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Ammonia volatilization from synthetic fertilizers and its mitigation strategies: A global synthesis

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ABSTRACT

Ammonia (NH_3) volatilization is a major pathway of nitrogen (N) loss in agricultural systems worldwide, and is conducive to low fertilizer N use efficiency, environmental and health issues, and indirect nitrous oxide emission. While mitigating NH_3 volatilization is urgently needed, a quantitative synthesis is lacking to evaluate the effectiveness of mitigation strategies for NH_3 volatilization from synthetic fertilizers applied in agricultural systems. To fill this knowledge gap, we conducted a meta-analysis of 824 observations on impacts on NH_3 volatilization of '4R Nutrient Stewardship' (right source, rate, place and time), farming practices (irrigation, residue retention, amendments), and enhanced efficiency fertilizers (fertilizers with urease inhibitors, nitrification inhibitors or controlled release coatings). We found that, globally, up to 64% (an average of 18%) of applied N was lost as NH_3. The use of non-urea based fertilizers, deep placement of fertilizers, irrigation, and mixing with amendments (pyrite, zeolite and organic acids) significantly decreased NH_3 volatilization by 75, 55, 35 and 35%, respectively. In contrast, NH_3 volatilization was not affected by split application, but significantly increased with N application rate and residue retention. Among the enhanced efficiency fertilizers, urease inhibitors and controlled release fertilizers decreased NH_3 volatilization by 54 and 68% respectively whereas nitrification inhibitors increased NH_3 volatilization by 38%. These results confirm that NH_3 volatilization represents a substantial loss of N from agricultural systems, and that this N loss can be mitigated through adaption of appropriate fertilizer products and/or improved management practices.

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1. Introduction

The excessive release of reactive nitrogen (Nr) poses adverse impacts on the natural biogeochemical cycle of N, causing negative consequences on water, air and land (Fowler et al., 2013; Galloway et al., 2008). As a species of Nr, ammonia (NH_3) is lost via volatilization as one of the main pathways of N loss in agricultural systems. While >40% of the applied N is reported to be lost as NH_3 under certain environmental and edaphic conditions (Singh et al., 2013), an average of 10–14% of N is lost via volatilization from synthetic fertilizers (Bouwman et al., 2002; De Klein et al., 2006). Globally, the approximated demand for N fertilizers was 112 million tons of N in 2014 (FAO, 2015). Using the IPCC default value (10%, De Klein et al., 2006) and Bouwman et al. (2002)'s average value (14%) for volatilization from applied N, 11.2–15.7 million tons of fertilizer-N are lost as NH_3-N globally. This N loss as NH_3 represents a substantial financial cost to farmers. Furthermore, based on the IPCC's default emission factor for indirect N_2O emission from N volatilization and deposition (EF_4) of 1% (De Klein et al., 2006), this loss equates 0.1–0.16 million tons of indirect N_2O-N emission, or 52.4–73.5 million tons of carbon dioxide equivalent (CO_2-e). However, this indirect connection between NH_3 and N_2O emissions is often neglected, and in most countries, there are no regulations or incentive programs to tackle the challenge of NH_3 volatilization (Behera et al., 2013).

Mitigation strategies for NH_3 volatilization from N applied in agricultural systems are widely studied. The 4R nutrient stewardship concept (right fertilizer source, rate, place and time) was introduced by Bruulsema et al. (2009) to achieve cropping system goals with economic, social and environmental benefits. For example, when compared to urea (the most commonly used N fertilizer), alternative N source such as ammonium sulphate, diammonium phosphate and calcium ammonium nitrate decreased NH_3 volatilization by 22–55% (Bayrakli, 1990). It is widely reported that NH_3 volatilization increased with N application rate (Black et al., 1985; Bosch-Serra et al., 2014; Turner et al., 2012).

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Sub-surface banding or deep placement of urea reduced NH_3 volatilization when compared to surface broadcast of urea on calcareous or well-buffered soils (Cai et al., 2002; Rao and Batra, 1983). Rochette et al. (2013) found that urea applied at depths >7.5 cm resulted in negligible NH_3 volatilization. Split, band application decreased NH_3 volatilization when compared to a single, surface application (Junejo et al., 2013). However, in Rodgers et al. (1984)'s study, NH_3 volatilization tended to increase under split application in summer.

Farming practices such as adjusting irrigation amount can mitigate NH_3 volatilization by 47–90% (He et al., 2014; Holcomb et al., 2011; Zaman et al., 2013). In contrast, compared to zero water application, NH_3 volatilization was increased by 9% when a 3 mm water was added to the soil immediately after urea application (Sanz-Cobena et al., 2011). The retention of crop residues on the soil surface is a common feature in conservation farming. Nevertheless, this may form a barrier which prevents urea from reaching the mineral soil, and may increase NH_3 volatilization (Su et al., 2014). Recent studies focused on mitigating NH_3 volatilization using inexpensive amendments such as natural mineral or industrial by-products or chemicals that have high ammonium binding capacity e.g. zeolite (Ahmed et al., 2006b; Bundan et al., 2011) or acidifying effects e.g. humic acid or fulvic acid (Ahmed et al., 2006a; Reeza et al., 2009).

In addition to farm management practices, there have been numerous studies on enhanced efficiency fertilizers in mitigating NH_3 volatilization from agroecosystems. For example, urease inhibitor N-(*n*-butyl) thiophosphoric triamide (NBPT) was found to be more effective than phenyl phosphorodiamidate in retarding urea hydrolysis and more widely used because NBPT works at a low concentration and is easy to store (Chien et al., 2009; Saggar et al., 2013). Nonetheless, the effects of urease inhibitors varied with edaphic and environmental conditions (Suter et al., 2013). Controlled-release fertilizers such as polymer sulphur-coated urea and polyolefin-coated urea can improve N use efficiency, grain yield and pasture quality (Chen et al., 2008). However, Hawke and Baldock (2010) found that sulphur coated urea showed higher NH_3 volatilization (10%) compared to uncoated urea. Nitrification inhibitors prevent or slow the microbial conversion of ammonium (NH_4^+) to nitrate (NO_3^-) (Lee et al., 1999). Although nitrification inhibitors are designed to target N_2O emissions, the use of these inhibitors may prolong the retention of NH_4^+ in the soil resulting in NH_3 volatilization (Kim et al., 2012; Lam et al., 2016; Ni et al., 2014).

While studies on the mitigation strategies for NH_3 volatilization are sometimes inconclusive, a systematic synthesis of these studies is lacking. To fill this knowledge gap we report the results of a quantitative synthesis of the current literature on the mitigation strategies of NH_3 volatilization to provide critical information on how to minimize N loss as NH_3 in agricultural systems. The information is crucial for improving global fertilizer N use efficiency, environmental quality, and climate change mitigation.

2. Materials and methods

2.1. Database compilation

This meta-analysis was conducted based on studies of the effects of mitigation strategies (the 4R nutrient stewardship, farming practices and enhanced efficiency fertilizers) on NH_3 volatilization in cropping and pasture systems published from 1971 to February 2016. We performed extensive keyword searches of several databases (Web of Science (ISI), SCOPUS, CAB Abstracts (ISI), Academic Search complete (EBSCO) and Google Scholar), and the reference list of cited references. The keywords used in the search included ammonia/NH_3 emission; volatilization; loss and/or mitigation; management practice; fertilizer N source; rate; time; place; split application; irrigation; urease inhibitors; controlled release fertilizers; nitrification inhibitors; name of the inhibitors such as NBPT; DCD; DMPP; agriculture; cropping; pastures; and their combinations. Original data were extracted from tables and data values presented in figures were obtained using digitizing software (Engauge Digitizer). Studies were included if they met the following criteria. The sample sizes and means of NH_3 volatilization had to be reported for control and treatment plots. Details on experimental location; year; design and conditions must be provided to enable the cross checking of duplicate publication. Multiple observations from the same experimental site over sampling time or year of study were averaged. For fertilizer source; we treated urea (the most commonly used N fertilizer that is associated with NH_3 volatilization) as a control and the other fertilizers as treatments. Fertilizer source was sub-divided into non-urea and urea-mixed fertilizers. For fertilizer application rate (kg N ha^{-1}); we calculated the factor of application rate relative to the lowest N rate (x); and was grouped into $1 < x \leq 2$; $2 < x \leq 3$; $3 < x \leq 4$ and $x > 4$. Location of fertilizer application included deep placement of fertilizers relative to surface application of fertilizers (control). Fertilizer application time was categorized according to the splitting frequency (singe application or splitting 3 or 4 times). Application time in terms of plant growth stage was excluded in the analysis because most of the relevant studies did not have a proper control treatment for growth stages. Irrigation management included irrigation as the treatment; whereas no irrigation (rainfed) and supplementary irrigation (to keep the plants alive) were treated as the control. Materials added as amendments comprised pyrite; zeolite and organic acid; as these materials have been widely studied on their use in tackling NH_3 volatilization. Enhanced efficiency fertilizers were classified into fertilizers added with urease inhibitors; nitrification inhibitors and controlled release coatings. A total of 824 observations (145 studies) were included in the meta-analysis (references are listed in Appendix S1 in Supplementary materials). A database (see Supplementary Tables S1–S10) was compiled based on these literatures and classified into different categories.

This database encompasses the majority of studies that reported NH_3 volatilization from cropping and pasture systems. From this, we assessed the significance of NH_3 volatilization from these systems and expressed the NH_3-N volatilization as a percentage of N applied. To determine NH_3 volatilization without the effect of mitigation strategies under field conditions, we assembled field experimental data from the treatment of surface broadcast of urea fertilizers (78 observations). The results were categorized by continents viz. Asia (East Asia, South Asia, Southeast Asia), Australasia, Europe, North America and South America (Table 1).

Table 1
Nitrogen loss as NH_3 of applied urea from agricultural land worldwide.

Continent	N loss as NH_3					
	%			kg N ha^{-1} per cropping season		
	Mean	Median	Range	Mean	Median	Range
Asia						
East Asia	15.9	13.3	1.7–48.0	20.6	16	1.8–96.0
South Asia	30.7	21.9	3.0–56.7	37.5	27.2	5.6–69.7
Southeast Asia	16.1	14.5	14.4–19.5	10.7	8.7	8.6–14.6
Australasia	16	18.5	2.0–30.0	13.7	11.2	0.8–49.2
Europe	13	10.6	0.9–29.8	17	17.8	0.6–29.8
North America	17.5	15.3	0.6–64.0	22.2	20.5	0.6–89.6
South America	14.2	13.3	1.7–31.8	11.8	10.1	0.9–25.4
Average	17.6	15.3	0.9–64.0	19.1	15.9	0.6–96.0

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