



Design and Validation of a Laboratory System for Measurement of Volatilized Ammonia

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ABSTRACT

The design of laboratory systems for studying ammonia (NH_3) released from fertilizers varies widely, and few designs have been tested to determine the accuracy and precision in measuring NH_3 loss. A standard volatilization system design is needed for reliable and comparable studies of NH_3 volatilization from N fertilizer. The objectives of this study are: (i) to describe the design of a system capable of controlling air flow rate and temperature for laboratory measurement of NH_3 volatilized from N fertilizers; and (ii) assess the system's efficiency and variation in recovering NH_3 lost from NH_4Cl applied to an alkaline sand media. The system is comprised of individual chambers for soil and fertilizer, where temperature can be varied from room temperature to $\sim 32^\circ\text{C}$; humidity is maintained near saturation, air flow rate can be varied, and acid traps are used to capture volatilized NH_3 . Two initial trials (I and II) were conducted at an N rate of 90 kg N ha^{-1} using air flow rates of 2.00 and 1.00 L min^{-1} and trapping acid volumes of 50 and 100 mL , respectively. A third trial was conducted at 30°C . A fourth trial (IV) was performed using a range of N application rates (25 – 250 kg N ha^{-1}). The system recovered 89.3 to 97.1% of the N applied over all four trials and provided accurate and repeatable results under the conditions tested. Rapid, precise comparisons of NH_3 volatilization losses from N fertilizers under laboratory conditions can be made with this system.

VOLATILIZATION OF NH_3 from N fertilizers is one of many processes where N is lost from the soil environment. Volatilization of NH_3 after fertilizer application did not receive substantial attention as a possible source for N loss until the 1950s (Frey et al., 1983). Ammonia volatilization reduces N-use efficiency (defined as N yield per unit of applied N) and creates uncertainty in the management of N at the farm level. The study of NH_3 volatilization requires equipment and practices that limit direct and indirect influences of factors that affect the volatilization of NH_3 . Developing models to accurately predict NH_3 volatilization amounts in cropping systems, pastures, or forests is difficult given the complexity of these biological systems.

Methods of measuring NH_3 volatilization from N sources, organic amendments, or inorganic fertilizers can be divided into two general classes: (i) in situ and (ii) in-lab or controlled environment experiments. All in situ NH_3 volatilization methods are disadvantaged by the inability to control climatic factors (e.g., rainfall timing and amount, humidity, and temperature) that directly influence NH_3 volatilization rates. These studies typically monitor these factors, but are unable to replicate exactly the factors across multiple studies or treatments unless all are performed during the same period and on

the same site. Also, seasonal fluctuations limit the period in which reliable in situ studies can be performed.

In-lab controlled studies can maintain environmental factors affecting NH_3 volatilization across multiple treatments and multiple treatment periods. Also, in-lab studies can be performed year-round with limited time needed for set-up between treatment periods. Reduced sample sizes allow for a larger number of treatments and replications. Results obtained from well-designed systems can provide reliable comparisons between treatments.

The primary method to measure NH_3 volatilization in laboratory studies uses a closed chamber, containing soil and N fertilizer amendments to be evaluated, and forced air flow across the treatment surface with an acid trap to capture the volatilized NH_3 (Hargrove and Kissel, 1979; Terman, 1979; Shi et al., 2001; Kissel et al., 2004; Portejoie et al., 2004; Todd et al., 2006; Cole et al., 2005; Miles et al., 2008; Ndegwa et al., 2009). Many in-lab systems have incorporated humidification features, temperature controls, acid traps to scrub NH_3 from air being drawn into the system, and air flow controls. The design of in-lab systems is inconsistent, but performance of several laboratory systems used to measure ammonia volatilization have been studied and NH_3 recovery values have varied from 72.9 to 103% with varying levels of consistency in the measurements (Table 1). Currently, in-lab volatilization systems are primarily being used to measure NH_3 released from manures (Cole et al., 2005; Miles et al., 2008; Portejoie et al., 2004; Shi et al., 2001; Todd et al., 2006). Inorganic fertilizer studies using in-lab systems are less common, but are increasingly being performed (Knight, 2007; Rochette et al., 2009; Susilawati et al., 2009). The detailed construction and operation of in-lab systems vary among studies, and again, few experiments have examined factors affecting NH_3 recovery within the specific system (Miles et al., 2008;

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Abbreviations: ATE, acid trap efficiency; RO, reverse osmosis; SRE, system recovery efficiency.

Table 1. Comparison of system efficiencies and variation for laboratory systems measuring NH₃ volatilization.

Study	N Source	Trapping acid	System efficiency†	System variation
		M (volume)	%	
O'Halloran (1993)	liquid hog manure	0.32 M H ₃ BO ₃ (50 and 100 mL)	82.1–83.5‡	nr§
		or 0.9 M H ₂ SO ₄ (50 mL)	94.9‡	nr
Kissel et al. (2004)	granular urea	0.05 M H ₂ SO ₄ (50 mL)	72.9–100.6‡	nr
Todd et al. (2006)	cattle manure	0.9 M H ₂ SO ₄ (100 mL)	nr	2.67 mg¶
Cole et al. (2005)	cattle manure	0.9 M H ₂ SO ₄ (100 mL)	nr	1.45¶ mg
Miles et al. (2008)	poultry litter	H ₃ BO ₃ (60 mL)	nr	2.6–6.3%#
Ndegwa et al. (2009)	NH ₄ Cl	0.2 M H ₂ SO ₄ (150 and 470 mL)	93.5–94.8	nr
Torello et al. (1983)	(NH ₄) ₂ SO ₄	1.5 M H ₃ BO ₃	95.1–103.0	nr

† System efficiency is accountable N post trial divided by applied or previously present N.

‡ Calculated from data provided in article for comparison reasons.

§ Data not reported in article.

¶ Standard error of the mean NH₃ recovered in the acid traps.

Standard deviation of the mean NH₃ recovered in acid traps.

Ndegwa et al., 2009). These factors include: air flow rate, trapping acid (source, concentration, and volume), temperature and humidity conditions. To ascertain the validity of data from controlled environment systems, newly designed in-lab systems need to be tested to determine the system's NH₃ recovery efficiency within an estimated range of potential NH₃ volatilization rates.

The objectives of this study were to: (i) describe a controlled-environment volatilization system used for laboratory studies of NH₃ volatilization; and (ii) assess the system's efficiency and variation in recovering NH₃ lost from NH₄Cl applied to an alkaline sand media.

MATERIALS AND METHODS

System Design

The NH₃ volatility measurement system as tested consists of three temperature-controlled enclosed cabinets that house six chambers each to which treatments are applied to soil or other media. Humidified (near 100%) air is passed through each chamber above the soil media of each chamber at a constant flow rate and temperature. Air exiting the chamber is collected by acid traps to recover NH₃ lost by volatilization. Soil temperature within each chamber is monitored using thermocouples to ensure accurate and even temperatures within and across each chamber (Brooks Whitehurst Associates Inc., New Bern, NC). A materials list and prices are in Table 2 and the schematic for the system is shown in Fig. 1.

The enclosed cabinets are constructed using 9.5 mm thick plywood with the internal dimensions of 61 cm in width, 61 cm in length, and 46 cm in depth. The lid of the cabinets lifts off and was constructed to overhang the outside edge of the cabinet. The lid has a rim that fits securely within the internal dimensions and was insulated using 13 mm thick polystyrene sheath insulation (*R* value = 3). The temperature within the cabinets is controlled using a 1/32 Din programmable controller (CN7533, Omega Engineering Inc., Stamford, CN). The air temperature sensor (RTD-805, Omega Engineering Inc., Stamford, CN) used by the temperature controller is mounted on the opposite side of the cabinet from the heating element. The heating element was fabricated by attaching a silicone rubber heat strip (2.5 cm by

20 cm, 80 W total, SRFG-108/10-P, Omega Engineering Inc., Stamford CN) to an angular aluminum strip mounted on a rectangular block (4.1 cm by 4.1 cm by 20 cm long–90°). An electric fan (2000 rpm, 120 by 120 by 25 mm, 115 V, 60 Hz, 0.10 A) (BT12025B1L, CoolerGuys.com, Kirkland, WA) was placed above the heating element to disperse heat and circulate air inside the cabinet. A wooden baffle (19 mm wide, 30.8 cm long, 28 cm tall) with ends that angle (10–30°) toward the chambers (14 cm long outside and 13 cm long inside) facilitates air circulation around the chambers. A raised platform for the chambers are used to ensure uniform heat dispersal around the chambers (Fig. 1). The air supply to the entire system is provided by an oil-less linear air pump (DDL80–101, Gast Manufacturing Inc., Benton Harbor, MI) that pressurizes and fills a supply tank. This pump has a max power output of 93 W, air flow rates range from 111 to 120 L min⁻¹ from 50 to 60 Hz, and maximum pressure of 0.48 bars. The lines carrying the air from pump to the supply block are 16 mm OD and 13 mm ID vinyl lines. The air pressure is monitored and regulated for the system at the supply tank. Air exiting the supply tank is supplied to three distribution manifolds via the same size vinyl line entering the supply tank. All fittings and connections for the 16 mm vinyl lines are secured by plastic hose clamps (SNP-2, Cole-Parmer Instrument Co. 95613-03) Each distribution manifold is used to supply air to six flow meters (0.4–5.0 L min⁻¹ flow meters- EW22461–50, Cole-Parmer Instrument Co., Vernon Hills, IL). Air exiting the distribution manifold flows through 6.4 mm OD and 4.3 mm ID vinyl hose. This size vinyl hose carries the air throughout the rest of the system. All fittings and connections for this size vinyl hose are secured with SNP-1 plastic hose clamps (Cole-Parmer Instrument Co. 06832-01) Air from the flow meters is then sparged through air stones (Coarse Bubbles, Kordon LLC., Hayward, CA) to reduce the bubble size inside a set of closed cylinders (external humistats) containing water purified by reverse osmosis (RO). This step saturates the air before entering the temperature controlled cabinet. Air exiting the external humistats is sparged through a second set of air stones inside a second set of closed cylinders containing RO water (internal humistats) within the controlled-temperature cabinets. This

Table 2. Detailed materials list with appropriate costs for volatilization system.

Section	Description	Quantity	Approximately cost†	Total cost†
Air supply	air pump	1	530	
	supply tank	1	100	
	distribution manifold	3	45	
	flow meter	18	1440	
	external humistat	18	500	
	internal humistat	18	200	
	tubing and connections		150	
Cabinet structure	61 by 61 cm paneling	15	165	
	lid panel	3	25	
	insulation	3	55	
	baffles	3	20	
	chamber cradle	3	130	
	misc. lumber and hardware		50	
Power supply	flanged inlet	3	70	
	red indicator lamp	3	15	
	enclosure	3	130	
	green indicator lamp	3	20	
	switch	3	25	
	terminal strips	6	40	
	wiring		10	
	power cord, 2.44 m	3	15	
Temperature control	controller	3	270	
	air sensor	3	260	
	heat strip, 20 cm	3	55	
	fan	3	55	
	wiring and connections		10	
Temperature data collection	A/D converter	3	3750	
	thermocouples	18	510	
Chamber	three hole cap	18	3630	
	beaker	18	840	
	fittings		30	
Calibration	traceable thermocouple	1	590	
	flow meter	1	900	
	drying tube	1 pk	30	
	fittings		50	
			Total	14,715

† U.S. currency.

ensures no decrease in humidity due to the change in temperature between outside and inside the cabinet. Also, the second humidification step ensures the air temperature is brought to the temperature within the cabinets. The system was designed to increase the humidity of the air entering the chambers to a level that approaches 100% humidity and levels cannot be varied with the current system. Air from the internal humistats is routed into the individual chambers and then into an acid trap specific to each chamber. Since this is a laboratory system and based on the assumption that ambient NH_3 concentrations are below our capacity to detect, the humistats are for humidity purposes only and do not act as NH_3 scrubbers.

The chambers consist of threaded 100 by 150 mm beakers (21650 B, Kimble Chase Life Science and Research Products LLC, Vineland, NJ) and three-hole plastic caps (21650 C3, Kimble Chase Life Science and Research Products LLC, Vineland, NJ). Two 9.5 mm holes with threaded fittings (threaded on top surface) are used in the cap for the air entry and exit ports, and a third 3.2 mm threaded hole is used to position the thermocouple into the soil media. The air entry port uses

a portion of a small PVC pipe, same size as the incoming vinyl tubing, allowing the air to enter 6.4 mm above the soil surface. The air exit port extends 6.4 mm below the bottom face of the lid. The design allows for the air to move across the soil surface collecting ammonia, before being forced up exiting the chamber. Once filled the head space above the sand is 0.527 ± 0.005 L, and at an air flow rate of 1.00 L min^{-1} the air within each chamber is replaced every 32 s.

Temperature data from the soil media chambers were collected by type T thermocouples (TT36-18U-6-SB, Omega Engineering Inc., Stamford, CN). Analog signals from the thermocouples were converted to digital temperature readings using a 22 bit A/D converter (DAQ-56, Omega Engineering Inc., Stamford, CN). Temperature data from type T thermocouples and temperature control equipment were calibrated against a NIST Traceable digital thermistor (90080-12, Cole-Parmer Instrument Co., Vernon Hills, IL). Software provided with the A/D converter enables temperature data storage on the linked computer.

The acid traps were 125 mL plastic bottles (PCR8DB, Specialty Bottles, Seattle, WA) filled with 50 or 100 mL of acid

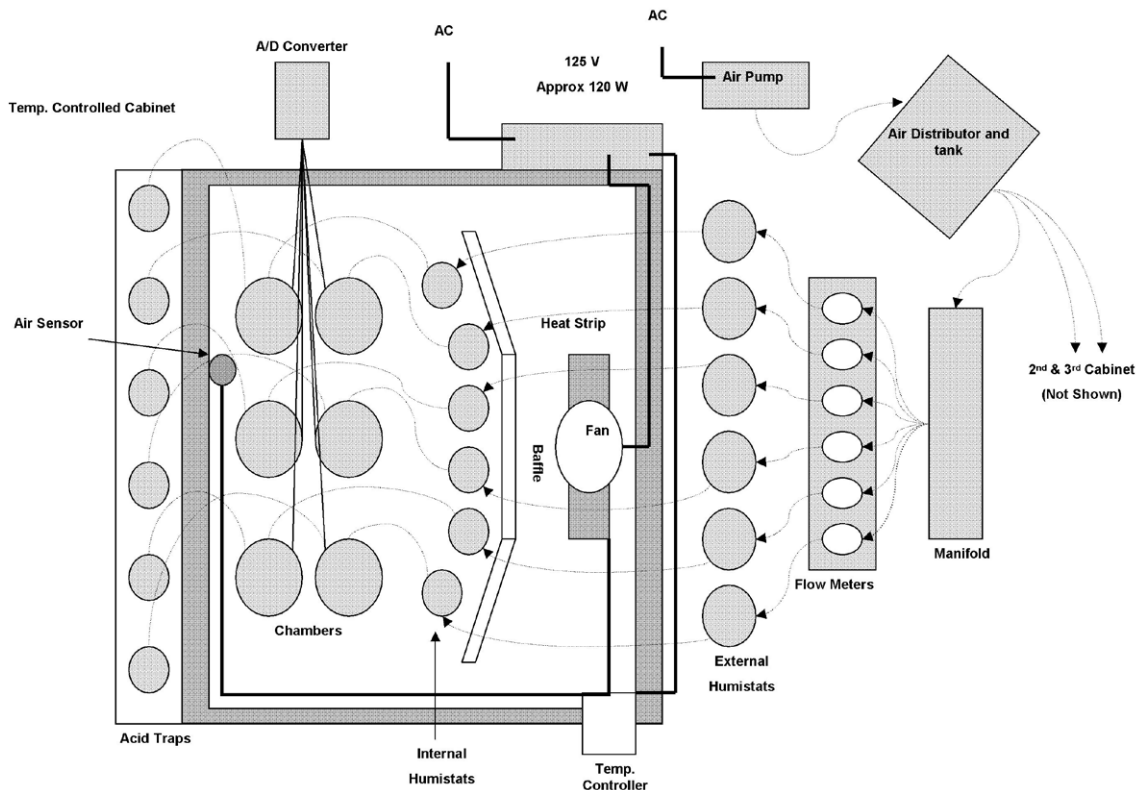


Fig. 1. General schematic of the system evaluated for in-lab NH_3 volatilization measurements.

solution. An air stone is used in each acid trap to reduce the bubble size passing through the 0.02 M phosphoric acid solution.

System Validation

To validate the laboratory system, four loss-and-recovery trials (I, II, III, and IV) were conducted to determine the recovery efficiency and variability of NH_3 volatilization between each individual chamber. We used a similar method outlined by Cabrera et al. (2001) in that we applied ammonium chloride (NH_4Cl) to an alkaline sand media. The sand media was a mixture of CaCO_3 and sand, purchased at a local hardware store. Trials I and II tested the accuracy and precision of the system to measure NH_3 loss at different air flow rates and acid trap volumes at a standard N rate of 20 mg N per chamber (90 kg N ha^{-1}) and a temperature of 26°C . Nitrogen rates were based on a weight basis, using 2.245 million kg soil per ha furrow slice, then calculating the 90 kg N ha^{-1} rate. Nitrogen was applied as an ammonium chloride solution to deliver the required N rate by dripping 5 mL of solution on the surface of the sand- CaCO_3 mixture. Trial III evaluated accuracy and precision of the system at 30°C . Trial IV tested the system over multiple N rates using the most accurate and precise air flow and acid trap volumes determined from Trials I and II.

The duration of Trial I was 3 wk (504 h). We limited the run length of Trials II, III, and IV to 2 wk as volatilization losses were minimal after 2 wk. The air flow rates were 2.00 L min^{-1} and 1.00 L min^{-1} for Trials I and II, respectively. The volume of acid in the acid traps for Trials I and II were 50 and 100 mL, respectively. Trial II air flow rate and acid volume were found to produce more precise NH_3 loss measurements; therefore, an air flow rate of 1.00 L min^{-1} and an acid volume of 100 mL were used

for Trial III, at a temperature of 30°C , and Trial IV with multiple N rates. Nitrogen rates for Trial IV were 0, 25, 50, 150, 200, and 250 kg N ha^{-1} replicated three times. The temperature during Trials I, II, and IV was $26.0 \pm 0.5^\circ\text{C}$ and $30.0 \pm 0.3^\circ\text{C}$ for Trial III.

The set-up of the system before commencing a trial consisted of making the alkaline sand media by adding calcium carbonate (CaCO_3) to oven-dried (60°C) sand at a rate of $12.5 \text{ g CaCO}_3 \text{ kg}^{-1}$ dry sand. The mixture was brought to 20% moisture and oven dried overnight at 60°C . The wetting-drying step was repeated three times to ensure the pH of the mixture equilibrated (pH 7.8–8.1). Five-hundred grams of the oven-dried mixture were placed into each chamber and the chambers placed inside the cabinets. Air flow was then calibrated using an National Institute of Standards and Technology (NIST) Traceable (<http://www.nist.gov/index.html>) digital flow meter (FMA 1700/1800, Omega Engineering Inc., Stamford, CN) at the inlet to each chamber. The external and internal humistats were filled with 900 and 450 mL of reverse osmosis (RO) purified water, respectively. The internal humistats were positioned in the cabinet and the cabinet temperature controls set to the desired temperature. The water in the internal humistats and the sand- CaCO_3 mixture was allowed to come to temperature overnight (~12 h).

The following day RO water was added to the sand- CaCO_3 mixture to attain 10% moisture content. The acid trap bottles for the initial sampling interval were filled to the desired volume with 0.02 M phosphoric acid and placed in position. A 5 mL NH_4Cl solution at an N concentration to deliver the desired N rate was surface applied onto the sand- CaCO_3 mixture. All air connections were secured and the pump was engaged to commence the trial.

Table 3. Volatilization N loss, acid trap N recovery, system N recovery and calculated efficiencies for Trials I, II, and III with a 90 kg N ha⁻¹ surface application.

Mean†	Trial I‡	Trial II§	Trial III§
	26°C		30°C
Volatilization loss, mg N	19.8 ± 0.2¶	17.4 ± 0.3	18.1 ± 0.3
Acid trap N recovery, mg N	18.7 ± 0.4	16.8 ± 0.4	16.7 ± 0.4
System recovery, mg N	18.8 ± 0.3	19.4 ± 0.3	18.6 ± 0.2
SRE#, %	94.1 ± 1.5	97.1 ± 1.6	93.0 ± 1.2
ATE, %	94.0 ± 1.6	96.7 ± 1.8	92.2 ± 1.3

† Averaged across all chambers per trial.

‡ 2.00 L min⁻¹ air rate and 50 mL trapping acid.

§ 1.00 L min⁻¹ air rate and 100 mL trapping acid.

¶ mg N ± standard deviation (SD).

SRE, system recovery efficiency; ATE, acid trap efficiency.

Trapping acid was changed with fresh acid at intervals of 1, 3, 6, 9, 12, 24, 48, 96, 144, 192, 240, 288, 336, 388, 432, and 504 h after starting the trial (Trials II, III, and IV ended at h 336). The replaced acid was then weighed and analyzed for NH₃ concentration colorimetrically with a Lachat QuickChem Automated Ion Analyzer (Lachat Instruments, Loveland, CO).

Once the trial concluded, a 5-g sample of dry sand-CaCO₃ mixture from each chamber was extracted using 2 M KCl and analyzed colorimetrically for NH₃ and nitrate (NO₃) with a Lachat QuickChem Automated Ion Analyzer. Moisture content of the sand-CaCO₃ mixture was determined and then used to calculate how much of the mixture was needed to attain a 5-g sample of dry sand-CaCO₃ mixture.

Statistics

Using PROC MEANS for SAS 9.2 (SAS Institute, Cary, NC) mean N captured and standard deviation, for each sampling interval as well as cumulative N captured were computed for each trial. System recovery efficiency (SRE) and acid trap efficiency (ATE) were calculated for all trials using the following formulas:

$$\frac{\text{acidtrapN} + \text{ResidualN}}{\text{Nadded} + \text{PriorN}} \times 100 = \text{SRE}(\%) \quad [1]$$

where:

acidtrapN = cumulative mg N captured in acid traps

ResidualN = total mg N extracted in 2 M KCl from the sand-CaCO₃ mixture after completion of the trial

Nadded = mg N added to each chamber

PriorN = total mg N extracted in 2 M KCl from the sand-CaCO₃ mixture with no N added

SRE = system recovery efficiency

$$(\text{Nadded} + \text{PriorN}) - \text{ResidualN} = \text{VolatilizationLoss (VL)} \quad [2]$$

where:

PriorN = N in media before addition of fertilizer N

ResidualN = NO₃-N + NH₄-N in the media at the end of the trial

VL = volatilization loss

$$\frac{\text{acidtrapN}}{\text{VL}} \times 100 = \text{ATE}(\%) \quad [3]$$

where ATE = acid trap efficiency.

Two samples of the sand-CaCO₃ mixtures with no N applied were taken from two separately mixed batches and used to

calculate PriorN for Trials I and II. Both batches were mixed at the same rates and with the same sources of sand, CaCO₃, and water. No detectable NO₃-N or NH₃-N was present in those samples using the 2 M KCl extraction method and colorimetric analysis.

Analysis of variance was conducted for SRE and ATE using PROC MIXED in SAS 9.2 to determine if acid trapping efficiency changed with N rate in Trial IV.

RESULTS AND DISCUSSION

Trials I, II, and III

Mean volatilization loss, acid trap N recovered, ATE, total N recovered from both the trapping acid and the sand-CaCO₃ mixture after completion of the trial (system recovery), and SRE for Trials I, II, and III are shown in Table 3. Volatilization loss would be a parameter of interest during the study of simulated production systems using this laboratory system. The sand and NH₄Cl system evaluated does not replicate agricultural environments and was only intended to serve as a means to validate the laboratory system. The mean amount of N recovered by the trapping acid was 18.7 ± 0.4 mg N. The mean total amount of system recovery was 18.8 ± 0.3 mg N. The SRE was 94.1 ± 1.5% and ATE was 94.0 ± 1.6%. Mean acid trap N recovery was 16.8 ± 0.4 mg N. The mean system recovery was 19.4 ± 0.3 mg N. The ATE and SRE were 96.7 ± 1.8% and 97.1 ± 1.6%, respectively. These values are similar or exceed the recovery efficiencies shown by Cabrera et al. (2001). The standard deviations of these values indicate that even relatively small, that is, 1 mg N loss during a 2 wk period, treatment differences in future studies should be readily detectable. Upon raising the temperature to 30°C the efficiency of the system decreased in Trial III (Table 3). However, recovery efficiencies were >90% for Trial III, and the variation between chambers was similar to Trial II (Table 3).

Mean cumulative N captured by the acid traps is shown in Fig. 2 for Trials I, II, and III. Between flow rates, temperatures, and acid trap volumes, the amount of N trapped is very similar at the 336 h sampling interval. The standard deviations for total acid trapped at various times in Trials I, II, and III are shown in Fig. 3. Variation in cumulative N captured by the acid traps increases from 1 to 96 h then decreases for the duration of the first three trials. The maximum variation observed at 96 h can be attributed to the longer sampling interval (48 h compared to 24 h), resulting in larger amounts of NH₃ collected in the acid traps. Trial II exhibited less variation in terms of N capture than Trial I, which indicates that by decreasing flow rate to 1.00 L min⁻¹ and increasing the volume of trapping acid to 100 mL the system's variation is decreased. Ndegwa et al. (2009) also found that as the air flow rate decreased, the efficiency of the acid trap increased. Since the acid trap container was kept constant during Trials I and II, doubling the volume of acid resulted in an increase in depth of the acid trap. Ndegwa et al. (2009) also found that deeper acid traps increased the efficiency of the trap. Because air flow rate was decreased and acid depth increased from Trial I to Trial II neither factor can solely be identified as responsible for the increase in acid trap and system efficiency, however both factors may have contributed to the increased recovery observed in Trial II.

Trial III showed that similar cumulative amounts of NH₃ were captured when compared to Trials I and II (Fig. 2). Based

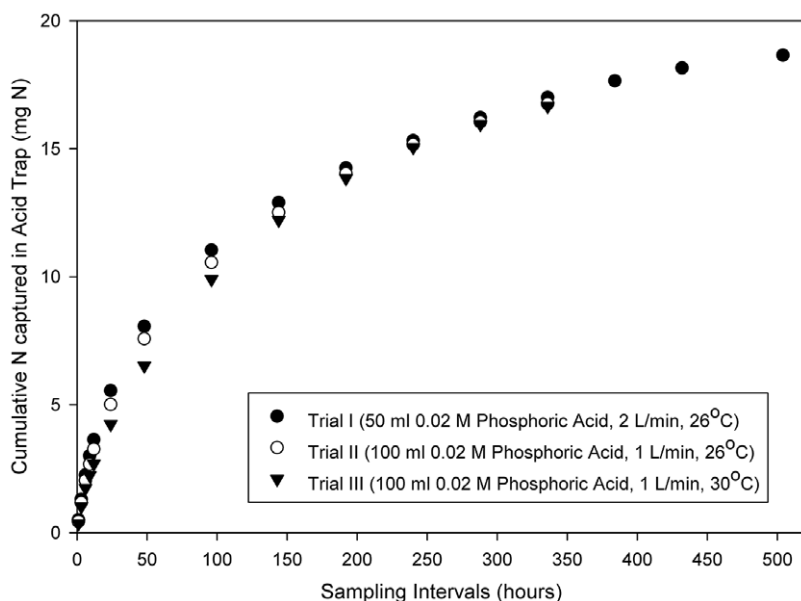


Fig. 2. Cumulative N captured in acid traps during Trials I, II, and III.

on the results from Trials I and II, the same flow rate and acid trap volume were used in Trial III. The variation in values was similar between Trials II and III (Fig. 3). Increasing the temperature to 30°C had little effect on variation among chambers within the system. This is evidence that the system will produce repeatable measurements up to 30°C. Measurements above 30°C were not obtainable due to the heating strip capacity.

From the results of Trials I and II, 100 mL of trapping acid and 1.00 L min⁻¹ air flow rate were chosen to evaluate the system over multiple N rates (Trial IV), since variation between chambers was decreased and SRE and ATE were highest in Trial II (Table 3).

Trial IV (Multiple Nitrogen Rates)

Six N rates were applied randomly to the soil chambers within each cabinet to evaluate the efficiency of the system over a wide range of N application rates. Equations 1, 2, and 3 were used to calculate SRE and ATE for each N application rate and mean

separations can be found in Table 4, respectively. Percentages for the 0 kg N ha⁻¹ are not given because no measurable N was found in the acid traps at each sampling interval or in the sand after the trial was completed. The SRE decreased as the N rate increased with the 25 kg N ha⁻¹ rate having the highest SRE, 95.7 ± 1.5% and 250 kg N ha⁻¹ rate having the lowest with 89.3 ± 2.3%. Standard deviations ranged from 1.5 to 3.0% (Table 4).

The ATE for all N rates applied in Trial IV decreased with increasing N application rates (Table 4). The highest ATE was 95.3 ± 1.2% for the 25 kg N ha⁻¹ rate and was significantly higher than all other treatments. When N rates increased to 250 kg N ha⁻¹ the ATE dropped to 84.7 ± 2.3%, and was significantly lower than all treatments, except the 200 kg N ha⁻¹ rate. The decrease in ATE with increasing N rates agrees with data by Ndegwa et al. (2009), who also found that the efficiency of the acid traps decreases as the amount of ammonia to be trapped increases. System recovery efficiency decreased as

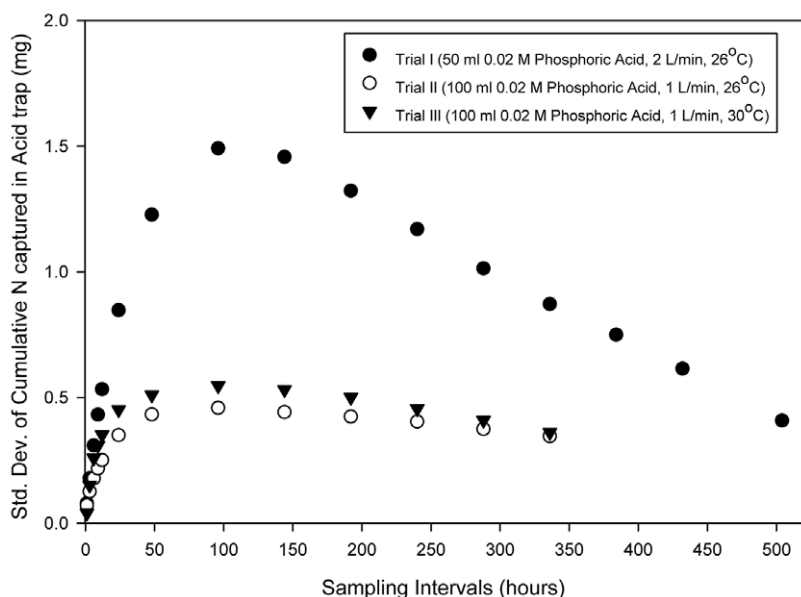


Fig. 3. Standard deviation for cumulative N captured during Trials I, II, and III

Table 4. Mean system recovery efficiencies (SRE) and standard deviation (SD) for all N rates over 2 wk for Trial IV at 1 L min air flow and 100 mL of 0.02 M phosphoric acid trap volume.

N rate	Total acid trap N	SRE	SD	ATE†	SD
kg ha ⁻¹	mg	%			
0	0 f‡	–	–	–	–
25	4.75 e	95.7 a§	1.5	95.3 a¶	1.2
50	8.48 d	93.0 b	3	91.7 b	3.5
150	22.55 c	91.0 bc	2	88.0 c	3
200	26.02 b	90.7 bc	1.1	86.0 cd	1.7
250	32.18 a	89.3 c	2.3	84.7 d	2.3

* Significant at the 0.05 probability level.

† ATE, acid trap efficiency.

‡ LSD 0.05 = 2.49 mg N.

§ LSD 0.05 = 2.4%.

¶ LSD 0.05 = 3.1%.

ATE decreased which is expected since both SRE and ATE are calculated using N captured in the acid traps as a variable.

SUMMARY AND CONCLUSIONS

The need to evaluate a system that will be used in quantitatively measuring a parameter of interest is essential in producing results that are precise and accurate. The laboratory ammonia volatilization system described was able to detect and capture more than 90% of the ammonia volatilized and maintain variation within individual chambers which will allow for reliable comparisons of fertilizer or simulated production systems in future trials. Decreasing the air flow rate to each chamber and increasing trapping acid volumes between Trial I and II resulted in the reduction of variation between chambers and increased ATE and SRE. We believe this is due to the increased time during the gas–liquid interface in the acid traps, which allows for increased conversion of NH₃ to ammonium (NH₄) in the acid. This increased reaction time may also allow the NH₃ to be captured by individual traps more consistently across all chambers. Since the system performed best at an air flow rate of 1.00 L min⁻¹ and with 100 mL of trapping acid this configuration was used for Trial III. The relatively low SD values (1.2–3.5%) for all N application rates indicate that relative comparisons between treatments can be made with confidence.

Increasing the temperature to 30°C decreased the SRE and ATE slightly compared to that of Trials I and II, but was still above 90% at this temperature. The variation remained similar to that in Trial II showing that repeatability did not decrease as temperature increased. With the high recovery efficiencies and low variation this system will be able to operate at temperatures up to 30°C to simulate different environments in future studies.

The SRE and ATE decreased as N rates increased from 0 to 250 kg N ha⁻¹. This range covered N fertilization rates that are routinely used in commercial agricultural production systems. The reduced SRE and ATE rates at higher N rates can be attributed

to the total amount of NH₃ volatilized per unit of time. As NH₃ volatilized per unit time increases, the amount of NH₃ within each air bubble increases, and since the time for the reaction to take place remains constant (constant depth of acid and air flow rate) a lower percentage of NH₃ is successfully captured in the trap. Greater acid trap volumes need to be tested to potentially increase SRE for higher N rates, that is, 200 to 250 kg N ha⁻¹.

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