). Moreover, a regional analysis pointed out that hotspots of NH_3 reduction potential coincided with a higher net benefit, implying that mitigation of NH_3 emission via most of the selected measures is cost-effective and needs urgent attention, especially in the more developed regions of China with large population densities. On the basis of this, more effort to promote NH_3 reduction from dairy production is needed and is also economically beneficial, even if only on a national scale rather than for an individual farm. It is likely that this statement holds true for livestock production in general.

Uncertainties in our analysis are mainly related to the input values and parameters used in the GAINS and NUFER models used for emission calculations. As shown earlier, results are robust beyond these uncertainties. The translation of reduction efficiencies for the mitigation measures from lab scale to farm and regional scale is provided with uncertainty estimates in this study. Some studies on reduction efficiencies have been performed,[16] but only a few of them for Chinese conditions. Hence, there is insufficient data at farm scale to provide accurate estimates for different regions of China. Therefore, the results from the laboratory trials were considered to be a reliable source of information about reduction efficiencies for application in Chinese dairy production systems, and the present study with uncertainty analysis provides an important contribution to close this knowledge gap. On the basis of the methods of technical implementation used in this study, all the selected measures should be able to be applied to all regions in China. For these reasons the results from the present study could represent an optimized reduction potential for dairy production in China.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.9b04284.

> Ammonia measurements for abatement options, reduction efficiency, and uncertainties (PDF)

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Notes

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