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Volatilization of Ammonia from Granular and Dissolved Urea Applied to Turfgrass[1]

Steve Titko, III, John R. Street, and Terry J. Logan[2]

ABSTRACT

Urea, applied in either granular or dissolved form, is a commonly used N fertilizer source for turfgrass, and volatilization of NH_3 produced by urea hydrolysis is considered to be a major contributor to reduced N fertilizer utilization by established turf. Ammonia volatilization losses from urea applied to turfgrass were studied in a controlled environment chamber. Kentucky bluegrass (*Poa pratensis* L., var. Merion) sod was placed on a Crosby silt loam soil (fine, mixed, mesic Aeric Ochraqualfs) in 17.5-L plastic containers with surface areas of 434 cm². Covers fitted to the containers had intake and exhaust ports such that air could be passed over the sod and NH_3 collected in a boric acid trap. Experiments were conducted to examine the effects of temperature, relative humidity, wetting and drying cycles, and irrigation on NH_3 loss from surface-applied urea. Ammonia losses were higher from granular than from dissolved urea in all cases, except where urea application was immediately followed by a 25.4-mm irrigation. Ammonia loss from granular and dissolved urea increased as temperature increased from 10 to 22.2°C, but there were no significant effects on NH_3 loss as temperature increased from 22.2 to 32.2°C. Ammonia losses from dissolved urea at 68% R.H. were greater than losses at 31% R.H., but NH_3 loss from granular urea was not significantly affected by relative humidity. Ammonia losses increased rapidly following periodic wetting of the turf fertilized with dissolved urea. Irrigation (25.4 mm) following urea application decreased NH_3 losses from both dissolved and granular ureas.

Additional index words: **Nitrogen fertilizer, Kentucky bluegrass, Nutrient losses, *Poa pratensis* L.**

NITROGEN fertilization is an important cultural practice in turfgrass management. Recent investigations into N utilization by plants have indicated that a substantial portion of the N applied is apparently lost and that crop recovery is often less than 50% (Torello et al., 1983). Nitrogen may be lost from turfgrass via many avenues including leaching, denitrification, volatilization, and immobilization.

Urea [$CO(NH_2)_2$] is the most popular N source of the turfgrass industry because of its high N content, ease of handling, and low cost. Urea undergoes enzymatic hydrolysis to form ammonium carbonate, which is very unstable and decomposes to form NH_3:

$$CO(NH_2)_2 + H^+ + 2H_2O \xrightarrow{\text{urease}} 2NH_4^+ + HCO_3^- \quad [1]$$

$$HCO_3^- + H^+ \rightleftharpoons CO_2(g) + H_2O \quad [2]$$

$$NH_4^+ + OH^- \rightleftharpoons NH_4OH \rightleftharpoons NH_3(g) + H_2O \quad [3]$$

Literature values regarding the magnitude of NH_3 volatilization losses from urea applied to turf are inconsistent. Volk (1959) found significant volatilization losses from urea applied to turf-covered soils; N losses from surface-applied pelleted urea reached 20 to 30%. Nelson et al. (1980) reported volatilization losses of 39% of urea–N applied to thatchy turf, while Torello et al. (1983) found only 1.6 and 4.6% volatilization losses from prilled- and liquid-applied urea on turf, respectively.

Factors affecting NH_3 volatilization have been examined by Denmead et al. (1974), Mills et al. (1974), Fenn (1975), Terman (1979), and Nelson (1982). Among the important variables affecting NH_3 volatilization are microenvironment pH, soil moisture, temperature, fertilizer source and rate, soil properties such as cation exchange capacity, and depth of fertilizer incorporation.

Hauck and Stephenson (1965), working with granular urea, found that an alkaline microenvironment was created around each hydrolyzed urea granule, with large granules producing pH values of 8.5 to 9.0 in the immediate granule environment. These results are in agreement with Volk (1959), who reported that up to 59% of the applied urea–N was volatilized on acid soil. Ammonia volatilization is more severe under alkaline conditions (Jewitt, 1942; Ernst and Massey, 1960; Martin and Chapman, 1951) as would be expected from the dissociation of NH_4OH. Based on a pK of −9.28 (Lindsay, 1979), 35% of dissolved NH_3 would be in the form of NH_3 at pH 9, but only 0.5% at pH 7.

In an established turf, surface application of fertilizer is the only practical method of fertilization. The nutrients must be solubilized and moved into the root zone for uptake by plants. Frequently, the movement of N into the soil may be delayed or prevented by the

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[2] Former graduate research associate, associate professor, and professor, Agronomy Dep., The Ohio State Univ., respectively. Senior author's present address is Tru Green, Tech. Ctr., P.O. Box 707, Fremont, IN 46737.

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turfgrass. Thus, the fertilizer N remains close to the surface where it is subject to fluctuating moisture levels, high temperatures, and microbial degradation, all of which contribute to NH_3 volatilization.

Many investigators have found greater NH_3 losses from sod or plant residues compared to bare soils (Volk, 1959; Watkins et al., 1972). Torello (1981) found urease activity to be as much as 30 times greater on the leaf surfaces, and in the thatch, of Kentucky bluegrass (*Poa pratensis* L.) than in the underlying soil. A dense turf thus provides an ideal environment for urea hydrolysis if enough moisture is present and if the urea is in close proximity to the blades or thatch.

The turfgrass environment frequently includes thatch, which has been defined as a tightly intermingled layer of living and dead stems, leaves, and roots of turfgrass that develops between the green vegetation and underlying soil surface (Beard, 1973). Nelson et al. (1980) found that thatch may contribute significantly to NH_3 volatilization. Thatch may prevent infiltration of the applied N into the soil and cause the urea to dry more rapidly than if applied to non-thatchy turf. A high level of urease activity in the thatch and leaves may also contribute to increased NH_3 volatilization by increasing NH_3 production from urea.

The purpose of this investigation was to assess the effects of temperature, relative humidity, wetting and drying cycles, and irrigation on NH_3 volatilization from urea applied to turf in a laboratory study. Secondly, the relative NH_3 losses from granular and dissolved urea, as affected by the variables under study, were compared.

MATERIALS AND METHODS

All experiments were conducted in a controlled environment room. Air temperature and humidity were varied according to the experimental variables studied. A 12-h photoperiod was used in all experiments. A mixture of incandescent and fluorescent lighting provided adequate light intensity for turf growth.

The general design of the NH_3 collection system was similar to that of Kissel et al. (1977) and is shown in side view in Fig. 1. Volatilization chambers were constructed from 17.5-L polyethylene buckets with sealing lids. The chambers were filled two-thirds full with a Crosby silt loam soil (fine, mixed, mesic Aeric Ochraqualfs) with a pH of 7.3. Kentucky bluegrass (var. Merion) sod grown on the same soil from an adjoining area was placed in the bucket so as to give an air volume above the turf of 2.4 L. The sod was taken from an area that had not been fertilized for 1 yr. The diameter of the turf samples was 23.5 cm, and the sod had a thatch layer of 2.0 cm. Sod was kept in the greenhouse until used in the experiment; after placement in the chambers, the soil and sod were brought to -33 kPa soil moisture content 24 h before treatment application. The chambers allowed natural drainage and percolation to occur, but the sod was fit tightly into the bucket so as to minimize air exchange between the sod and soil.

A vacuum pump was used to pull a stream of air through an acid scrubber and a drierite flask. The scrubber containing 0.5 *M* HCl removed any ambient NH_3 in the atmosphere, and the drierite flask was used to adjust the humidity of the air before entering the volatilization chambers. The air was then dispersed across the top of the volatilization chamber. Twelve volatilization chambers were sampled simultaneously. Air-flow through the chambers, individually controlled by means of a vacuum manifold, was maintained at 35 L/min. This corresponds to about 15 air volume exchanges/min. A Gilmont flow meter (Gilmont Instruments, Inc., Great Neck, NY) was used to measure and adjust airflow through individual chambers. The air exchange rate of the environmental room was also maintained at 15 exchanges/min. An indicator boric acid trap (Fig. 1) ran continually to monitor the NH_3 concentration in the room. Only traces were detected, indicating that the air exchange rate was adequate to remove NH_3 lost from the chambers. Kissel et al. (1977) found that NH_3 volatilization increased rapidly up to 14 volume exchanges/min. Any further increase in air exchange rate did not significantly increase volatilization. Based on field measurements of air flow above bermudagrass (*Cynodon dactylon* L.), Kissel et al. (1977) concluded that NH_3 volatilization would not be limited by their sampling method if air exchanges were >15 to 20/min.

Ammonia was picked up in the moving air stream and bubbled through a boric acid-indicator solution. The solution was then titrated with standardized HCl, and the percent NH_3–N volatilized was calculated. The detection limit was 50 μg N/chamber.

During sampling, covers were tightly fitted over the volatilization chambers and the air sampled for a 30-min period. Covers were then removed to expose the turf to the normal environment. Sampling times varied according to when volatilization was expected to be the greatest, based on preliminary studies. By extrapolating between any two sampling times, an estimate was obtained of the total NH_3 volatilized during that period. This system allowed open growing conditions to exist most of the time and minimal condensation problems. Time zero for sampling was immediately after urea application to the turfgrass.

The efficiency of the trapping system was determined by generating a known quantity of NH_3 in a generation flask and running the system. The NH_3 trapped by the boric acid was determined by direct titration. The N left in the generation flask was determined by steam distillation (Keeney and Nelson, 1982). The overall efficiency of the system av-

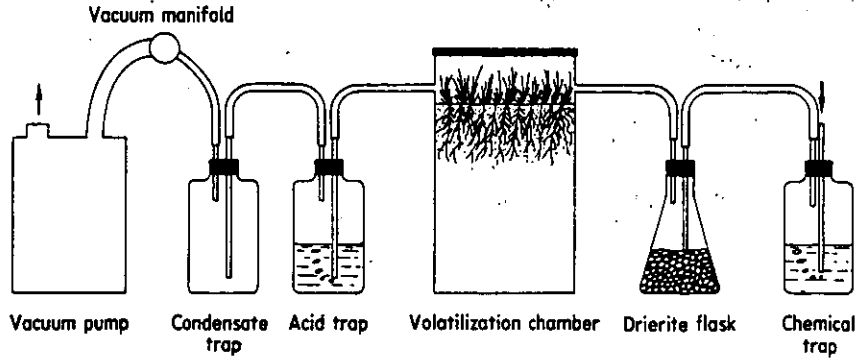

Fig. 1. Schematic side view of the NH_3 volatilization apparatus.

eraged 98.4 ± 4.7% N recovery for 10 experimental runs.

The N rate used in all experiments for liquid and dry urea treatments was the equivalent of 73 kg N/ha. Granular urea (46-0-0) was applied by hand. The granules were sieved to obtain a particle diameter of approximately 2 mm to provide uniform distribution. Dissolved urea treatments were sprayed on with a hand-held CO_2-pressurized (1.4 kg/cm^2) sprayer using a single Tee-Jet 8002 even-fan nozzle (Spraying Systems Co., Wheaton, IL). A spray volume of 163 mL/m^2 (equivalent to 1630 L/ha), typical for most commercial sprayers, was used. This gave a calculated dissolved urea concentration of 98 g/L.

Four separate experiments were conducted to evaluate the effect of temperature, humidity, wetting and drying cycles, and irrigation on NH_3 volatilization; NH_3 losses from liquid and granular urea were compared in all experiments.

Treatment means for NH_3-N lost per chamber were calculated, and a factorial analysis of variance was performed using the general linear models (GLM) procedure in the Statistical Analysis Systems (SAS Institute, 1979). Means were separated by calculating the LSD at the 0.05 level. The fertilizer treatments were replicated from three to six times depending on the variable under evaluation and experiment size. A completely randomized design was used throughout the study. During the first (temperature) experiment, check (no urea) treatments were included. Ammonia losses from untreated samples remained constant from all replicates. A total of only 177 μg N/chamber was collected at the 22.0°C temperature during the entire 84-h experimental period. Subsequent experiments did not include checks so that the additional chambers could be used to increase treatment replication.

Experiment 1: Temperature

Ammonia volatilization was evaluated at temperatures of 10.0, 22.2, and 32.2°C. A separate experiment with replication was conducted at each temperature. The relative humidity was maintained at 68 ± 4%. Sampling times were varied for each experiment because of varying NH_3 volatilization rates. The experiments were terminated when the acid traps no longer changed color.

Experiment 2: Relative Humidity

Relative humidities of 68 ± 4% and 31 ± 4% were used. Temperature was maintained at 32.2°C. The humidity was regulated in the environmental control room with a high-capacity room-dehumidifier. Humidity of the ambient air crossing the turf during sampling was adjusted with indicator drierite flasks. Saturated drierite traps maintained the relative humidity in the chambers at 68 ± 4%. Fresh indicator drierite reduced relative humidity to 31 ± 4%. This drierite had to be replaced every five to six sampling periods to maintain relative humidity at 31%. Relative humidity was measured with a hygrothermograph and by periodically checking with an Assmann psychrometer (Systron-Donner Corp., WeatherMeasure Div., Sacramento, CA).

Experiment 3: Wetting and Drying Cycles

The experiment was conducted at 22.2°C and 68 ± 4% R.H. Relative humidity in the volatilization chambers did fluctuate with the wetting and drying cycles. However, relative humidity of the air entering the volatilization chambers and in the environmental control room remained relatively constant at 68 ± 4%.

The turfgrass was wet (35 mL/chamber, <1 mm) every 24 h with a misting bottle. The turf was then allowed to follow a normal drying cycle. Water applied at this volume covered the leaf surfaces and moistened the thatch, but was not enough to move below the thatch layer.

Ammonia losses were measured prior to misting and at 1 and 3 h after mist application. All dissolved and granular urea treatments were misted.

Experiment 4: Irrigation

The experiment was conducted at 22.2°C and at a relative humidity of 68 ± 4%. Irrigation was applied to half of the dissolved and granular urea treatments immediately after fertilizer application. The water was sprayed on with a hand-pump sprayer with a coarse droplet size. A total of 25.4 mm of water was applied over a 1-h period. The water was applied four times at a rate of 6.3 mm/15 min. This was considered to adequately simulate a normal irrigation rate of 25.4 mm/h in the field.

RESULTS AND DISCUSSION

In all experiments, NH_3 volatilization ceased within 5 days after treatment application. Losses were detected at the first sampling in all treatments (30 min–5 h), and most of the NH_3 was usually lost within the first 2 days after treatment application, although this was somewhat treatment-dependent. Patterns of NH_3 volatilization varied for all experiments. Thus, each experiment will be discussed separately.

Experiment 1: Temperature

The NH_3-N recovered per chamber per sampling period is shown graphically in Fig. 2, and cumulative (90 h) NH_3 losses are reported in Table 1. Granular

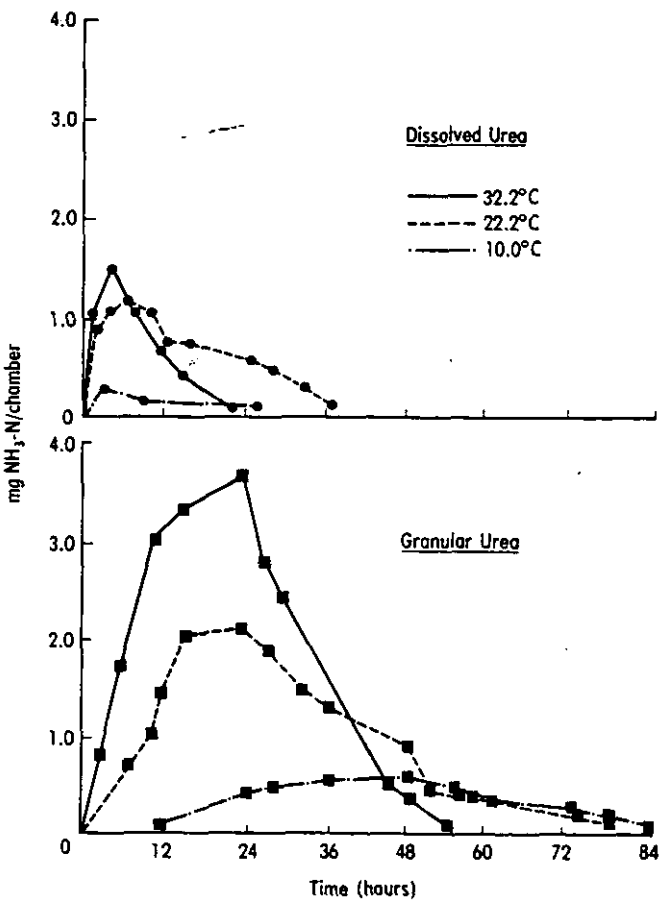

Fig. 2. Effects of temperature on NH_3 volatilization with time from granular and dissolved urea.

Table 1. Cumulative NH_3-N losses from granular and dissolved urea applied to sod as affected by the experimental treatments.

Experiment	Cumulative (90 h) NH_3-N losses (mg/chamber)				
	Granular		Dissolved		Significance†
	Mean	CV	Mean	CV	
		%		%	
1. Temperature (°C)					
10.0	57.3 (18.1)‡	34.2	8.6 (2.7)	61.4	*
22.2	135.6 (42.8)	34.8	52.1 (16.5)	19.4	*
32.2	192.4 (60.8)	17.2	38.0 (12.0)	22.4	*
LSD (0.05)	70.2		16.4		
2. Relative humidity (%)					
31	124.5 (39.3)	44.9	7.1 (2.2)	110	*
68	192.6 (60.8)	17.3	38.0 (12.0)	22.4	*
LSD (0.05)	104.2		18.7		
3. Wetting and drying					
No wetting	134.4 (42.4)	39.3	46.4 (14.7)	28.2	NS
Wetting	205.0 (64.7)	31.8	99.3 (31.4)	15.9	*
LSD (0.05)	76.3		20.6		
4. Irrigation					
No irrigation	161.7 (51.1)	22.0	51.0 (16.1)	16.0	*
Irrigation	6.3 (2.0)	0	16.8 (5.3)	47.2	NS
LSD (0.05)	56.9		18.2		

* Significant at the 0.05 level of probability.
† Significance between granular and dissolved treatments.
‡ Percent of NH_3-N applied.

urea consistently lost more NH_3–N than did dissolved urea at all temperatures, and differences in cumulative losses were significant at all three temperatures. The urea granule applied to moist sod will adsorb moisture, and the microenvironment pH around this granule can become high (Hauck and Stephenson, 1965). Volk (1959) reported NH_3 volatilization losses of 20 to 30% of the applied N (granular urea) on grass sod, with a greater loss from large versus small urea pellets surface-applied to soil. We expect that the lower urea concentration of the dissolved urea produced a less alkaline environment than that developed around the granular form, giving a lower potential for NH_3 (g) formation following urea hydrolysis. Thus, the granular urea should have lost more NH_3 than the dissolved urea because of a higher microenvironment pH. The dissolved-urea volume applied in this study, which is commonly used in the commercial lawn care industry, is not sufficient to move the urea into the root zone, and much of the urea is deposited on the leaf surface. The dissolved urea treatments were, therefore, more susceptible to drying, which, in turn, may have slowed urea hydrolysis (McInnes et al., 1986); on the other hand, granular urea is very hygroscopic and can adsorb moisture necessary for urea hydrolysis.

Ammonia volatilization from both granular and dissolved urea was significantly higher at 22.2 than at 10.0°C (Table 1). Ammonia losses were not significantly different, however, between 22.2 and 32.2°C for either urea treatment, although there was a trend for increased loss at the highest temperature with granular urea, and decreased loss with dissolved urea. The 32.2°C temperature may have resulted in drying of the dissolved urea with decreased hydrolysis, whereas the granular urea is hygroscopic and could have adsorbed moisture from the turf and thatch.

Many researchers (Ernst and Massey, 1960; Watkins et al., 1972) have found greater NH_3 volatilization from urea at higher temperatures. The enzyme necessary for urea hydrolysis is urease, which is synthesized by microbes and living plants. The activities of these organisms are temperature dependent. Enzyme activity is also temperature dependent (Bremner and Mulvaney, 1978). Ernst and Massey (1960) found greatest NH_3 losses from granular urea at 32.2°C, but in our experiment there was no significant difference in NH_3 volatilization from dissolved urea at temperatures of 22.2 and 32.2°C. Again, this is probably due to the higher temperatures causing the dissolved urea to dry out faster. Hydrolysis here would not be limited because of urease activity, but probably because of a lack of moisture.

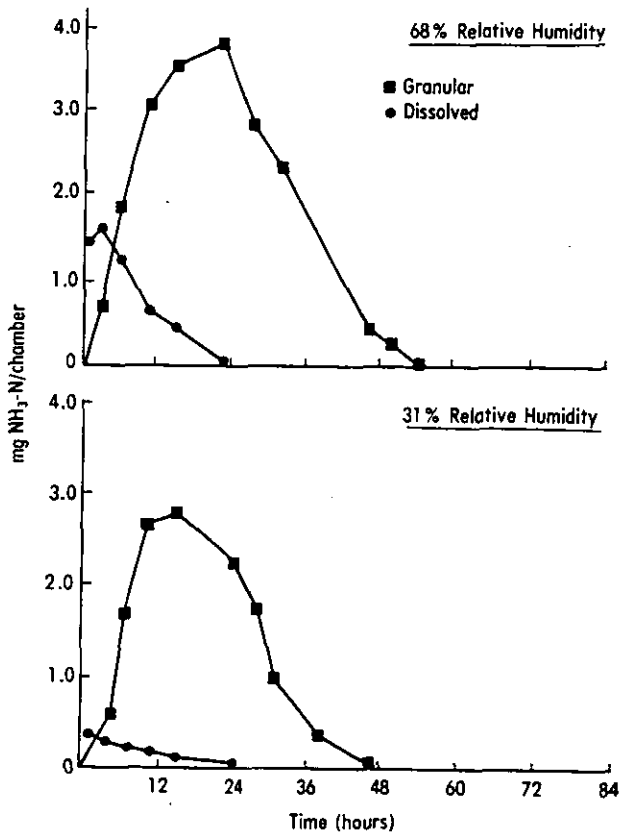

Fig. 3. Effects of relative humidity on NH_3 volatilization with time from granular and dissolved urea.

Ammonia volatilized sooner at 32.2°C than at the lower temperatures (Fig. 2). At 32.2°C, high urease activity would have hydrolyzed urea quickly, and, thus, NH_3 loss started within the first few hours after application. Maximum NH_3 loss for the granular urea treatment at 32.2°C occurred 24 h after application, and 6 h after application for the dissolved urea treatments. Although dissolved and granular urea lost NH_3 at 32.2°C sooner than at 22.2 and 10.0°C, volatilization dropped off rapidly at 32.2°C, ceasing after 20 h for dissolved urea, and after 55 h for granular urea. Volatilization continued for a longer period at the lower temperatures, probably because of less rapid drying, allowing hydrolysis to occur for a longer time.

Experiment 2: Relative Humidity

Ammonia losses from granular urea were 54% higher at 68% R.H. compared to those at 31% R.H., although this difference was not significant. The higher relative humidity did, however, significantly increase dis-

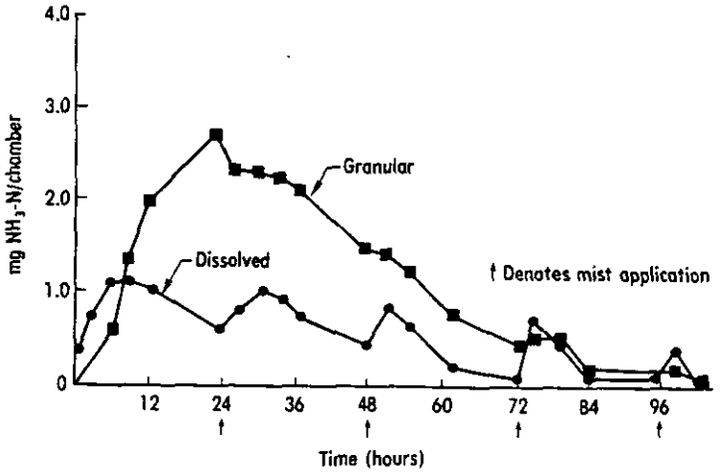

Fig. 4. Effects of alternate wetting (misting) and drying cycles on NH_3 volatilization with time from granular and dissolved urea.

solved urea NH_3 losses (Table 1, Fig. 3) by an average of more than five times.

The relative humidity experiment was conducted at 32.2°C. Under severe drying conditions, such as low humidity and high temperature, NH_3 losses may be lower due to incomplete hydrolysis (McInnes et al., 1986). Subsequent wetting should allow hydrolysis to occur and increase volatilization losses.

Experiment 3: Wetting and Drying Cycles

The effect of wetting and drying cycles on NH_3 volatilization for both dissolved and granular urea treatments is shown in Fig. 4, and cumulative losses are given in Table 1.

After each misting, a surge in NH_3 volatilization occurred with the liquid urea treatments. Ammonia volatilization peaked 2 to 3 h after each mist application. Granular urea treatments showed little response to misting application except at the 72-h misting, and this treatment did not significantly affect NH_3 loss from the granular urea (Table 1).

Martin and Chapman (1951) reported that NH_3 volatilization from urea occurred in cycles when soil was repeatedly moistened and allowed to dry. They concluded that evaporation of water was necessary for the volatilization process. In this experiment, water was very critical for urea hydrolysis. Dissolved urea on the leaf blades dried quickly, thus stopping hydrolysis. McInnes et al. (1986) found that drying of the soil surface virtually stopped urea hydrolysis. After each misting, hydrolysis probably proceeded, and NH_3 evolution again occurred. Granular urea showed no response to wetting and drying during the first three mistings. Granular urea was hygroscopic enough to adsorb moisture from either the thatch or soil, or both. Only after 72 h, when the thatch or soil, or both, became dry, did the granular urea treatment respond to misting with a surge of NH_3 evolution.

The wetting and drying experiment was conducted at 22.2°C and 68% R.H. These environmental parameters provided conditions for low evaporative losses. More liquid urea would be expected to dry on the leaf blades at higher temperatures and lower relative humidity. Under such conditions, wetting and drying would be expected to affect NH_3 volatilization to a greater degree than under the conditions used here.

Experiment 4: Irrigation

Irrigation, applied over a 1-h period to simulate a normal irrigation intensity, resulted in significantly lower losses of NH_3 than nonirrigated treatments for both dissolved and granular urea (Fig. 5, Table 1).

The irrigation effect was so large that there were no significant differences in NH_3 losses between irrigated dissolved and granular urea (Table 1). Irrigation was more effective in reducing NH_3 losses from granular than from dissolved urea, reducing NH_3 losses by 96.4% for granular and 66.0% for dissolved urea. Irrigation was applied as a coarse droplet spray to simulate a field sprinkler. The water droplets are apparently not as efficient in moving urea from the leaf blades as they are in dissolving and moving a granule of urea into the soil. Dissolved urea that has coated the plant sur-

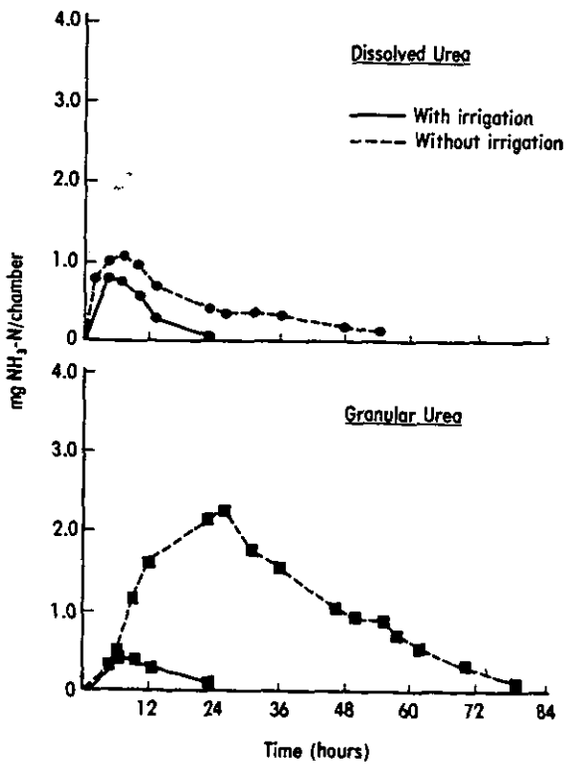

Fig. 5. Effects of irrigation on NH_3 volatilization with time from granular and dissolved urea.

faces and thatch has many lodging sites for physical entrapment (i.e., collar, underside of blade, sheath, etc.) and reduces the mobility of urea even where irrigation is applied. This may partially explain why irrigation had less of an effect in reducing NH_3 losses from dissolved compared to granular urea.

In addition, irrigation probably allowed the urea granule to dissolve and move into the soil. Soil probably has a higher cation exchange capacity and has been shown to have lower urease activity than leaf blades and thatch (Torello, 1981). A slower hydrolysis rate in soil would result in a slower production of NH_4^+, and the NH_4^+ produced could be more readily adsorbed by the soil or be nitrified. Dissolved urea has a greater distance to move and more barriers to pass before reaching the soil and interacting with the exchange complex. The total losses of NH_3 from dissolved and granular ureas under irrigation were very low, and this treatment was particularly effective in reducing NH_3 losses of granular urea.

This research has shown that as much as 60% of urea surface-applied to sod can be lost as NH_3 under conditions that simulate those found in the field with commercial N fertilization of turfgrass. The greatest losses occurred with granular urea unless the sod was irrigated immediately following application. Temperatures $>10°C$, high relative humidity, and periodic wetting of the soil surface all favored increased NH_3 loss from surface-applied urea, probably because of their effects on urea hydrolysis.

The results of this research need to be confirmed in the field, and the findings used to tailor N fertilization management for turfgrass where urea is the primary N source.

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