THESIS

EFFECT OF ORGANIC NITROGEN FERTILIZER SOURCE, APPLICATION METHOD, AND APPLICATION RATE ON AMMONIA VOLATILIZATION FROM DRIP IRRIGATED VEGETABLES

Submitted by

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ABSTRACT

EFFECT OF ORGANIC NITROGEN FERTILIZER SOURCE, APPLICATION METHOD, AND APPLICATION RATE ON AMMONIA VOLATILIZATION FROM DRIP IRRIGATED VEGETABLES

Ammonia (NH_3) volatilization is an important issue with both agricultural and environmental aspects. The hypotheses investigated in this experiment are: i) liquid fertilizers will have lower NH_3 emissions compared with solid fertilizers and ii) application methods which place fertilizers below the soil surface will lower NH_3 volatilization rates. This study was designed to measure apparent NH_3 volatilization from four organic nitrogen (N) fertilizers to evaluate the impacts of fertilizer source, application method, and rate on NH_3 volatilization. The fertilizers used in this study were both solid fertilizers (blood meal and feather meal) and liquid fertilizers (fish emulsion and liquid cyano-fertilizer), and control, which received no fertilizer application. The study was conducted at the Colorado State University Horticulture Field Research Center, Fort Collins, CO in 2014 and 2015. In 2014, two application rates (28 and 56 kg N ha^{-1}) were applied to an organic lettuce (*Lactuca sativa*) crop to evaluate the effect of rate on NH_3 loss. The application schedule was different for each fertilizer type (liquid and solid). Solid fertilizers were applied in a sub-surface band all at once a few days before transplanting, while liquid fertilizers were applied through a drip irrigation system throughout the growing season beginning two weeks after transplanting. The measurements of NH_3 volatilization from solid fertilizer treatments occurred every three days, while on liquid fertilizers, the measurements took place on the first, third, and sixth days following each application. In 2015, the crop used was cucumber

(*Cucumis sativus*), and solid fertilizers were applied using two methods, sub-surface banded and surface banded. In addition, all fertilizers were applied at 28 kg N ha^{-1} in 2015. The NH_3 volatilization measurements on solid fertilizer treatments were taken daily for the first seven days, and after that the measurements were taken every three days until liquid fertilizer application began; then measurements were taken on the third and seventh day of each week. In contrast, NH_3 volatilization measurements from liquid fertilizer treatments were made 1, 3, and 7 days after each application. Moreover, cucumber measurements of length, diameter, weight, fruit number, and plant dry weight were taken to evaluate the effect of the fertilizer treatments on yield. Semi-open static chambers were used to measure NH_3 volatilization. After collecting the samples from the field, samples were extracted using 2M KCl and analyzed using DIN method # 38406. Using a Randomized Complete Block Design (RCBD) with four replications in SAS, the 2014 results indicated that there was a significant difference in apparent NH_3 volatilization among the fertilizer treatments. On the other hand, there was no difference between the application rates. Furthermore, the Tukey-Kramer test specified which treatments were different from each other. Feather meal had greater apparent NH_3 volatilization than cyano-fertilizer and fish emulsion. Blood meal applied at 56 kg N ha^{-1} had significantly more NH_3 loss than cyano-fertilizer and fish emulsion. In addition, NH_3 flux from feather meal at both application rates and blood meal applied at 56 kg N ha^{-1} were also higher than the control with 0.05 mg/cm^2 mean flux (by Dunnet's test), but cyano-fertilizer and fish emulsion had NH_3 fluxes similar to the control. Among the four fertilizers, blood meal at 56 kg N ha^{-1} with a 0.09 mg/cm^2 mean flux and feather meal at both rates with 0.08 and 0.09 mg/cm^2 mean flux had the highest NH_3 volatilization rates compared with other treatments. In 2015, the overall test indicated that there was a significant difference in apparent NH_3 volatilization among the fertilizer treatments. The Tukey-Kramer test showed that surface banded blood meal with a 0.07 mg/cm^2 mean flux and feather meal with 0.09 mg/cm^2 mean flux had higher NH_3 emissions than cyano-fertilizer, fish emulsion, and sub-surface banded blood and feather meals. Furthermore, sub-surface banded blood meal, sub-surface banded feather meal, cyano-fertilizer, and fish emulsion were not different from control with 0.04 mg/cm^2 mean flux. Volatilization from solid fertilizers did not occur immediately and usually peaked within 14 d, while liquid fertilizers had peak volatilization rates immediately following fertigation and declined thereafter. Application methods that involved burying the fertilizers under the soil surface or applying liquid fertilizers through drip irrigation had less apparent NH_3 volatilization. All fertilizer treatments had similar cucumber fruit number in the first harvest, but in the second harvest, surface banded blood meal had the highest fruit number. Sub-surface banded blood meal had the highest cucumber yield in the first harvest, while all fertilizers had similar yield in the second harvest. In addition, there was no significant difference in plant dry weights among fertilizer treatments. Fish emulsion had the lowest cucumber yield compared to the other fertilizers. Temperature and days after application can affect NH_3 volatilization rate according to the correlation results. In 2014, the correlation between NH_3 volatilization and mean soil temperature (at 5-15 cm depth) was not significant for any fertilizer treatments, except feather meal applied at 28 kg N ha^{-1}. In 2015, NH_3 volatilization from solid fertilizers was negatively correlated with soil temperature over the entire growing season, while there was a significant positive correlation when the correlation was calculated for the first ten days only. There was a strong negative correlation between NH_3 volatilization and days after application for all fertilizers in 2014, while in 2015, only solid fertilizers had significant correlation. As hypothesized, liquid fertilizers had lower NH_3 emissions as compared to solid fertilizers due to their timing and placement, while application methods that place fertilizers

beneath the soil surface resulted in lower NH_3 volatilization. No previous studies have compared NH_3 volatilization from these organic fertilizers; therefore, this study provides an important addition to the literature.

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INTRODUCTION

Nitrogen (N) is an essential element for plant growth, plant productivity, and crop quality. Non-leguminous plants can only take advantage of gaseous nitrogen (N_2) after it is fixed by microorganisms in legume nodules or in the soil. Some bacteria (Rhizobium, Cyanobacteria, Azotobacter, etc.) can convert gaseous N into organic N in the form of amino acids. When these microorganisms die, the N in their bodies is mineralized by other microorganisms, which produce mineral N in the forms of ammonium (NH_4^+) and nitrate (NO_3^-), which plants can use. Nitrogen application to the soil as fertilizers is very important to support plant growth, but adding N without proper management can lead to releasing gaseous compounds such as ammonia (NH_3) and nitrous oxide (N_2O). Ammonia is an active form of gas and can quickly interact with nitrate (NO_3^-) and sulfate (SO_4^{-2}) to create a particulate in acid cloud droplets (Sommer and Hutching, 2001). NH_3 volatilization from organic and inorganic fertilizers is a critical concern for many reasons including: i) NH_3 emissions contribute to particulate matter formation in the air that can affect human health and cause regional haze, ii) when excess NH_3 is deposited onto land and water bodies, ecosystems can be negatively impacted, and iii) there is an economic concern due to loss of NH_3 from fertilizer applications, which leaves less available N for plants, leading to lower plant productivity (Meisinger and Jokela, 2000). As a result, as NH_3 emissions from N fertilizer increase, the N use efficiency of crops decreases (Bouwman et al., 2002).

Every year, more than ninety million Mg of N fertilizers are applied to crops around the world (Charles, 2013). Improper use of these substances by farmers can lead to adverse impacts on the environment. Furthermore, when these fertilizers are applied without the optimum methods, plants do not get adequate N for growth, and N can be lost through leaching, runoff, denitrification, and NH_3 volatilization. There are many environmental factors that contribute to NH_3 volatilization from N fertilizers including: high temperature, high soil pH, dry soil surface, and low cation exchange capacity (Jantalia et al., 2012). It is important to optimize fertilizer selection, rate, and application method, in order to protect the environment.

Ammonia volatilization can be significantly affected by application techniques. The application methods which bury fertilizers below the soil surface are better in decreasing ammonia volatilization than broadcasting applications on the soil surface. Huijsmans et al. (2001) reported that about 77% of the total N applied using manure was lost by NH_3 volatilization from surface spreading application while only 20% was lost from narrow-band application and only 6% from shallow injection. Similarly, a result from a study conducted by Potter et al. (2001) showed that 3.9% of total N applied to cotton was lost through NH_3 volatilization when fertilizers were injected 10-20 cm deep using anhydrous ammonia or Urea Ammonium Nitrate (UAN). On the other hand, ammonium sulfate application lost 6.6% of total N applied to an almond orchard using surface application, and no NH_3 loss was measured using UAN injected through micro-sprayer/drip. The result of a third study by Jokela et al. (2013) indicated that 33 to 56 kg/hectare of NH_3- N were lost from pre-plant surface application of manure applied at 168 N kg/ha. The amount of NH_3 volatilization decreased 60 -80% when fertilizers were incorporated into soil, and up to a 90% reduction was measured from injected fertilizer (Jokela et al., 2013). The reduction of NH_3 volatilization from applied manure can reach 90% when it is incorporated directly under the soil surface after application (Webb et al., 2010; Lupis et al., 2012). These results demonstrate that application practices are a very important factor to consider in reducing NH_3 volatilization.

In addition to application method, fertilizer type and application rate can also affect NH_3 emission. The developed MANNER model (The ADAS MANure Nitrogen Evaluation Routine) is used to approximate the amount of NH_3 volatilization from manure applied to arable crops (Chambers et al., 1999). This model was developed by collecting the results of different experiments, and it proposes that each 1% increase in the dry matter of manure leads to a 5% increase in NH_3 volatilization (Chambers et al., 1999). In like manner, a study conducted in the Central Valley of California to evaluate the effect of N application rate on NH_3 emission confirms that high application rates of fertilizer can increase NH_3 loss. The plots with high N application rate were the highest in NH_3 volatilization among the three N rates applied (56, 127, 198 kg/ha) (Beene et al., 2016). Therefore, applying manure with high rate and high dry matter content can increase NH_3 loss. Moreover, Mikkelsen (2009) articulated that NH_3 emission could be greatly different due to particular fertilizer characteristics and their reaction after entering the soil. For instance, when ammonium nitrate and ammonium sulfate diffuse in the soil they produce acidic solution (pH 4.5 -5.5) which reduces NH_3 loss. On the other hand, urea application to soil produces ammonium carbonate $(NH_4)_2CO_3$ due to its reaction with water (hydrolysis), and $(NH_4)_2CO_3$ is rapidly dissolved to release NH_3 gas. Previous studies indicate that the type of fertilizers and their interactions with soil impact the amount of NH_3 volatilization (Rostami et al., 2015). Total N and ammonium concentrations and dry matter content of manure can significantly affect the amount of NH_3 emission. Furthermore, NH_3 volatilization can be reduced by reducing the dry matter content of dairy manure in land application (Atia, 2008).

Several methods have been used to measure NH_3 volatilization from N fertilizers applied to the soil such as the semi-open chamber and the open chamber (Jantalia et al., 2012). The chamber method is generally utilized to measure NH_3 loss from small-scale areas. Static chambers are commonly used in NH_3 measurement because of their low cost and availability of materials, in particular, for comparison of several treatments in the same crop season (Ma et al., 2010). Many studies of NH_3 volatilization have used the static chamber developed by Nommik (1973) with a semi-open design (Figure 1). The semi-open chamber design is cylindrical, and the top is partially covered with a plastic plate to allow gas exchange between the soil and the air. Polyethylene foam is placed inside the chamber and immersed in an acid solution to act as an NH_3 trap. The most common acid traps used are sulfuric, phosphoric, and hydrochloric acids (Jantalia et al., 2012). Recently, Araújo et al. (2009) modified a semi-open chamber to reduce cost, simplify design, and allow more air movement at the soil surface. This new design does not need to be forced into the soil like the chamber designed by Nommik (1973).

This experiment is part of a broader study on development of a cyanobacterial bio-fertilizer (cyano-fertilizer) produced on-farm in shallow raceways and its evaluation as a replacement for other organic fertilizers used by local farmers. Cyanobacteria can fix N and deliver it to the plants when applied as fertilizer. Also, it can be produced on the farm without the need for transportation. When cyanobacteria are applied to soil as a fertilizer, the organic N in their bodies will be mineralized by soil microbes to convert it to inorganic N that is plant available. The three other fertilizers being evaluated (blood meal, feather meal, and fish emulsion) are commercially available and commonly used but require energy to produce and transport them to the farm. Blood meal is made by drying animal blood collected from slaughterhouses and then it is ground to a powder to use as fertilizer (Mikkelsen and Hartz, 2008). Blood meal contains a high proportion of N in the NO_3-N form which is readily available for plant uptake (Rosen and Allan, 2007). Feather meal is made from ground poultry feathers which contain about 80 - 90%

protein and almost all of the N exists as non-soluble keratin (Liang et al., 2011). Mazotto et al. (2011) stated that the N in feather meal fertilizer is released slowly because the keratin is a rigid substance, and it is not easily degraded by microorganisms to provide available N forms to plants. Fish emulsion is a liquid fish waste that can be mineralized rapidly to provide N to plants (Stevenson et al., 2014). Volatilization of NH_3 from these different N forms depends on the other N reactions occurring as each fertilizer breaks down. For example, high mineralization rates will increase the N available in the soil, which in turn, will increase potential volatilization (Jones et al., 2013).

The aim of this study was to quantify NH_3 volatilization from different types of organic fertilizers applied using different methods and rates. Four organic N fertilizers were tested: two solid fertilizers (blood meal and feather meal) and two liquid fertilizers (fish emulsion and liquid cyano-fertilizer). Most of the previous studies of NH_3 volatilization have focused on conventional fertilizers and manure. Sheppard et al. (2010) reported that using urea and UAN instead of ammonium nitrate could increase the possibility of N loss in the form of NH_3. Among four treatment applications (Urea, Agrotain-coated urea 0.75 kg/MT, Agrotain-coated urea 1.5 kg/MT, and ammonium nitrate) urea had the highest NH_3 volatilization flux followed by Agrotain-coated urea at both rates, and the least NH_3 loss was from ammonium nitrate (Butler and Simmons, 2011). A report published by the International Fertilizer Industry Association and the Food and Agriculture Organization of the United Nations outlines the measurements of NH_3 emission from the major type of fertilizers, which are shown in Table 1 (IFA and FAO, 2001). There is no known scientific literature comparing NH_3 volatilization from organic N fertilizers. Therefore, this experiment contributes new findings to the literature.

The objectives of this study were to:

1- Compare NH_3 volatilization of four organic N fertilizers (blood meal, feather meal, fish emulsion and cyano-fertilizer).
2- Evaluate the effect of fertilizer application methods (pre-plant sub-surface banding of solid fertilizers vs. split application of liquid fertilizers through drip irrigation) on NH_3 volatilization.
3- Evaluate the effect of fertilizer application rates (28 and 56 kg of N ha^{-1}) on NH_3 emissions.
4- Compare the amounts of NH_3 emitted from liquid fertilizers above the emitter of the drip line and halfway between the emitters.
5- Compare the effect of application methods of solid fertilizers (sub-surface banded vs. surface banded).
6- Determine the effect of temperature and days after application on NH_3 volatilization rates.
7- Compare the effect of the different fertilizers on cucumber yield.

Two hypotheses were related to the above objectives: 1- liquid fertilizers will have lower ammonia emissions compared with solid fertilizers due to the large amount of water applied with the N which will move NH_3 into the soil and away from the soil surface and 2- Application methods which place fertilizers below the soil surface will result in lower NH_3 volatilization rates from the different fertilizers.

MATERIALS AND METHODS

2014

The first experiment was conducted in the summer of 2014 at the Colorado State University (CSU) Horticulture Field Research Center, Fort Collins, CO. The soil was classified as a fine clay loam, mesic Aridic Argiustoll of the Nunn series (NRCS, 1980). The crop was organic lettuce (*Lactuca sativa*), and drip irrigation was used. Certified organic seeds of lettuce variety 'Concept' (Johnny's Selected Seeds, Waterville, ME) were germinated 9 May 2014 in the CSU greenhouse and then were transplanted to the field on 9 June 2014. Four different fertilizers were applied in the experiment: two solid fertilizers (blood meal and feather meal) and two liquid fertilizers (Alaska non-hydrolyzed fish emulsion and cyano-fertilizer), and each fertilizer treatment was applied at two rates, 28 and 56 kg N ha^{-1}. Inorganic N concentrations (NH_4-N and NO_3-N) and percentage of N fertilizer applied as inorganic-N are shown in Table 2. The solid fertilizers were applied in a sub-surface band 6 cm deep and 6 cm from the row a few days before transplanting, while liquid fertilizers were applied through drip irrigation every week over the course of the growing season starting two weeks after transplanting.

Pre-plant soil testing was performed to measure the initial N content before any fertilizer application. Samples of the soil were collected to a 30cm depth and sent to the Soil, Water, and Plant Testing Laboratory at Colorado State University to be analyzed. The results showed that organic matter (OM) content was 2.7 %, NH_4^+- N concentration was 30.8 kg ha^{-1}, and NO_3^--N concentration was 19.6 kg ha^{-1}. Also, Cation Exchange Capacity (CEC) was measured to be 29 meq 100 g^{-1} and soil pH was 7.5 (Sukor, 2016).

The field was 25 m long by 15.24 m wide, and it was divided into four blocks, 5.5 m by 15.24 m each with at least 0.5 m space between the blocks. Each sub-plot was 4.57 m by 0.76 m.

Nine treatments were randomly assigned within each block: Feather meal (28 and 56 kg N ha^{-1}) and Blood meal (28 and 56 kg N ha^{-1}) (Down To Earth, Inc., Eugene, OR) (12- 0- 0), Alaska Fish emulsion (28 and 56 kg N ha^{-1}) (Planet Natural, Bozeman, MO) (5- 1- 1), Cyano-fertilizer (28 and 56 kg N ha^{-1}) *Anabaena sp.* grown on site, and no fertilizer (control).

Ammonia (NH_3) volatilization semi-open chambers were made according to Araújo *et al.* (2009) by using green plastic bottles of polyethylene terephthalate (PET), with a capacity of 2L and 0.008 m^2 cross-sectional area, 260 mm length and 100 mm diameter (Figure 1, 2, and 3). The bottom piece of the bottle was removed and placed on top using two wires in order to eliminate the effect of rain or irrigation water. There was a wire hook placed inside each chamber to attach a 50 ml plastic vial and a strip of foam. Each bottle was painted silver using Rust-Oleum Hammered spray paint and covered with Reflective Mylar Sheet (Hydrobuilder Company, Chico, California) to protect the trap solution from direct sunlight. Thirty-six semi-static chambers (one per plot) were used in this experiment. A trap solution of sulfuric acid and glycerin was placed inside the chamber to catch the volatilized NH_3 from each treatment. This trap solution was made by mixing 55.5 mL of concentrated H_2SO_4 and 10 mL of glycerin in 1 L of distilled water. Polyethylene foam (made by cutting a foam sheet into strips 2.5 cm wide and 25 cm long) was used to absorb 50 mL of trap solution and placed inside the plastic vial. In the field, the chambers were stabilized with the aid of three metal sticks (rebar) forced into the soil around the chamber and rubber bands. Each chamber was placed above an emitter of the drip irrigation line. To address the objective of comparing the amount of NH_3 emitted between the emitters, four extra chambers were used. The extra chambers were placed between emitters of the drip line for one week in the 28 kg N ha^{-1} cyano-fertilizer plots.

In the solid fertilizer treatments, measurements were taken every three days (72 hours) from the first day of application until the end of the experiment after lettuce harvest. In contrast, for liquid fertilizers, measurements were taken 1, 3, and 6 days after each application. Furthermore, measurements on the control plots followed the schedule for both solid and liquid fertilizers to facilitate comparison. At the beginning of the experiment and before liquid fertilizer application began, control measurements were taken on the solid fertilizer schedule. After applying the liquid fertilizers, the control measurements followed both solid and liquid schedules because there was an overlap on most of the days. The different sampling schedules for the different fertilizer types were developed because ammonia from solid fertilizers is known to be released slowly, unlike liquid fertilizers, which are usually released more quickly. Samples collected from each chamber were placed directly in acrylic jars containing 100 ml of 2 M KCl and were then transferred to the lab for ammonia extraction. During the experiment, soil pH and temperature were measured in the field because high pH and temperature can increase NH_3 emission. The soil pH was measured three times: at the beginning of the experiment after transplanting, in the middle, and in the end of the experimental period. The pH measurements were performed using pH meter in the laboratory in 1:2 ratio mixtures of soil and water. Soil samples were taken from the field randomly from the top 2 cm and mixed with distilled water in small cups. The soil mixtures were left for 1 minute to settle. Before each measurement, the pH meter was calibrated with three buffer solutions (pH 4.01, pH 7.01, and pH 9.01) and cleaned with distilled water after every use. Temperature was measured twice every week in the morning from 8:30 am to 9:00 am throughout the experiment using the sensor EC-TM Moist/Temp (Colorado State University, Fort Collins, Colorado). Temperature was measured by inserting the probe vertically into the soil from 0-10 cm depth.

2015

The second experiment was conducted in the summer of 2015 at the Colorado State University (CSU) Horticulture Field Research Center, Fort Collins, CO. The crop was organic cucumber (*Cucumis sativus*), and drip irrigation was used. Certified organic "Corinto" (F1) seeds of cucumber were purchased from Johnny's Selected Seeds (Winslow, ME) and germinated 13th May 2015 in the CSU greenhouse and then were transplanted to the field on 25th May 2015. In each row, ten cucumber plants were transplanted 8 cm away from the center of the drip tape. Four different fertilizers were applied in the experiment, two solid fertilizers (blood meal and feather meal) and two liquid fertilizers (fish emulsion and liquid cyano-fertilizer), and all fertilizer treatments were applied at the 28 kg N ha^{-1} rate. The solid fertilizers were applied a few days before transplanting using two different application methods, a sub-surface band 6 cm deep and 6 cm from the row and on the soil surface 6 cm from the row in a surface band, while liquid fertilizers were applied through drip irrigation every week over the course of the growing season starting four weeks after transplanting.

Pre-plant soil testing was done to determine the N content in the soil before any application. Soil samples were collected to a depth of 58.8 cm and sent to the Soil, Water, and Plant Testing Laboratory at Colorado State University to be analyzed. The analysis results showed that OM content was 2.7 %, NH_4^+-N concentration was 50.2 kg ha^{-1}, and NO_3^--N concentration was 8.5 kg ha^{-1}. The average soil pH was 8.1 (Wickham, 2016).

The field was divided into four blocks. Seven treatments were randomly assigned within each block: feather meal (sub-surface band and surface band), blood meal (sub-surface band and surface band), fish emulsion, cyano-fertilizer, and no fertilizer (control). The plot site was moved within the same field from the 2014 site to eliminate N residual impact from the previous year's treatments.

Twenty-eight semi-static chambers (one per plot) were used in this experiment following the same method as in 2014. In the solid fertilizer treatments, measurements were taken every day for the first seven days after application. Then the measurements were taken every three days until the time of liquid fertilizer application. Thereafter, the solid fertilizer measurements were taken on the third day and the seventh day each week (day 3 and day 7). In contrast, for liquid fertilizers, measurements were taken 1, 3, and 7 days after each application. Furthermore, measurements on the control plots followed the schedule for both solid and liquid fertilizers. At the beginning of the experiment and before liquid fertilizer application began, the control measurements were taken on the solid fertilizer schedule. After applying the liquid fertilizers, the control measurements followed both solid and liquid schedules because there was an overlap on most of the days. Samples were collected as in 2014.

In addition, the length (cm), diameter (cm), weight (kg), fruit number, and plant dry weight (kg) of the harvested cucumbers were measured to compare yield effects. The length and diameter were measured on each cucumber fruit for every treatment using a measuring tape, while the weight was measured on all the cucumber fruits of each plot in total. The plant dry weight was measured after the final harvest by putting all aboveground plant material from each plot into a paper bag, and placing it in the oven at 70° C for two days.

The soil pH was measured twice, at the beginning of the experiment after transplanting and toward the end of the experimental period. Soil samples were taken randomly from the area under the chambers of each treatment to observe if there was an effect of fertilizer treatment on soil pH. In addition, soil temperature readings were observed from the CoAgMet website (http://www.coagmet.colostate .edu) from the first of June to the 14th of August. There were two cucumber harvests: July 26 and August 14. There was no pesticide, herbicide, or fungicide application in the experiment duration, and weeding was done by hand and by hoe.

IRRIGATION

John Deere® drip tape (Deere & CO., Moline, IL) was used for irrigation in both years. In 2014, irrigation took place once every day starting at 08:00 am until 08:30 am using automatic irrigation. Early in the season, irrigation took place 15 minutes /day and then was increased to 30 minutes /day as the plants grew (Sukor, 2016). In 2015, an automated irrigation system was used to deliver 10.5 mm/ day of irrigation water in each row by watering for 45 minutes 5 days per week. The irrigation schedule was developed to water 5 days weekly followed by a fertigation day. After fertigation, the control and fish fertilizer plots were watered that day or the following day to ensure equivalent amounts of water were applied to all treatments. The amount of water used to irrigate cucumbers in 2015 was 700 mm over the growing season (Wickham, 2016).

LABORATORY ANALYSIS OF ACID TRAPS

After taking the samples from the field, acid traps were brought to the lab for NH_3 extraction. 250 ml of 2M KCl was used to extract the NH_3 from each strip of polyethylene foam (100 ml was used in the field, and 150 ml more added in the lab). The foam, 50 mL bottle, and the acrylic jars were washed twice with 2M KCl to capture any NH_3 on them. Then this solution was transferred through a funnel using 12.5 cm filter paper (Whatman, 42 Ashless, Cat No 1442 110) into a 250 ml volumetric flask and swirled for approximately 10 sec. In addition, before transferring the solution through the funnel, the filter papers were washed using 0.25 M KCl to make sure that there was no ammonia in the final solution from the filter paper. After transferring the solution to 250 mL volumetric flasks, 40 mL of the solution was transferred to sealed, plastic bottles and frozen at -20° C until the time of analysis. Extracts were sent to CSU's Natural Resources Ecology Lab (NREL) for NH_3 analysis. The instrument used was an Alpkem Flow Solution IV (O.I. Analytical, College Station, Texas), and the ammonium method was DIN # 38406 method modified from a German manufacturer standard (Deutsches Institut für Normung, 1983).

STATISTICAL ANALYSIS

The overall apparent NH_3 flux from each plot was calculated for each growing season in Microsoft Excel (Microsoft Corp., Redmond, WA). The NH_3 concentration data received from the NREL lab were reported in mg/L, and in Excel these numbers were multiplied by 250 mL (from the KCl extract) and divided by 1000 mL/L and 95 cm^2 (the chamber area) to convert them to mg/cm^2. Then the resulting numbers were divided by the number of days the strip was exposed in the field to determine the flux in mg/cm^2/ day and then to get the final NH_3 flux, the data were multiplied by the actual number of days that the strips represent (to incorporate the gaps in measurement times into the total NH_3 flux calculation). Due to the different measurement days between solid and liquid fertilizers, there were some gaps in the data set. Hence, an interpolation of that data was necessary to fill these gaps. As mentioned before, the solid fertilizer plots were sampled every three days, while liquid fertilizer plots were sampled on the first, third, and sixth days of each application week. On the third and sixth days of liquid fertilizer measurement, solid fertilizer measurements were also taken on the same days, but for the first sampling day of liquid fertilizer, there was no solid fertilizer sampling which resulted in a missing measurement for the solid fertilizers comparing with liquid fertilizers. Interpolation was done for each point by taking the value before the targeted point plus the value after the point, and then dividing by two. A Randomized Complete Block Design (RCB) was used with a

PROC MIXED statement in SAS version 9.3 (SAS Institute Inc., Cary, NC). The Tukey-Kramer test was used to compare treatments, and Dunnet's test was used to compare between the control and treatments. The significance level used for analyzing the data was P-value < 0.05. Apparent ammonia flux (mg/cm^2) was considered as a continuous response variable (numerical), treatments were random predictor categorical variables, and blocks were fixed predictor categorical variables. In Excel, the average apparent ammonia emission in mg/cm^2 per day was calculated for the different fertilizers by summing the NH_3 emissions of the four replicates and dividing by 4.

In SAS, using PROC MIXED procedure, the length (cm), diameter (cm), weight (kg), fruit number, and plant dry weight (kg) of cucumbers were considered as continuous response variables (numerical), treatments were random predictor variables (categorical), and blocks were fixed predictor variables (categorical).

Correlations to determine the relationship between mean soil temperature and NH_3 volatilization were calculated for each treatment in Excel. Another set of correlations was performed to evaluate the relationship between days after application and NH_3 volatilization, and Proc Corr in SAS was used to generate the p-values.

RESULTS AND DISCUSSION

2014

According to qqplot, histogram, and residual vs. predicted plot, there was a lack of normality in the data. As a result, a log transformation was performed which made the data approximately normal. The result of the overall test indicated that there was a significant difference among the treatments ($P = 0.0004$). There was no difference in apparent NH_3 volatilization between blood meal applied at 28 kg N ha^{-1} with 0.06 mg/cm^2 mean flux, cyano-fertilizer applied at 28 and 56 kg N ha^{-1} with 0.04 mg/cm^2 mean flux, fish emulsion applied at 28 and 56 kg N ha^{-1} with 0.04 mg/cm^2 mean flux, and control (Table 3). The results of the Tukey-Kramer adjustment test indicated that feather meal applied at 28 and 56 kg N ha^{-1} with 0.08 and 0.09 mg/cm^2 mean flux and blood meal applied at 56 kg N ha^{-1} with 0.09 mg/cm^2 mean flux resulted in NH_3 fluxes that were significantly greater than the control with 0.05 mg/cm^2 mean flux. On the other hand, neither fish emulsion nor cyano-fertilizer with 0.04 mg/cm^2 mean flux applied at either rate resulted in NH_3 fluxes different from control. In addition, the percentage of NH_3 volatilized from the total N applied as fertilizer is shown in Table 3. In 2014, the percentage of N lost from sub-surface banded feather and blood meal applied at 28 kg N ha^{-1} was the highest among treatments with 28.6% and 21.4% lost, respectively. In 2015, surface banded feather and blood meal had the highest percentage of N lost with 32% and 25%, respectively. Liquid fertilizers had lower N percentage loss compared to solid fertilizers. Application rate also affected the percentage of N loss as seen in 2014; fertilizers applied at 28 kg N ha^{-1} had a higher percentage of N loss than fertilizers applied at 56 kg N ha^{-1} (Table 3).

Soil pH over the three measurements during the experiment were 7.84, 7.77, and 7.64, respectively, while the soil temperature ranged from 14.0 to 23.3°C.

Figure 4 represents the effect of time (days after application) on the average NH_3 volatilized from fertilizers applied at 56 kg N ha^{-1}. The highest NH_3 emission was from blood meal and feather meal in the first 15 days following application, while fish emulsion and cyano-fertilizer were no different from control (Fig. 4). The volatilization from control plots varied throughout the season, which is probably a reflection of changing temperature and soil moisture content (Fig. 4 and Fig. 5).

Figure 5 represents the effect of time (days after application) on the average NH_3 volatilized from fertilizers applied at 28 kg N ha^{-1}. The highest NH_3 emission was from feather meal during the first 18 days, while blood meal, fish emulsion and cyano-fertilizer were not different than control (Fig. 5).

There was no observed difference between the two application rates 28 kg N ha^{-1} and 56 kg N ha^{-1}, except for blood meal (Table 3). In addition, there was no difference in NH_3 volatilization mid-way between the emitters (0.00085 mg/cm^2) and above the emitters (0.000975 mg/cm^2) of the drip line.

2015

The overall test indicated that there was a significant difference among the fertilizer treatments (P= 0.0001). According to qqplot, histogram, and residual vs predicted plot, there was a lack of normality in the raw data. Therefore, a log transformation was performed which made the data normal. Fertilizer treatments that were sub-surface banded in 2015 did not significantly increase apparent NH_3 flux as compared to the control with 0.04 mg/cm^2 mean flux (Table 3). The Tukey-Kramer and Dunnet's tests specified that there was a significant difference between surface banded blood meal with 0.07 mg/cm^2 mean flux and feather meal with 0.09 mg/cm^2 mean flux as compared to the control and the fertigated and sub-surface banded treatments. Apparent NH_3 emission was less when solid fertilizers were applied in a sub-surface band than in a surface band, while applying liquid fertilizers through the drip irrigation system resulted in emission rates similar to the control plots. The average soil pH values were 8.10 for both fish emulsion and cyano-fertilizers, 8.23 for feather and blood meals that were surface banded, 7.95 for sub-surface banded feather meal, and 7.89 for sub-surface banded blood meal. In addition, precipitation ranged from 0 to 20.83 mm (Fig. 6), and soil temperature readings at the 5-15 cm depth ranged from 14.9 to 30.0^{o}C (Fig. 7). Cumulative average NH_3 volatilization mg/cm^2 with time for 2014 is represented in Figures 8 and 9. The highest cumulative emissions were for blood meal at 56 kg N ha^{-1} and feather meal at both rates. There is a difference in cumulative NH_3 volatilization for blood meal between the different rates, with blood meal at 56 kg N ha^{-1} being higher than blood meal at 28 kg N ha^{-1}.

In 2015, blood meal with 0.07 mg/cm^2 mean flux and feather meal with 0.09 mg/cm^2 mean flux banded on the soil surface had the highest NH_3 fluxes according to mean estimates, Tukey-Kramer test, and Dunnet's test (Table 3). In contrast, NH_3 fluxes from sub-surface banded blood meal with 0.04 mg/cm^2 mean flux, sub-surface banded feather meal with 0.05 mg/cm^2 mean flux, cyano-fertilizer with 0.04 mg/cm^2 mean flux, and fish emulsion with 0.05 mg/cm^2 mean flux were not different from control with 0.04 mg/cm^2 mean flux according to Dunnet's test. Due to the different types of fertilizers used in the study, different amounts of NH_3 were volatilized. Rostami et al. (2015) stated that fertilizer type and its interaction with soil type could affect NH_3 emission. Overall, liquid fertilizers had lower NH_3 loss than solid fertilizers even when applied at higher rates. In the same manner, Balasubramanian et al. (2015) stated that one of the factors affecting NH_3 emission is fertilizer type. For example, for anhydrous ammonia, volatilization happens within the first few hours after application and it is reduced by 70-90 % after 24 hours. In contrast, NH_3 loss from urea occurs within a day after application because it needs to hydrolyze to produce NH_3 (Balasubramanian et al., 2015). Cumulative average NH_3 volatilization over time is represented for 2015 in Figure 10. The highest cumulative volatilization was from surface banded feather and blood meals with 0.046 and 0.0399 mg/cm^2, respectively, while liquid fertilizers and sub-surface banded feather and blood meal were similar to the cumulative volatilization of the control.

Jantalia et al. (2012) used the same chamber method in a study at the Agricultural Research Development and Education Center (ARDEC) near Fort Collins, CO in 2011 and the soil was clay loam and soil pH of 7.8, but they reported lower % loss of NH_3 volatilization than measured in our study. Jantalia et al. (2012) compared four conventional fertilizers: dry granular urea (46% N), liquid urea ammonium nitrate (UAN) (32% N), controlled-release, polymer-coated urea (ESN) (44% N), and stabilized urea source (Super U) (46% N), which were applied to corn. There were 13 sampling days (6, 9, 12, 16, 22, 29, 34, 37, 42, 47, 54, 62, and 68 d after application), and the fertilizers were applied at 200 kg N ha^{-1} in a surface band. The results were 2.4%, 3.7%, 4.0%, and 0.3% of NH_3 lost as a percent of N applied, respectively. There was a significant difference between treatments ($P < 0.001$) with ESN and UAN having higher NH_3 emissions than urea, and urea having higher emissions than Super U (Jantalia et al., 2012). There are several possible reasons for this difference between Jantalia et al. (2012) results and this study including the differences in fertilizer type, the sampling schedule, and the weather conditions during the experiment.

When it comes to application method and rate, the fertilizers applied beneath the soil surface and applied through the irrigation system had less NH_3 volatilization than surface applied fertilizers, although there was usually no effect of application rate. The same result has been reported in studies evaluating manure and conventional fertilizers; application techniques that involved burying or injecting fertilizers under the soil surface had less NH_3 flux than surface application (Huijsmans et al., 2001; Potter et al., 2001; Jokela et al., 2013). Liquid fertilizer application through the drip irrigation system led to NH_3 emission rates similar to sub-surface banding. Lupis et al. (2012) stated that fertigation of liquid manure can be a sufficient technique to deliver N to the plants while reducing NH_3 loss.

Fertilizer treatments resulted in similar cucumber fruit length in both harvests (Table 4). Fruit diameter was different among the four fertilizers in the two harvests. Sub-surface banded feather meal had the highest fruit diameter in the first harvest (6.7 cm), and sub-surface banded blood meal had the highest fruit diameter in the second harvest (7.0 cm). All fertilizers produced similar fruit number in the first harvest, but they were different in the second harvest, where surface banded blood meal had the highest fruit number among them (28.3). Furthermore, the highest cucumber yield in the first harvest was for sub-surface banded blood meal (6.7 kg ha^{-1}), and in the second harvest the yield was similar among the different fertilizers. Aboveground plant dry weight (leaf and stem weight) also was almost the same among the different fertilizers, with sub-surface banded blood meal being the highest (154.0 g/plant). Fish emulsion performance was the lowest in all the cucumber yield measurements.

In general, soil temperature increased with time as the growing season progressed (Fig. 4). The correlation between the mean soil temperature measured at 5-15 cm depth and NH_3 volatilization of fertilizers applied at 28 kg N ha^{-1} in 2014 was not significant for all fertilizer treatments except feather meal applied at 28 kg N ha^{-1} (Table 5 and Table 6. Furthermore, correlation between NH_3 emission and days after application was examined, and the results showed a strong negative correlation for all fertilizer treatments (Table 6).

The correlation between mean soil temperature measured at the 5-15 cm depth and apparent NH_3 volatilization in 2015 showed that NH_3 volatilization from all the solid fertilizers had significant negative correlations with soil temperature over the entire growing season (78 d), but the relationship changed when the correlation was calculated for the first ten days for some of the fertilizers (Table 5). NH_3 volatilization from surface banded blood meal, surface banded feather meal, and sub-surface banded feather meal had strong positive linear relationships with temperature in the first ten days following application. Furthermore, a correlation between NH_3 emission and days after application was performed, and the results showed a strong negative correlation for all solid fertilizer treatments (Table 7). Moreover, correlation between NH_3 emissions and air temperature was examined, but there was no significant improvement in the correlation with air temperature as compared to the correlation with soil temperature. Most NH_3 loss occurred shortly after application, and the solid fertilizers were only applied once during the season (2014 and 2015). In contrast, there was no significant correlation between days after application and NH_3 volatilization for fish emulsion or cyano-fertilizer in either year (Table 7).

The average soil pH before fertilizer application was 8.1 in 2015, which was not affected by fertilizer application; mid-season soil pH ranged from 7.89 (sub-surface banded blood meal) to 8.23 (surface banded blood and feather meal) across treatments, about ±0.1 pH units. High soil pH contributes to the conversion of NH_4 to NH_3; as soil pH becomes higher, the volatilization of NH_3 generally increases. Rochette et al. (2013) claimed that NH_3 emissions increased rapidly with pH above 7 and that pH was the primary factor controlling the NH_3 response in their study.

Ammonia volatilization rates decreased over time according to the significant negative correlations (Table 7). Apparent NH_3 volatilization from all fertilizers had strong negative correlations with days after application in 2014, while in 2015, only solid fertilizers had significant negative correlation with days after application. Most of the NH_3 volatilization occurred shortly after application and declined as the season progressed. Many studies confirm that NH_3 volatilization is greater in the first days following fertilizer application (Sommer and Hutchings, 2001; Jokela et al., 2013).

In addition to this study, there was another experiment conducted in 2013 and 2014 within the same lettuce field to measure N_2O emissions from the same four organic fertilizers. Results reported for N_2O emissions from solid fertilizers followed a similar pattern as the NH_3 volatilization (Toonsiri et al., 2016). Toonsiri et al. (2016) stated that N_2O emissions from solid fertilizers were low during the first few weeks after fertilization and increased gradually until reaching its highest values in the fourth and fifth weeks and then declined toward the end of the growing season. N_2O emissions rates reached its highest values during the decline of NH_3 volatilization. Similarly, there was a delay in apparent NH_3 volatilization in the first week which started to increase in the second week to reach is highest values in the second and third weeks before declining later in the growing season. The percentage of N lost as NH_3 from solid fertilizers ranged from 16.1 to 28.6% (Table 3), which was much higher compared to N_2O emissions which ranged from 2.6 to 11%. On the other hand, N_2O emissions from liquid fertilizer treatments were very low even on the day of fertigation, while for NH_3 volatilization there was a peak on the first day following each liquid fertilizer application which then declined. The percentage of N lost from liquid fertilizers as NH_3 ranged from 7.1 to 14.3 % (Table 3), while for N_2O the percentage ranged from 0 to 0.10%. Khalil et al. (2006) reported that emissions of N_2O from agricultural land ranges from 0.03 to 2.7% and can reach 5.8%, while NH_3 volatilization from N fertilizers ranges from 0 to > 50% depending on the fertilizer type, application methods and rates, and soil and environmental factors. Another article by Aneja et al. (2012) presented the global estimate of both NH_3 and N_2O emissions from soils, and their values were 8.1 Tg N yr^{-1} of N_2O emissions from natural sources and agricultural soils and 12.6 Tg N yr^{-1} of NH_3 from fertilizers and cropland, while in the USA alone, the values were 2362 Gg N yr^{-1} NH_3 and 302 Gg N yr^{-1} N_2O in 1998, and 2729 Gg N yr^{-1} NH_3 and 506 Gg N yr^{-1} N_2O in 2005. Therefore, the higher NH_3 loss compared to N_2O loss from the same field is predictable, according to these other scientific studies.

It is important to optimize fertilizer application method, rate, and selection in order to minimize the release of NH_3 to the air. Losing NH_3 through volatilization can damage our environment and at the same time negatively affect plant productivity. Agricultural practices such as fertilizer application to land can contribute to this issue. Proper application of fertilizers is one of the best management practices that can be used to reduce NH_3 volatilization. Applying solid fertilizers below the soil surface and fertigation of liquid fertilizers through drip irrigation can reduce NH_3 emissions. Furthermore, considering application timing is an important aspect to decrease NH_3 emission, such as applying fertilizers during cool weather. Even though this experiment showed that there was no effect of application rate on NH_3 volatilization up to 56 kg N ha^{-1}, it is not recommended to apply fertilizer at excessive rates. The cyano-fertilizer treatment volatilized NH_3 at a rate similar to control while producing a sufficient yield. Hence, the use of cyano-fertilizer to support plant growth is possible while at the same time resulting in less NH_3 volatilization.

CONCLUSION

This experiment was conducted to quantify NH_3 volatilization from four different organic fertilizers applied at different N rates and using different application methods. In 2014 and 2015, the results showed that solid fertilizers had higher apparent NH_3 emission fluxes than liquid fertilizers. As predicted in the hypothesis, liquid fertilizers had lower NH_3 emissions compared to solid fertilizers. Furthermore, application method had an important effect on the amount of NH_3 volatilization; banding fertilizers under the soil surface and applying liquid fertilizers through a drip irrigation system reduced NH_3 emission rates. Moreover, there was a significant difference in yield measurements among the different fertilizers, with fish emulsion resulting in the lowest yield in cucumber diameter, number, and yield. The correlation results indicated that temperature and time impacted NH_3 volatilization rates. There were no previous studies on comparing NH_3 volatilization rates from these four organic fertilizers; for that reason, this study presents valuable new findings for the scientific literature.

Table 1. Summary of NH_3 emission measurements from major fertilizer types of fertilizers (IFA and FAO, 2001).

Fertilizer Type	Measurement Technique	NH_3 Rate
Anhydrous ammonia	Not mentioned	Low
Ammonium bicarbonate	Enclosure technique without forced drought	21%
	Laboratory measurements with forced drought	30-70%
Ammonium nitrate	Mass balance technique at low pH	6%
	Mass balance technique at high pH	60%
Ammonium sulfate	Micrometeorological technique	0-2%
	Forced drought system	90%
Urea	Forced system, forced drought, and micrometeorological technique	15-20%
Urea ammonium nitrate	Micrometeorological technique	8-18%
	Forced drought system	45%

Table 2. Fertilizer inorganic-N concentrations and percentage of N applied as inorganic N.

Fertilizer Types	NH_4^+-N¶	NO_3^--N¶	N as NH_4^+-N	N as NO_3^--N
	---------------mg kg^{-1}	----------------	---------------%	---------------------
Blood meal (12-0-0)	27.7	8.40	0.02	0.006
Feather meal (12-0-0)	1232	2.30	0.95	0.002
Cyano-fertilizer	4.7	0.01	0.24	0.0005
Fish emulsion (5-1-1)	23.7	0.12	0.05	0.0002

¶Samples were extracted using 2M KCl and were analyzed using an auto analyzer.

Table 3. Mean apparent seasonal ammonia (NH_3) flux (2014 and 2015), as affected by fertilizer type and application rate and method. Ctrl = control, Blood = blood meal, Feather = feather meal, Fish = fish emulsion, Cyano = cyano-fertilizer. Application Method: sub-surface band = fertilizers were sub-surface banded at 5 cm depth. Surface banded = fertilizers were applied in a band on the soil surface, and Fertigation = fertilizers were applied through a drip irrigation.

Application rate	Fertilizer type	Application method	NH_3 flux Lettuce (2014)	NH_3 flux Cucumber (2015)	NH_3 volatilized (2014) ¶	NH_3 volatilized (2015) ¶
kg N ha^1			---------mg/cm^2-------		-----------%-----------	
0	Control	No application	0.05 b†	0.04 b	0	0
28	Blood	Sub-surface Band	0.06 b	0.04 b	21.4%	14.3%
28	Feather	Sub-surface Band	0.08 a	0.05 b	28.6%	17.9%
28	Fish	Fertigation	0.04 b	0.05 b	14.3%	17.9%
28	Cyano	Fertigation	0.04 b	0.04 b	14.3%	14.3%
28	Blood	Surface banded	-	0.07 a		25.0%
28	Feather	Surface banded	-	0.09 a		32.1%
56	Blood	Sub-surface Band	0.09 a	-	16.1%	
56	Feather	Sub-surface Band	0.09 a	-	16.1%	
56	Fish	Fertigation	0.04 b	-	7.1%	
56	Cyano	Fertigation	0.04 b	-	7.1%	

†a, b fertilizer treatments with a common letter within column are not significantly different ($p < 0.05$) by the Tukey-Kramer test.

¶ NH3 volatilization is expressed as % of total N applied.

Table 4. Mean cucumber length, diameter, number, yield, plant dry weight in 2015. ACL 1 = average cucumber length in the first harvest (cm), ACL 2 = average cucumber length in the second harvest (cm), ACD 1 = average cucumber diameter in the first harvest (cm), ACD 2 = average cucumber diameter in the second harvest (cm), NUM 1 = Number of cucumbers harvested from each row in the first harvest, NUM 2 = Number of cucumbers harvested from each row in the second harvest, Yield 1 = weight of cucumbers in kg/ha, Yield 2 = weight of cucumbers in kg/ha for the second harvest, DW: Average dry weight per plant (g). Ctrl = control, Blood-B = blood meal applied in a sub-surface band, Blood-T = blood meal surface banded, Feather-B = feather meal applied in a sub-surface band, Feather-T = feather meal surface banded, Cyano = cyano-fertilizer, Fish = fish emulsion.

Fertilizer	ACL 1	ACL 2	ACD 1	ACD 2	NUM 1	NUM 2	YIELD 1	YIELD 2	PDW
	-----------------cm------------------						-------kg/ha-------		g/plant
Ctrl	25.1	22.7	6.2 ab†	5.9 ab	5.2	10.0 b	2.3 c	14.8	98.1
Blood- B	24.1	25.6	6.6 ab	7.0 a	12.2	24.8 ab	6.7 a	14.9	154.0
Blood-T	24.9	21.2	6.2 ab	6.8 ab	6.0	28.3 a	2.6 b	16.3	131.3
Feather-B	25.3	24.6	6.7 a	6.5 ab	9.0	19.3 abc	5.2 ab	12	119.9
Feather-T	24.4	25.5	6.1 ab	6.8 ab	10.5	22.0 abc	5.8 ab	13.4	142.1
Cyano	24.4	24.0	6.4 ab	6.4 ab	8.3	14.8 abc	1.9 c	16.7	114.6
Fish	23.0	22.2	5.6 b	5.8 b	4.0	8.3 c	1.0 c	6.4	60.3

†a, b, c, Fertilizer treatments with a common letter within column are not significantly different ($p < 0.05$) by the Tukey-Kramer test.

Table 5. Correlation coefficients relating NH_3 volatilization to soil temperature (5-15 cm depth) for the solid fertilizer applications in 2014 and 2015 within the first ten days of the experimental period and for the whole season. Blood 28 = blood meal at 28 kg N ha^{-1}, Blood 56 = blood meal at 56 kg N ha^{-}1, Feather 28 = feather meal at 28 kg N ha^{-1}, Feather 56 = feather meal at 56 kg N ha^{-1}, Blood-B = blood meal sub-surface band, Blood-T = blood meal surface banded, Feather-B = feather meal sub-surface band, Feather-T = feather meal surface banded.

	2014		2015	
Fertilizer	0-10 days	0-60 days	0-10 days	0 -78 days
Control	0.35*†	0.13	- 0.18	- 0.33
Blood 28	0.03	- 0.23	--	--
Blood56	- 0.21	- 0.37	--	--
Feather28	- 0.30	- 0.46 *	--	--
Feather56	- 0.18	- 0.37	--	--
Blood-B	--	--	- 0.04	-0.40*
Blood-T	--	--	0.83**	-0.43*
Feather-B	--	--	0.26*	-0.55*
Feather-T	--	--	0.85**	-0.38*

† * p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001.

Table 6. Correlation coefficients relating NH_3 volatilization to soil temperature for liquid fertilizer treatments in 2014 and 2015. Cyano 28 = cyano-fertilizer at 28 kg N ha^{-1}, Cyano 56 = cyano-fertilizer at 56 kg N ha^{-1}, Fish 28 = fish emulsion at 28 kg N ha^{-1}, Fish 56 = fish emulsion at 28 kg N ha^{-1}.

Fertilizer	2014		2015	
	Application period (10 days)	0-60 days	Application period (18 days)	0-78 days
Cyano28	- 0.40	0.10	0.20	0.11
Cyano56	- 0.29	0.09	- 0.08	- 0.28
Fish28	- 0.22	0.16	--	--
Fish56	- 0.24	0.17	--	--

Table 7. Correlation coefficients relating days after application to NH_3 volatilization for solid and liquid fertilizer treatments in 2014 and 2015. Control = control, Blood 28 = blood meal at 28 kg N ha^{-1}, Blood 56= blood meal at 56 kg N ha^{-1}, Feather 28 = feather meal at 28 kg N ha^{-1}, Feather 56 = feather meal at 56 kg N ha^{-1}, Blood-B = blood meal sub-surface band, Blood-T = blood meal surface banded, Feather-B = feather meal sub-surface band, Feather-T = Feather meal surface banded. Cyano 28 = cyano fertilizer at 28 kg N ha^{-1}, Cyano 56 = cyano-fertilizer at 56 kg N ha^{-1}, Fish 28 = fish emulsion at 28 kg N ha^{-1}, Fish 56 = fish emulsion at 28 kg N ha^{-1}.

Fertilizer	2014	2015
Control	0.25	-0.34*†
Blood 28	- 0.54*	--
Blood56	- 0.52*	--
Feather28	- 0.63**	--
Feather56	- 0.56*	--
Blood-B	--	- 0.34*
Blood-T	--	- 0.66***
Feather-B	--	- 0.71***
Feather-T	--	- 0.56***
Cyano28	- 0.31*	0.22
Cyano56	- 0.41*	--
Fish28	- 0.44*	- 0.08
Fish56	- 0.34**	--

† * p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001.

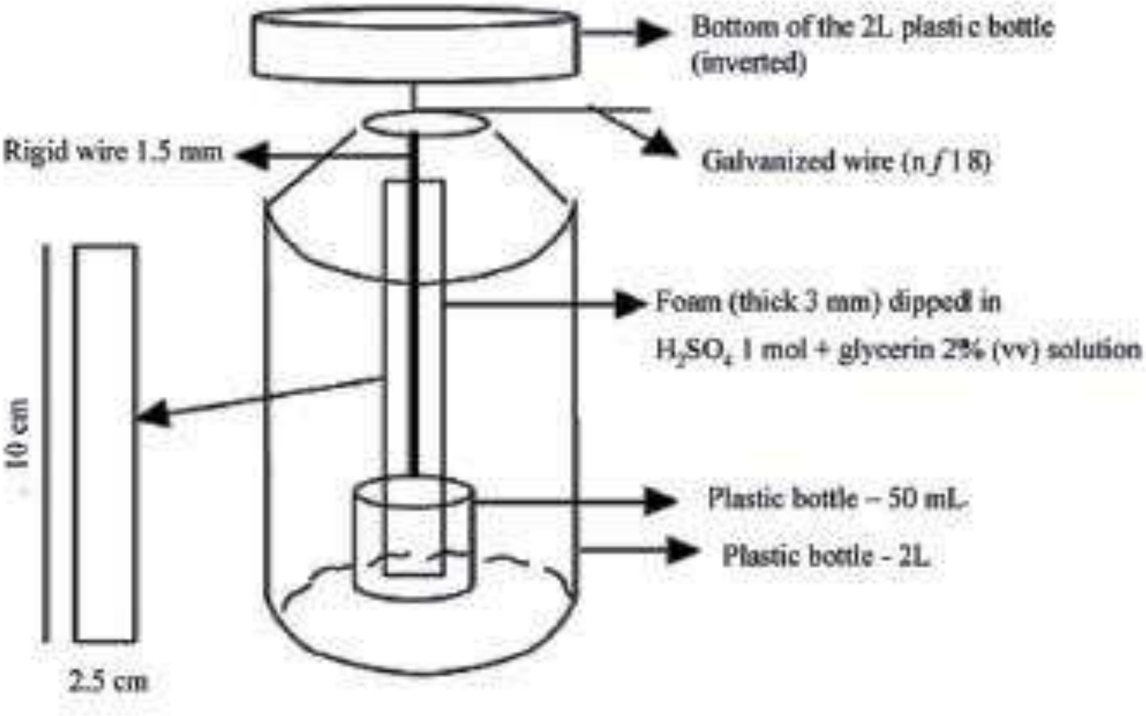

Figure 1. Semi-open chamber used to measure apparent NH_3 volatilization (Costa et al., 2014).

Figure 2. Semi-open chambers made according to Araújo et al. (2009).

Figure 3. Semi-open chamber placement in the field.

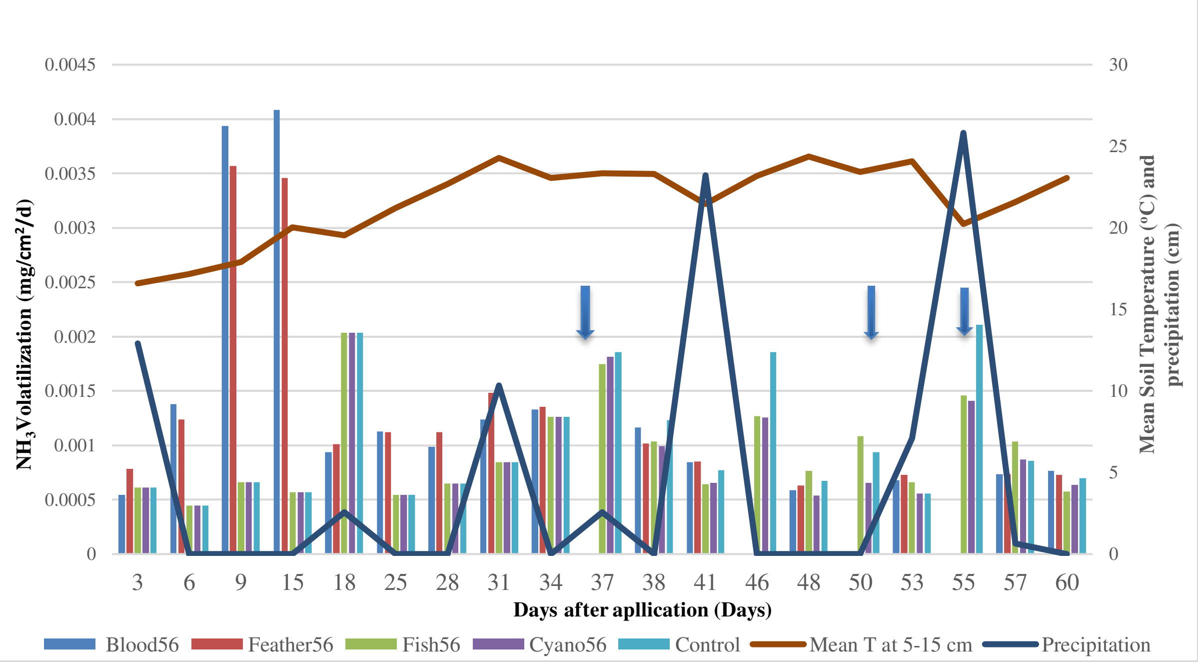

Figure 4. Average apparent daily NH_3 volatilized (mg/cm^2) from fertilizers applied at 56 kg N ha^{-1} as a function of time after application in 2014. Blood56 =blood meal, Feather56 = feather meal, Cyano56 = cyano-fertilizer, Fish56 = fish emulsion, Control = control. The blue arrows document liquid application times, while the red arrow documents solid application time. The solid brown line is the mean soil temperature (°C) measured at 5-15 cm during the experimental period (days) in 2014. The black line shows the precipitation throughout the growing season.

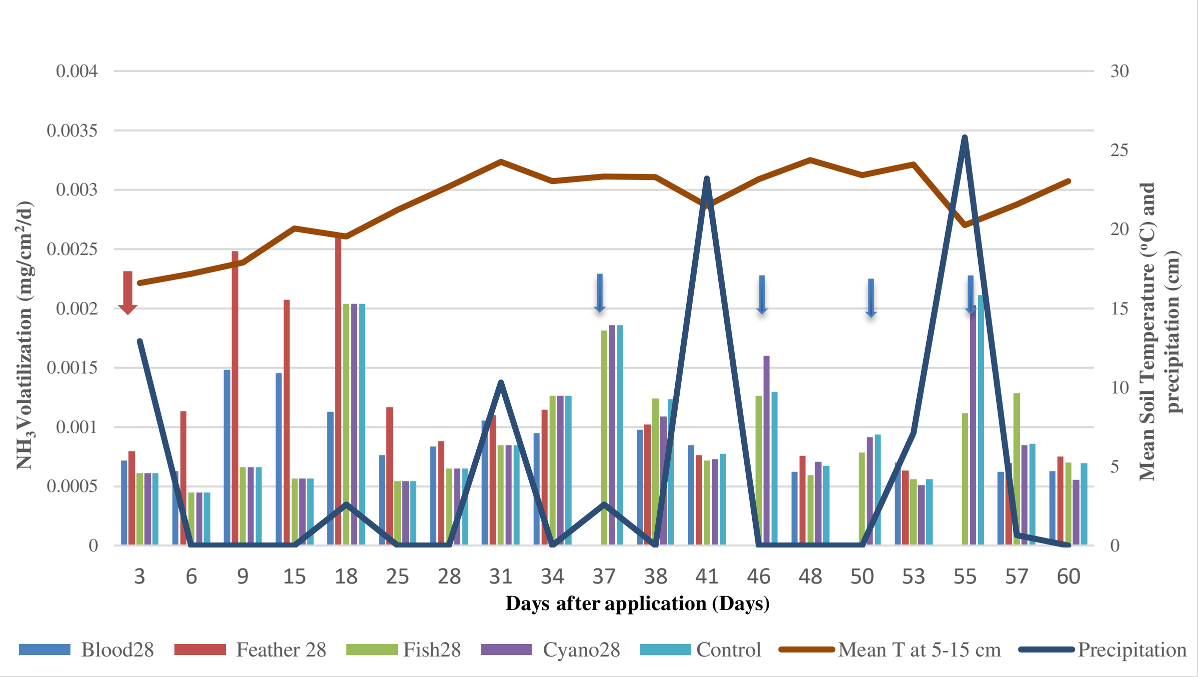

Figure 5. Average apparent NH_3 volatilized (mg/cm^2/d) from fertilizers applied at 28 kg N ha^{-1} as a function of time after application in 2014. Blood 28 =blood meal, Feather 28 = feather meal, Cyano 28 = cyano-fertilizer, Fish 28 = fish emulsion, Control = control. The blue arrows document liquid application times, while the red arrow documents solid application time. The solid brown line is the mean soil temperature (°C) measured at 5-15 cm during the experimental period (Days) in 2014. The black line shows the precipitation throughout the growing season.

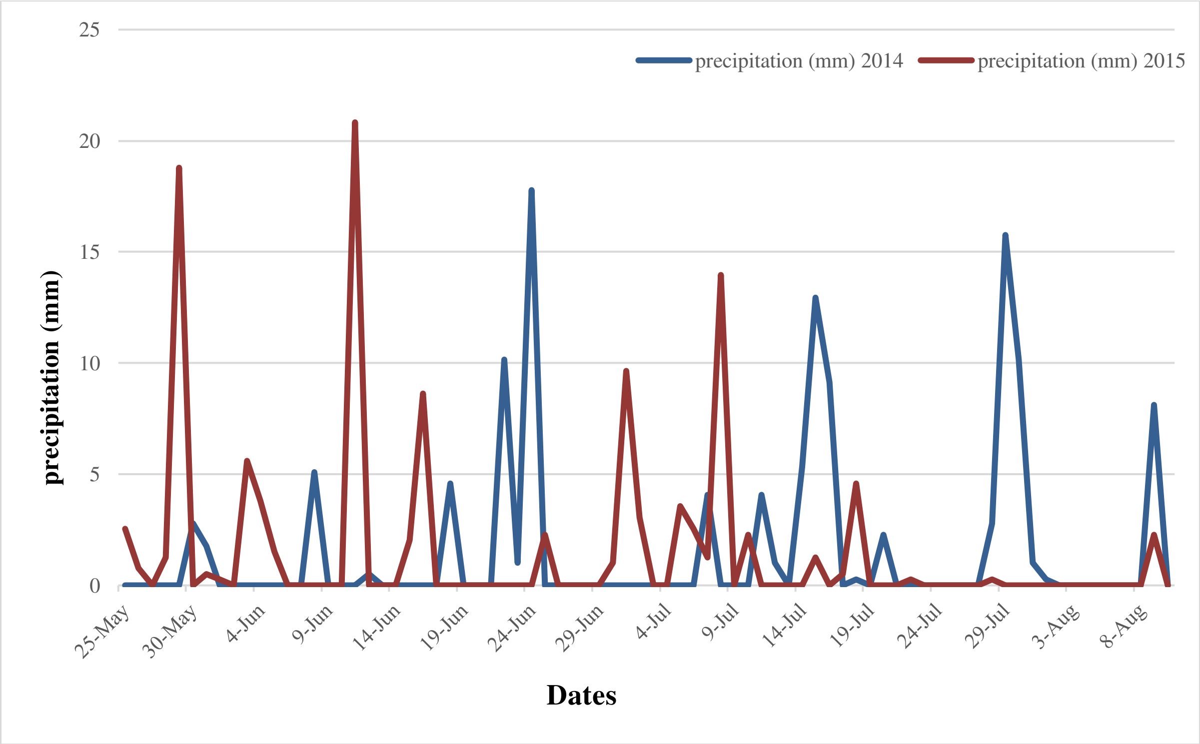

Figure 6. Precipitation (mm) during the experimental period in 2014 and 2015 obtained from CoAgMet.colostate.edu. The blue line represents the precipitation in 2014. The red line represents the precipitation in 2015.

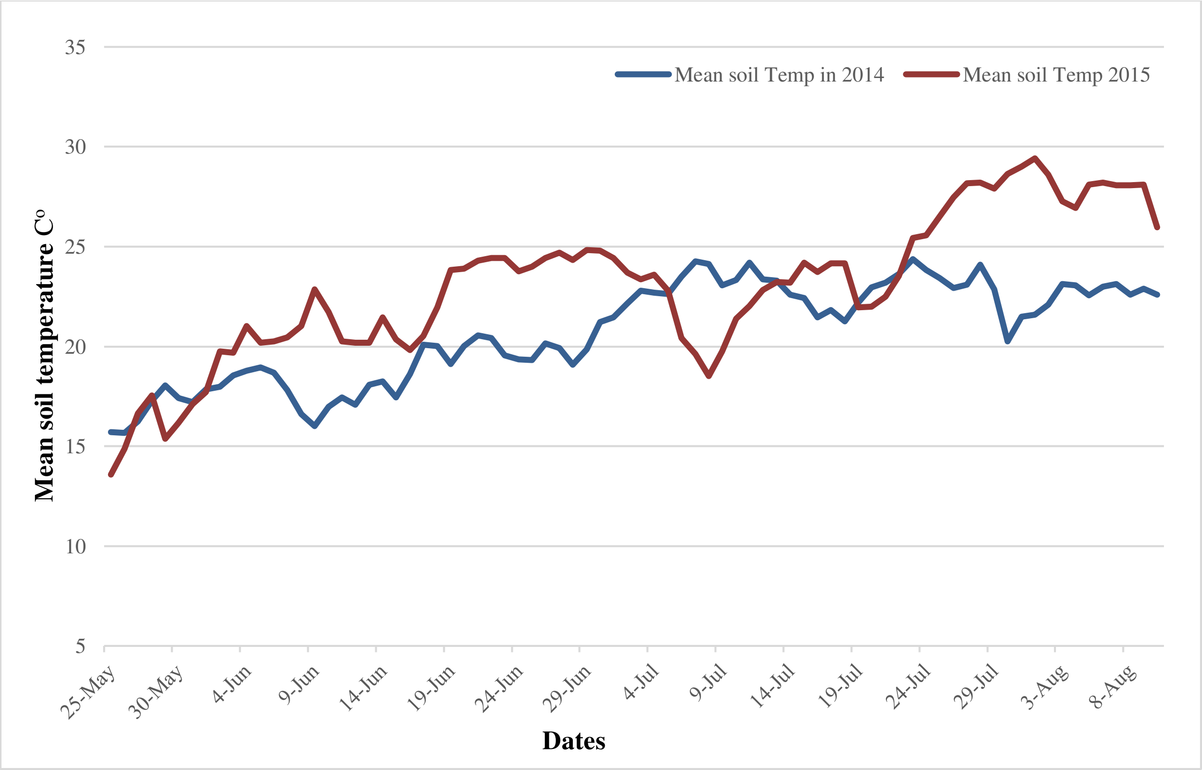

Figure 7. Mean soil temperature Cº measured at 5-15 cm during the experimental period in 2014 and 2015. The blue line represents the mean soil temperature at 5-15 cm in 2014. The red line represents the mean soil temperature at 5-15 cm in 2015

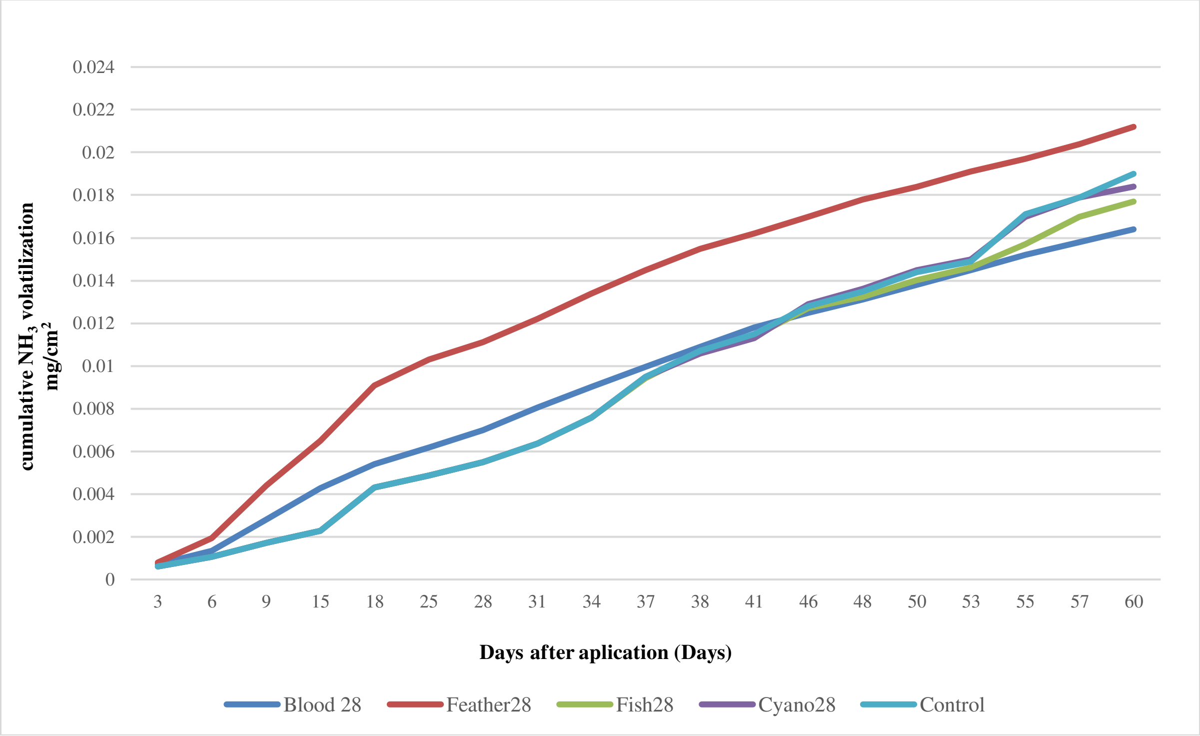

Figure 8. Cumulative average NH_3 volatilized (mg/cm^2) from fertilizers applied at 28 kg N ha^{-1} as a function of time after application in 2014. Blood 28 =blood meal, Feather 28 = feather meal, Cyano 28 = cyano-fertilizer, Fish 28 = fish emulsion, Control = control.

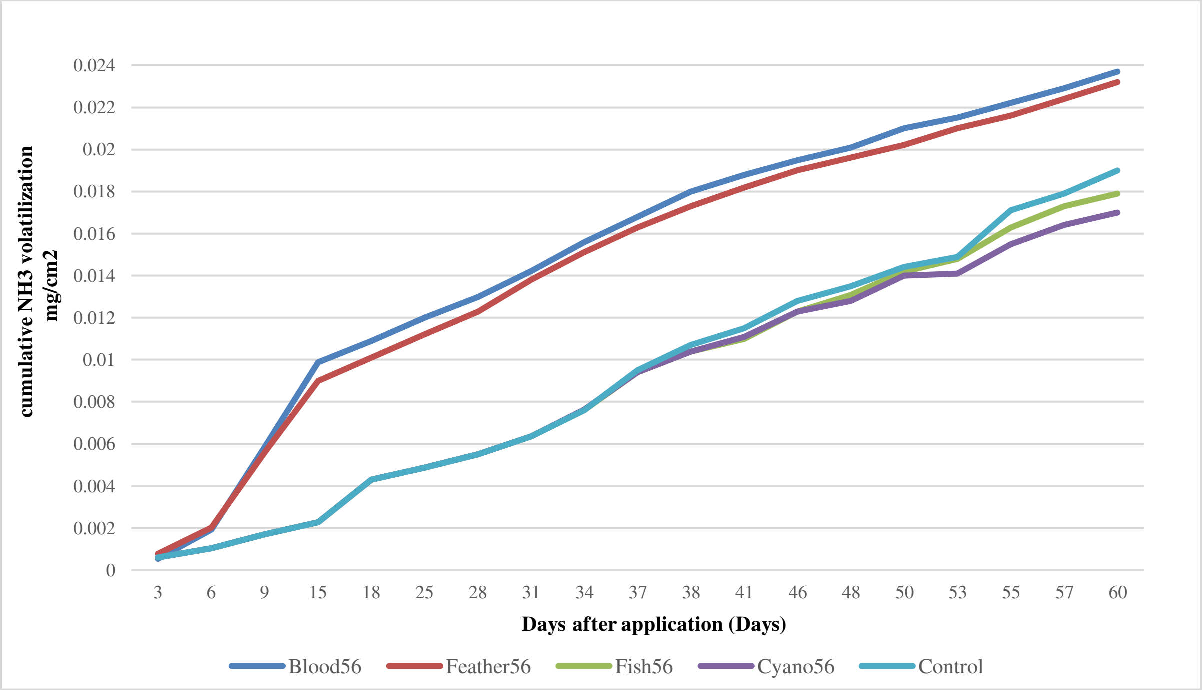

Figure 9. Cumulative average NH_3 volatilized (mg/cm^2) from fertilizers applied at 56 kg N ha^{-1} as a function of time after application in 2014. Blood56 =blood meal, Feather56 = feather meal, Cyano56 = cyano-fertilizer, Fish56 = fish emulsion, Control = control.

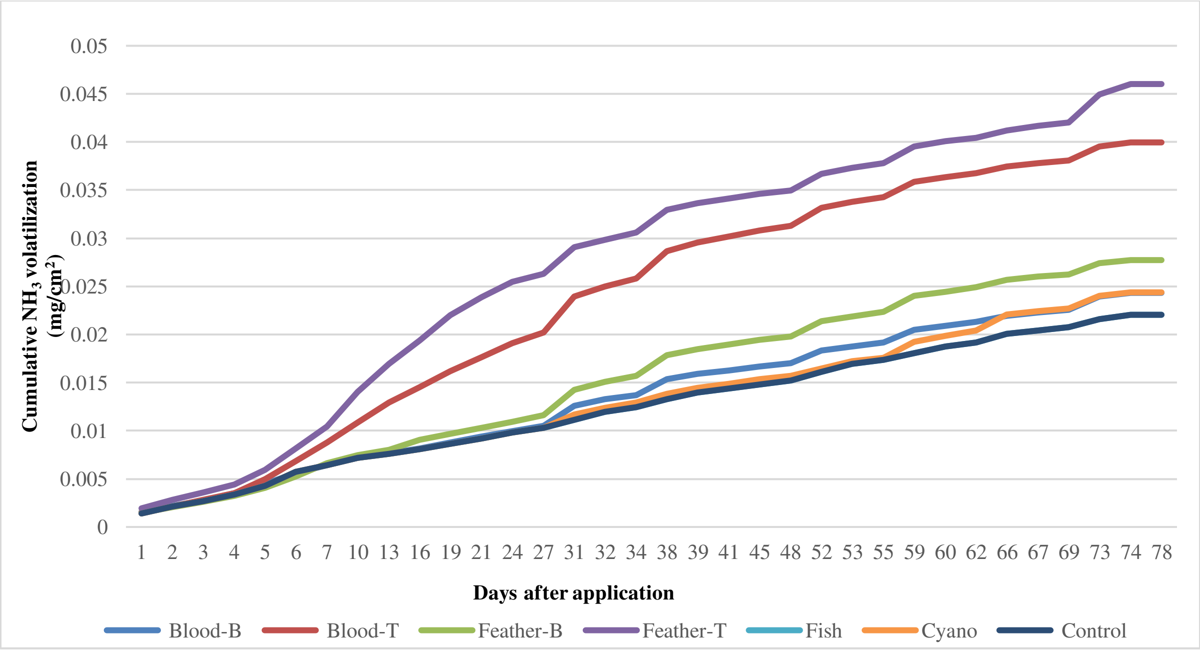

Figure 10. Cumulative average NH_3 volatilized (mg/cm^2) from fertilizers as a function of time after application in 2015. Blood-B = blood meal sub-surface band, Blood-T = blood meal surface banded, Feather-B = feather meal sub-surface band, Feather-T = feather meal surface banded, Fish = fish emulsion, Cyano = Cyano-fertilizer.

REFERENCES

Aneja V. P., W. Schlesinger, J. W. Erisman, S. N. Behera, M. Sharma, and W. Battye. 2012. Reactive nitrogen emissions from crop and livestock farming in India. Atmospheric Environment. 47:92–103. https://doi.org/10.1016/j.atmosenv.2011.11.026

Araújo, E. S., T. Marsola, M. Miyazawa, L. H. B. Soares, S. Urquiaga, R. M. Boddey, and B.J.R.Alves. 2009. Calibration of a semi-opened static chamber for the quantification of volatilized ammonia from soil. (In Portuguese, with English abstract.) Pesqi. Agropecu. Bras. 44:769–776.

Atia, A. 2008. Ammonia volatilization from manure application. Alberta Agriculture and Forestry. http://www1.agric.gov.ab.ca/

Balasubramanian, S., S. Koloutsou-Vakakis, D. M. McFarland, and M. J. Rood. 2015. Reconsidering emissions of ammonia from chemical fertilizer usage in Midwest USA. J. Geophys. Res. Atmos. 120: 6232–6246. doi:10.1002/2015JD023219.

Beene, M., C. Krauter, D. Goorahoo, and B. Robert. 2016. Ammonia emissions related to fertilizers on field crops using precision application practices in the Central Valley of California. http://www.academic.edu/22225254/Ammonia_Emission_Related_to_Fertilizers_on_Field_Crops_Using_Precision_Application_Practices_in_the_Central_Valley_of_California

Bouwman, A.F., L. J. M. Boumans, and N. H. Batjes. 2002. Estimation of global NH_3 volatilization loss from synthetic and animal manure applied to arable lands and grasslands. Global Biogeochem. Cycl. 16: 8 –13. doi: 10.1029/2000GB001389

Butler, M., and R. Simmons. 2011. Quantifying ammonia volatilization from surface-applied fertilizers in kentucky bluegrass grown for seed. Oregon State University. cropandsoil.oregonstate.edu/system/files/u1473/butler_and_simmons_nitrogen_volatilization.pdf

Charles, D. 2013. Our fertilized world. National Geographic 223 (5). http:// www.ebscohost.com.skyline.ucdenver.edu

Chambers, B. J., E. I. Lord, F. A. Nicholson, and K. A. Smith. 1999. Predicting nitrogen availability and losses following application of organic manure to arable land: MANNER. Soil Use Management 15 (3) :137–143. doi**:** 10.1111/j.1475-2743.1999.tb00079.x

Costa, M., F. Shigaki, B. Alves, P. Klenman, and M. Pereira. 2014. Swine manure application methods effects on ammonia volatilization, forage quality, and yield in the Pre-Amazon Region of Brazil. Chilean Journal of Agricultural Research 74 (3): 311-318.

Deutsches Institut für Normung e.V. 1983. German standard methods for the examination of water, wastewater and sludge; cations (group E) determination of ammonia-nitrogen (E5), Berlin, Germany. DIN 38406-5:1983-10

Huijsmans, J. F. M., J. M. G. Hol, and M. M. W. B. Hendriks. 2001. Effect of application technique, manure characteristics, weather and field conditions on ammonia volatilization from manure applied to grassland. NJAS-Wageningen Journal of Life Sciences 49(4): 323-342. doi: 10.1016/S1573-5214(01)80021-X

International Fertilizer Association (IFA) and the Food and Agriculture Organization of the United Nations (FAO). 2001. Global estimate of gaseous emission of NH_3, NO and N_2O from agricultural land. 1-82. ftp://ftp.fao.org /agl/agll/docs/globest.pdf

Jantalia, C. P., A. D. Halvorson, and R. F. Follett. 2012. Nitrogen source effects on ammonia volatilization as measured with semi-static chambers. Agronomy Journal 104(6): 1595-1603.

Jokela, B., C. Laboski, and T. Andraski. 2013. Manure application method and timing effects on emission of ammonia and nitrous oxide. Cooperative Extension System of University of Wisconsin, Madison, WI. http://articles.extension.org/pages/67611/manure-application-method-and-timing-effects-on-emission-and-nitrous-oxide

Jones, C., B. D. Brown, R. Engel, D. Horneck, K. Olson-Rutz. 2013. Factors affecting nitrogen fertilizer volatilization. Montana State University. 1-5. landresources.montana.edu/soilfertility/documents/PDF/pub/UvolfactEB0208.pdf

Khalil, M. I., U. Schmidhalter, R. Gutser. 2006. N2O, NH3 and NOx emissions as a function of urea granule size and soil type under aerobic conditions. Water, Air, and Soil Pollution 175:127-148. https://mediatum.ub.tum.de/doc/1304689/1304689.pdf

Liang, J. D., Y. F. Han, J. W. Zhang, W. Du, Z. Q. Liang, and Z. Z. Li. 2011. Optimal culture conditions for keratinase production by a novel thermophilic *Myceliophthora thermophila* strain GZUIFR-H49-1. Journal of Applied Microbiology, 110: 871–880. doi:10.1111/j.1365-2672.2011.04949.x

Lupis, S. G., J. G. Davis, and N. Embertson. 2012. Best management practices for reducing ammonia emission: manure application. Colorado State University Extension fact sheet 1.631D. extension.colostate.edu/docs/pubs/livestk/01631d.pdf

Ma, B. L., T.Y. Wu, N. Tremblay, W. Deen, N. B. McLaughlin, M. J. Morrison, and G. Stewart. 2010. On-farm assessment of the amount and timing of nitrogen fertilizer on ammonia volatilization. Agronomy Journal 102:134–144. doi: 10.2134/agronj2009.0021

Mazotto, A. M., R. R. Coelho, S. M. Cedrola, M. F. de Lima, S. Couri, E. P. de Souza, and A.B. Vermelho. 2011. Keratinase production by three Bacillus spp. using Feather meal and whole feather as substrate in a submerged fermentation. Enzyme Res. 52:3780-3787.

Meisinger, J. J., and W.E. Jokela. 2000. Ammonia volatilization from dairy and poultry manure. Managing Nutrients and Pathogens from Animal Agriculture (NRAES-130), Natural Resource, Agriculture, and Engineering Service, Ithaca, NY. 1-21. http:// www.dairyn.cornell.edu.

Mikkelsen, R. 2009. Ammonia emission from agriculture operation: fertilizers. Better Crops 93 (4): 9-11. https: //www. researchgate. net/profile/Robert_ Mikkelsen2/publication/ 304011934 _Ammonia_emissions_from_agricultural_operations_Fertilizer/links/ 57f6caf708ae886b8981cb5a.pdf

Mikkelsen, R., and T. K. Hartz. 2008. Nitrogen sources for organic crop production. Better Crops 92 (4): 16-19. ucanr.edu/sites/nm/files/76659.pdf

Nômmik, H. 1973. The effect of pellet size on the ammonia loss from urea applied to forest soils. Plant Soil 39:309–318.

NRCS. 1980. Soil survey of Larimer County Area, Colorado. http://soils.usda.gov/survey/ online_surveys/colorado/larimer/Text-Part%201.pdf. Accessed 29 September 2013.

Rochette, P., A. D. Angers, H. M. Chantigny, M. Gasser, J. D. MacDonald, E. D. Pelster, and N. Bertrand. 2013. NH_3 volatilization, soil NH_4 concentration and soil pH following subsurface banding of urea at increasing rates. Canadian Journal of Soil Sciences 93(2):261-268. https://doi.org/10.4141/cjss2012-095

Potter, C., C. Krauter, and S. Klooster. 2001. Statewide inventory estimates of ammonia emissions from fertilizer applications in California. Project report to California

Air Resources Board, Sacramento, CA. Contract# ID 98-76. https://epa.gov/ttn/chief/conference/ei11/ammonia/krauter.pdf

Rosen, C. J., and D. L. Allan. 2007. Exploring the benefits of organic nutrient sources for crop production and soil quality. HortTechnology 17:422- 430. horttech.ashspublications.org/content/17/4/422

Rostami, M., S. Monaco, D. Sacco, C. Grignani, and E. Dinuccio. 2015. Comparison of ammonia emissions from animal wastes and chemical fertilizers after application in the soil. International Journal of Recycling Organic Waste Agriculture 4(2): 127-134. doi:10.1007/s400093-015-0092-4

Sheppard, S. C., S. Bittman, and T. W. Bruulsema. 2010. Monthly ammonia emissions from fertilizers in 12 Canadian ecoregions. Canadian Journal of Soil Science 90(1): 113-127. doi: 10.4141/CJSS09006

Sommer, S. G., and N. J. Hutchings. 2001. Ammonia emission from field applied manure and its reduction—invited paper. European Journal of Agronomy 15: 1-15.

Stevenson, K.T., H. B. Rader, L. Alessa, A. D. Kliskey, A. Pantoja, M. Clark, and J. Smeenk. 2014. Sustainable Agriculture for Alaska and the Circumpolar North: Part III. Meeting the Challenge of High-Latitude Farming. Arctic Institute of North America 67(3): 320 - 339. http://dx.doi.org/10.14430/arctic4402

Sukor, A. 2016. Organic nitrogen fertilizers influence nutritional value, water use efficiency, and nitrogen dynamics of drip irrigated lettuce and sweet corn. Colorado State University. ProQuest Dissertations and Theses.

Toonsiri, P., S. J. Del Grosso, A. Sukor, J. G. Davis. 2016. Greenhouse gas emission from solid and liquid organic fertilizers applied to lettuce. Journal of Environmental Quality. 45(6):

1812-1821. doi:10.2134/jeq2015.12.0623

Webb, J., B. Pain, S. Bittman, and J. Morgan. 2010. The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response-A review. Agriculture, Ecosysytems and Environment 137(1-2): 39-46. http://dx.doi.org/10.1016/j.agee.2010.001

Wickham, A. 2016. Effect of cyanobacterial fertilizer, commonly-used organic fertilizers, and plant growth regulation on yield and growth characteristics of carrot (*DAUCUS CAROTA VAR.SATIVUS*), cucumbers (*CUCUMIS SATUVUS*), and bell peppers (*CAPSICUM ANNUUM*). Colorado State University. ProQuest Dissertations and Theses.