Effect of Urease Inhibitor Application Rate and Rainfall on Ammonia Emissions from Beef Manure

D. B. Parker, M. B. Rhoades, N. A. Cole, V. P. Sambana

Abstract. *Social, economic, and environmental factors have prompted the desire to reduce global atmospheric ammonia emissions. A research project was conducted to assess the efficacy of the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) for reducing ammonia emissions from simulated open-lot beef cattle feedyard surfaces. A mixture of beef cattle feces and urine (manure) was placed into small emission chambers (167 × 167 × 170 mm deep). A urea solution was added every 2 days to simulate continual urine deposition in the feedyard. Clean air (1.4 L min^{-1}) was passed over the manure surface, and ammonia was trapped in an acid solution. The six treatments (three replications per treatment) included combinations of NBPT application rate with or without simulated rainfall. NBPT was applied at zero, steady (5 kg ha^{-1} every 4 days), or increasing (5 kg ha^{-1} initially, doubled every 4 days up to 40 kg ha^{-1}) rates. Rainfall treatments received 6 mm every 4 days. For all treatments, mean ammonia emissions from the manure were lower ($p < 0.05$) when simulated rainfall was added. Mean ammonia emission rates for the NBPT treatments were 26% to 33% of the non-NBPT treatments, demonstrating that NBPT was effective at reducing emissions from the manure surfaces in both wet and dry conditions. There were no statistical differences in mean ammonia emission rates for the steady and increasing NBPT application rates, showing that a steady NBPT application of 5 kg ha^{-1} every 4 days was effective in reducing ammonia emissions from the manure. The use of NBPT appears promising for reducing ammonia emissions at beef cattle feedyards. Additional research is warranted to study the effectiveness under long-term conditions in an outdoor feedyard setting.*

Keywords. *Air quality, Cattle, Feces, Feedlot, Feedyard, Urea, Urine.*

Ammonia is emitted to the atmosphere from many natural, anthropogenic, industrial, and agricultural sources. Concentrated animal feeding operations (CAFO) have been noted for their contribution to global ammonia emissions. Cattle excrete more than 75% of the nitrogen consumed in their diet (Bierman et al., 1999; Cole et al., 2006, 2007, 2009b), and much of this nitrogen is subsequently emitted to the atmosphere as ammonia gas (Cole and Todd, 2009; Todd et al., 2008; Rhoades et al., 2010). In the Texas Panhandle region alone, feeding of cattle has become a primary agricultural enterprise, and there are more than 70 feedyards with capacities greater than 20,000 animals (Parker et al., 1997).

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Manure is the combination of feces and urine excreted from beef cattle. Most of the ammonia emitted from the pen surface comes from urine (Cole et al., 2009a, 2009b). Under favorable temperature, moisture, and pH conditions, and in the presence of the urease enzyme, the urea ($CO(NH_2)_2$) present in urine and manure is hydrolyzed to produce ammonia. Initially, urea hydrolyzes to produce ammonium carbonate ($(NH_4)_2CO_3$) (eq. 1), which is subsequently converted to ammonium (NH_4^+) (eq. 2). A more precise description of the urea hydrolysis process can be found in Mobley et al. (1995). There exists a chemical equilibrium between NH_4^+ and NH_3 in solution that is affected by pH and temperature (eq. 3). Some of the NH_3 in solution is volatilized into the air. The concentrations of NH_3 in the air and in solution are governed by Henry's law constant (H), which is a function of temperature (eq. 4). The flux of NH_3 from manure is primarily dependent on the NH_3 concentration, pH, temperature, and wind velocity (Muck and Steenhuis, 1982).

$$CO(NH_2)_2 + 2H_2O \rightarrow (NH_4)_2CO_3 \qquad (1)$$

$$(NH_4)_2CO_3 + 2H^+ \rightarrow 2NH_4^+ + CO_{2\uparrow} + H_2O \qquad (2)$$

$$NH_4^+ + OH^- \leftrightarrow NH_{3\,(solution)} + H_2O \qquad (3)$$

$$[NH_{3\,(air)}] = H\,[NH_{3\,(solution)}] \qquad (4)$$

Under field conditions, the pH of the feedyard surface often increases to greater than 8.0 (Cole et al., 2009a, 2009b). The total ammonia nitrogen (TAN) is defined as the sum of NH_4^+ and NH_3. As shown in equation 3, the equilibrium between NH_4^+ and NH_3 is pH dependent. At pH = 9.4, approximately half of the total ammonia content of the solution is in NH_3 form, and at pH greater than 10.8, essentially 100% of the total ammonia is in NH_3 form (Hammer and Hammer, 1996). The hydrolysis of urea to produce ammonia occurs rapidly and requires only a few hours for substantial conversion and a few days for complete conversion (Muck and Steenhuis, 1982; Cole et al., 2009a).

For several social, environmental, and economic reasons, there is a desire to minimize ammonia emissions from feedyards. Ammonia volatilization is a complex process that is generally driven by ammonium concentration, temperature, pH, and wind exchange (Harper et al., 2004; Sommer and Hutchings, 1995).

Ammonia Emission Control

Ammonia emission control measures can be grouped into two primary management strategies: pre-excretion strategies such as altering animal diets, and post-excretion strategies such as altering pH or applying surface additives.

Pre-Excretion Strategies

Cattle consume nitrogen in the forms of protein and non-protein (crude protein, CP) and convert it into body tissue or excrete it in urine and feces. One method for reducing the quantity of ammonia volatilized is to improve the utilization of CP through dietary modifications. Ideally, cattle would be fed the exact amount of nutrients that their bodies require for optimum growth because as N intake exceeds animal requirements, a greater proportion of fed nitrogen is excreted in urine (Cole et al., 2005, 2006; Vasconcelos et al., 2009). Several researchers have evaluated the effect of dietary CP concentration on potential ammonia losses (Cole et al., 2005; Gleghorn et al., 2004; Todd et al., 2006; Vasconcelos and Galyean, 2007; Vasconcelos et al., 2006). While reducing dietary CP reduced potential ammonia emissions, decreasing the CP to less than 10% adversely affected dry matter intake and gain efficiency. Others have shown that ammonia losses may be decreased by shifting N excretion from the rapidly degraded urinary urea N pool to more slowly degraded fecal N (Bierman et al., 1999; Erickson et al., 2003).

Because cattle have the ability to recycle N from one section of the digestive tract to another via the bloodstream, feeding methods that shift digestion to the lower digestive tract may increase fecal N excretion while decreasing urinary N excretion. However, these methods can potentially decrease animal performance.

Post-Excretion Strategies

Scientists working on control measures have typically focused on reducing ammonium concentrations, controlling pH, and reducing the exposed area and air exchange over the emitting area (Sommer and Hutchings, 1995). Several post-excretion applied chemical amendments and additives have been studied to reduce ammonia emissions (Shi et al., 2001). In addition to chemical and enzymatic amendments, several commercial products are now marketed for reducing ammonia emissions. Zhu et al. (1997) evaluated several commercial additives for reducing ammonia emissions from swine lagoons. They found that, depending on the additive, ammonia emissions actually increased (up to 37%) in some cases, while others did indeed decrease emissions (36%).

Perhaps the most promising way to reduce ammonia production is to slow or stop the conversion of urea to ammonium. Urease inhibitors can block the hydrolysis of urea to ammonium and thereby decrease ammonia production. The N-(n-butyl) thiophosphoric triamide (NBPT) molecule acts as a strong urease inhibitor due to its ability to bind to the active sites of urease. These active sites are thought to be occupied by nickel (Ni^{2+}) ions. NBPT binds to these nickel ions before the urea can. NBPT thus slows urea hydrolysis but does not completely block it (Benini, 2000).

In a laboratory experiment, Varel (1997) evaluated the urease inhibitors cyclohexylphosphoric triamide (CHPT) and phenyl phosphorodiamidate (PPDA) on beef cattle manure slurries. Both inhibitors prevented hydrolysis of urea for 4 to 11 days. The weekly addition of PPDA prevented 38% to 70% of urea from being hydrolyzed after 28 days. In further laboratory studies, Shi et al. (2001) applied NBPT to mixtures of soil and beef manure at rates of 1 and 2 kg ha^{-1}, and reported 36% and 34% reduction in ammonia emissions, respectively.

Varel et al. (1999) conducted a field experiment to evaluate the urease inhibitors CHPT and NBPT when applied to open-lot beef cattle feedlot pens. The NBPT was applied every 7 days for 6 weeks at 22.8 kg ha^{-1}. Urea accumulated to a peak concentration of 17 g urea per kg dry manure at day 31 and stabilized at this concentration until week 6 when NBPT application was halted. Urea concentration in the manure then decreased to about 10 g kg^{-1} one week later and to 5 g kg^{-1} two weeks later, suggesting that the urease inhibitor lost its activity over time or that additional urease enzyme was produced that exceeded the capacity of the urease inhibitor.

Parker et al. (2005) conducted a laboratory experiment to evaluate how NBPT application frequency affected ammonia emission from beef manure. NBPT was applied at rates of 0, 1 and 2 kg ha^{-1} and at frequencies of 8, 16, and 32 days. The 8-day application frequency was most effective, with the 1 and 2 kg ha^{-1} treatments resulting in 49% to 69% reduction in ammonia emission rates. Varel et al. (2007) later determined that the combination of thymol and NBPT further increased the efficiency of ammonia reduction from beef manure, with an added benefit of reducing odor production and coliform bacteria in the manure.

Urease inhibitors have been used successfully for years in farming applications where slowing the conversion of urea fertilizer to ammonium provides extra time for the crops to utilize the nitrogen (Fox and Piekielek, 1993; Gioacchini et al., 2002). However, the use of urease inhibitors in feedyard conditions is entirely different, as the ammonium is not consumed by plants but most likely will eventually convert to ammonia gas and volatilize. Because urease inhibitors currently have a finite life of 7 to 10 days, and as more urea is deposited daily on the feedyard surface, it could be that additional urease inhibitor application would also be needed to control all or most of the ammonia emissions. If a given amount of urease inhibitor were applied at the beginning of the feeding period, then in week 2 the same amount of urease inhibitor could be needed plus additional urease inhibitor to account for the recently added urea (i.e., 2× that of the first week). In the third week, 3× that of the first week would be required. If urease inhibitor application were ceased prior to removal of the manure, then it is possible that the buildup of urea could be hydrolyzed rapidly, resulting in a large flush of ammonia gas.

The hydrolysis of urea requires water, as shown in equation 1. Soil scientists have shown that dry soils inhibit the hydrolysis of urea (Gould et al., 1973) and that precipitation has an effect on urea transport and NH_3 volatilization (Ferguson and Kissel, 1986). However, there have been few studies assessing how moisture conditions affect urease inhibitors in manure, or how increasing urease inhibitor application rate over time affects ammonia emissions.

Objectives

With these concerns in mind, a laboratory research project was conducted to further evaluate the effectiveness of NBPT in minimizing ammonia emissions from simulated beef feedyard pen surfaces. The specific objectives were to:

- Determine whether the continual addition of urea from urine application to the simulated feedyard pen surface would require an increasing application of NBPT with time.
- Determine the effect of rainfall on ammonia emissions.
- Determine the effectiveness of NBPT in retaining urea-N in the manure pack.

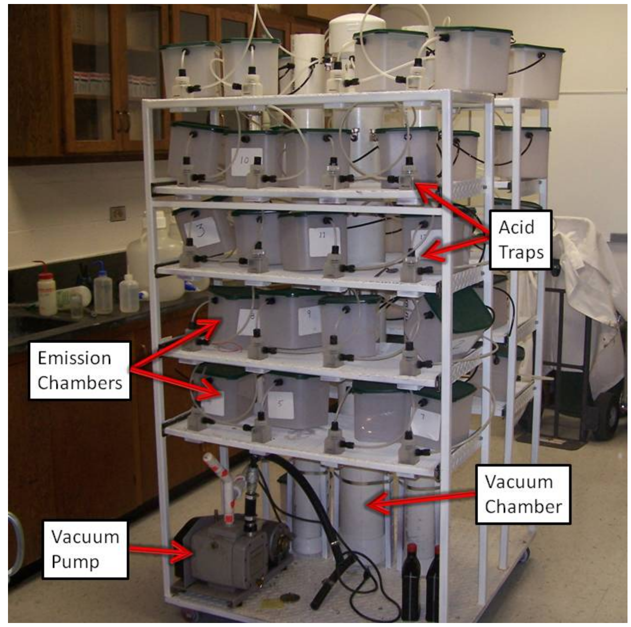

Figure 1. Photograph of the emission apparatus used to quantify ammonia emissions from beef manure surfaces. Clean air was pulled by vacuum across the emitting surface, and ammonia was trapped after bubbling through a sulfuric acid trap.

Materials And Methods

Experimental Design

The experimental treatments included two factors: NBPT application rate, and simulated rainfall application rate. The experimental design consisted of a blank (empty container with no manure or synthetic urine added) and six treatments resulting from the combination of the two factors. There were three replications per treatment for a total of 21 emission chambers. The six treatments were as follows:

- No NBPT, with no rainfall ($NBPT_{0,NR}$)
- No NBPT, with rainfall ($NBPT_{0,R}$)
- NBPT applied at 5 kg ha^{-1} every 4 days, with no rainfall ($NBPT_{5,NR}$)
- NBPT applied at 5 kg ha^{-1} every 4 days, with rainfall ($NBPT_{5,R}$)
- NBPT applied at 5 kg ha^{-1} initially and then doubled every 4 days to a maximum of 40 kg ha^{-1}, with no rainfall ($NBPT_{5/40,NR}$)
- NBPT applied at 5 kg ha^{-1} initially and then doubled every 4 days to a maximum of 40 kg ha^{-1}, with rainfall ($NBPT_{5/40,R}$).

Manure Collection and Preparation

Aged and air-dried manure (dried feces, moisture content <10%) was collected from the feedyard pen surface at the West Texas A&M University research feedyard. The beef cattle had been fed a standard steam-flaked corn based diet balanced to 13.5% CP. The manure was ground to a uniform consistency (5 mm), thoroughly mixed, and frozen prior to use in the experiment. The manure was thawed at room temperature (21°C) one day before being placed into the emission chambers. An initial composite manure sample (500 g) was stored (-20°C) and analyzed at the completion of the experiment along with the other samples.

Emission Apparatus

The emission apparatus consisted of 21 plastic emission chambers (167 length × 167 width × 170 mm depth, Tupperware Corp., Orlando, Fla.). Clean air was pulled by vacuum across the emitting surface and through an NH_3 trap (acid trap) containing 100 mL of 0.9 M H_2SO_4 (fig. 1). To equalize head loss and airflow to each chamber, each acid trap was connected with equal lengths of PVC tubing to a common vacuum chamber, which consisted of a 2 m length of 150 mm diameter PVC pipe. The common vacuum chamber was connected to a vacuum pump (model 80M48S17D1180JP, Marathon Electric, Wausau, Wisc.). Airflow to each chamber was controlled via individual flow control valves. Airflow was adjusted to 1.4 L min^{-1} per chamber using a rotameter (model FL-105, Omega Engineering, Inc., Stamford, Conn.) at the beginning of the test period.

Synthetic Urine Preparation

Manure (1000 g dry mass) was placed into each chamber to a depth of 100 mm. Synthetic urine (23 mL, equivalent to 6 L d^{-1} over 14 m^2 pen surface area) was added to each chamber every 2 days to simulate the continual addition of urine, as would occur in actual feedyard conditions. The synthetic urine was sprayed evenly over the surface using a handheld sprayer, which had been calibrated earlier. The synthetic urine was prepared fresh before each application to avoid potential urea-N loss in storage. The synthetic urine recipe was adapted from Shand et al. (2000) and prepared as follows. Urea (21.4 g) was dissolved in 500 mL of distilled water. Potassium bicarbonate ($KHCO_3$, 23.1 g), potassium chloride (KCl, 3.8 g), and potassium sulfate (K_2SO_4, 1.9 g) were dissolved in another 500 mL of distilled water. The two solutions (1 L total) were mixed immediately before application.

Rainfall Application

In the treatments with simulated rainfall, 173 mL of water was added to the manure surface at 4-day intervals (equivalent to 6 mm precipitation depth per application). Simulated rainfall was applied immediately following the synthetic urea application using a handheld sprayer.

Urease Inhibitor Application

Concentrated NBPT with 20% active ingredient (Agrotain International, St. Louis, Mo.) was mixed with water per the manufacturer's specifications and sprayed evenly across the manure surface using a handheld sprayer. Both $NBPT_{5,NR}$ and $NBPT_{5,R}$ received 5 kg ha^{-1} NBPT at each interval (days 0, 4, 8, 12). Both $NBPT_{5/40,NR}$ and $NBPT_{5/40,R}$ received 5 kg ha^{-1} NBPT initially, and thereafter the NBPT application rate was doubled at each interval (5 kg ha^{-1} at day 0, 10 kg ha^{-1} at day 4, 20 kg ha^{-1} at day 8, and 40 kg ha^{-1} at day 12). Because a small amount of water was added to the manure whenever NBPT was applied, an equal amount of water was added to the control treatments to minimize any differences in manure moisture contents. The synthetic urine, NBPT solution, and water were all added by applying a misting spray with a handheld sprayer equally across the manure surface after removing the top from the chamber.

The experiment was conducted for 16 days. The final NBPT and water applications were on day 12, and the final synthetic urine application was on day 14. Acid traps were changed every 48 h. Approximately 25 mL of the acid solution was transferred into glass vials and stored at -20°C. At the completion of the experiment, the manure in each chamber was mixed thoroughly, and approximately 150 g of manure was stored in a polyethylene bag at -20°C.

Sample Analyses

At the completion of the experiment, acid samples were analyzed for total nitrogen by automated procedures using a flow injection analyzer (Lachat ASX 8000, Hach Co., Loveland, Colo.) at the USDA-ARS Laboratory in Bushland, Texas. Initial and final manure samples were analyzed for urea-N by the modified diacetyl monoxime method of Mulvaney and Bremner (1979). All values were standardized to a 100% dry weight basis.

Statistical Analysis

Nitrogen mass balance, mean NH_3 emission rates, and manure urea-N concentrations over the 16-day treatment period for each treatment were compared to test the effects of different application rates. Statistical analyses were performed by ANOVA with subsequent mean separation tests using Tukey's honestly significant difference (HSD) comparisons. Analyses were conducted using SPSS version 17.0 (SPSS, 2010) with a significance level of 0.05. Tukey's test controls the familywise (experimentwise) error rate as opposed to the individual (comparisonwise) error rate (Berthouex and Brown, 1994). Regression analyses were conducted using standard regression procedures to evaluate changes in ammonia emission rate with time.

Results and Discussion

Ammonia Emissions

All NBPT treatments, regardless of application rate or rainfall application, were effective in reducing ammonia emissions (table 1). The blank (empty container with no manure) had a calculated mean NH_3-N emission rate of only 1.6 μg m^{-2} min^{-1}, confirming that the air entering the chambers was essentially ammonia-free as compared to the magnitude of emissions from the six treatments.

$NBPT_{5/40,R}$ had the lowest mean ammonia emission rate, producing 26% of the ammonia emission rate of $NBPT_{0,R}$ (table 1). For those NBPT treatments receiving rainfall, the emission rates ranged from 394 to 499 μg m^{-2} min^{-1}, and these differences were not statistically significant. For those NBPT treatments receiving no rainfall, the emission rates ranged from 642 to 707 μg m^{-2} min^{-1}, and these differences also were not statistically significant.

Ammonia emissions from $NBPT_{0,R}$ were lower than from $NBPT_{0,NR}$. The non-rainfall treatment had the highest mean emission rate (2380 μg m^{-2} min^{-1}), the rainfall treatment had the lowest (1511 μg m^{-2} min^{-1}), and these differences were statistically significant (table 1).

The Tukey's HSD analysis indicated that NBPT applied at the steady 5 kg ha^{-1} rate did not differ from treatments that were applied at the variable 5 to 40 kg ha^{-1} rate (table 1). This indicates that application of increasing quantities of urease inhibitors may not be necessary to control ammonia emissions over time.

For the first ten days of the experiment, daily average ammonia emissions were similar for all four treatments receiving NBPT (fig. 2). Beginning at day 12, there was a visible departure between the rainfall and non-rainfall treatments, with a considerable increase in ammonia emissions for the non-rainfall treatments and a decrease in the rainfall treatments. On days 6 and 10, ammonia emissions seemed to be driven down following rainfall applications on days 4 and 8, respectively (fig. 2).

Despite these trends, only the two NBPT rainfall treatments ($NBPT_{5,R}$ and $NBPT_{5/40,R}$) changed statistically over time, as evidenced by their statistically significant negative slopes of 0.049 and 0.025, respectively (table 2). The two

Table 1. Mean ammonia emission rates (μg m^{-2} min^{-1}) over the 16-day study period. Each treatment mean was calculated from three replications.

Treatment	NBPT Application Rate (kg ha^{-1})		Rainfall Applied	NH_3-N		Percent of $NBPT_{0,NR}$	Percent of $NBPT_{0,R}$
	Initial	Final		Mean[a]	SD		
Blank (no manure)	0	0	0	1.6 a	0.1	n/a	n/a
$NBPT_{0,NR}$	0	0	No	2380 e	190	100	n/a
$NBPT_{0,R}$	0	0	Yes	1511 d	247	n/a	100
$NBPT_{5,NR}$	5	5	No	707 c	203	30	n/a
$NBPT_{5,R}$	5	5	Yes	499 bc	101	n/a	33
$NBPT_{5/40,NR}$	5	40	No	642 bc	40	27	n/a
$NBPT_{5/40,R}$	5	40	Yes	394 b	67	n/a	26

[a] Means followed by different letters are significantly different using Tukey's HSD test (α = 0.05).

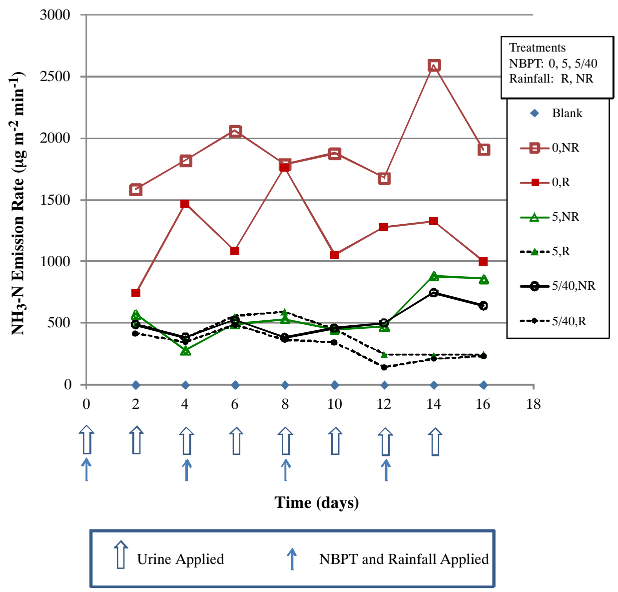

Figure 2. Plot showing how ammonia emissions rates varied with time over the 16-day study period for each treatment. Urine was applied every 2 days, and NBPT and rainfall were applied every 4 days. Each data point is the mean of three replications.

NBPT non-rainfall treatments ($NBPT_{5,NR}$ and $NBPT_{5/40,NR}$) had small positive slopes, indicating a general increase in emission rates with time, but the slopes were only marginally different from zero, with p-values of 0.057 and 0.066. The two treatments receiving no NBPT ($NBPT_{0,R}$ and $NBPT_{0,NR}$) exhibited no trends with time over the full 16-day period, with p-values of 0.83 and 0.23, respectively.

According to Shi et al. (2001), there is a minimum urease inhibitor application rate required to inhibit the activity of the enzyme, and application greater than this rate provides no further benefit. In our laboratory experiment, ammonia emissions from the variable NBPT application rate were not statistically different from the steady application rate. Thus, there does not appear to be any additional advantages in applying increasing quantities of NBPT over time.

These results suggest that the concentration of urea present in the feedyard manure requires a definitive quantity of urease inhibitor to slow the urea hydrolysis. This quantity may depend more on the amount of urease enzyme in the manure than on the quantity of urea in the manure.

All treatments receiving simulated rainfall produced lower NH_3 emissions than the non-rainfall treatments. This indicates that ammonia emissions in arid climates could be higher than in parts of the country that receive more precipitation, all other things being equal. Of course, this assumes that there is adequate moisture for the initial hydrolysis of urea. If there is insufficient moisture for hydrolysis of urea (eq. 1), then ammonia emissions could be hindered. Given the continual addition of moisture to the feedlot surface in the form of urine and feces, it is unlikely that this would ever occur. Possible reasons for lower ammonia emissions with higher rainfall include (1) ammonia is soluble in water, and the higher the rainfall the lower the overall ammonia concentration in solution; (2) evaporative cooling in the wetter manure could lower the temperature and reduce the Henry's constant, which is actually temperature dependent; and (3) rainfall could potentially affect the pH of the manure surface, and pH has a profound influence on NH_3 emissions. Volatilization of water-soluble compounds like ammonia and VOCs has been shown to be positively correlated with evaporation (Parker et al., 2009, 2010, 2011).

Table 2. Regression statistics for ammonia emission rate (μg m^{-2} min^{-1}) with time (d).

Treatment	y-Intercept	Slope	p-Value
$NBPT_{0,NR}$	1639	30.3	0.23
$NBPT_{0,R}$	1162	5.7	0.83
$NBPT_{5,NR}$	305	29.2	0.057
$NBPT_{5,R}$	585	-20.7	0.049[a]
$NBPT_{5/40,NR}$	362	17.2	0.066
$NBPT_{5/40,R}$	478	-17.9	0.025[a]

[a] Regression is significant at α = 0.05 (slope significantly different from zero).

This effect of simulated rainfall is consistent with Whitehead and Raistrick (1991), who showed that when 2 mm of rainfall was applied 2 h after urine application, ammonia volatilization was reduced by 15%, whereas the equivalent of 12 mm rainfall reduced ammonia volatilization by 81%. Parker et al. (2005) also reported lower ammonia emissions when simulated rainfall was applied.

The use of solid-set sprinkler systems to reduce dust emissions from open-lot feedyards is becoming more common in parts of Texas and Kansas (Amosson et al., 2006; Auvermann et al., 2001; Razote et al., 2007). Given that simulated rainfall has been shown to reduce ammonia emissions as well, there could be some added benefit, in addition to dust control, of installing sprinklers. When pen conditions are wet, ammonia may tend to stay in solution. Conversely, rainfall events at feedyards in arid environments have been shown to cause spikes in ammonia emissions (Rhoades et al., 2010). Under very wet conditions, the ammonia may be diluted throughout the manure pack, where it is less easily volatilized. In addition, the ammonia could be converted to NO_3, which is susceptible to leaching through the manure pack.

Urea-N

The NBPT treatments retained significantly more urea in the manure than those without NBPT (table 3). $NBPT_{5/40,NR}$ retained the most urea-N (2119 μg g^{-1}) and $NBPT_{5,R}$ retained the least (1206 μg g^{-1}). Three of the four NBPT treatments were not statistically different.

Despite producing lower ammonia emissions, the rainfall treatments retained less urea-N in the manure than their respective non-rainfall treatments (fig. 3). Generally, lower ammonia emissions should translate into more nitrogen being retained. However, the results are the opposite of those

Table 3. Mean urea-N concentrations (μg g^{-1} dry matter) in the manure at the completion of the 16-day experiment. Each treatment mean is calculated from three replications.

	NBPT Application Rate (kg ha^{-1})			Urea-N	
Treatment	Initial	Final	Rainfall Applied	Mean[a]	SD
$NBPT_{0,NR}$	0	0	No	123 a	19
$NBPT_{0,R}$	0	0	Yes	103 a	14
$NBPT_{5,NR}$	5	5	No	1624 bc	255
$NBPT_{5,R}$	5	5	Yes	1206 b	652
$NBPT_{5/40,NR}$	5	40	No	2119 c	325
$NBPT_{5/40,R}$	5	40	Yes	1979 c	415

[a] Means followed by different letters are significantly different using Tukey's HSD test (α = 0.05).

Table 4. Manure urea-N mass balance. All nitrogen concentrations were converted to µg g^{-1} dry matter.

Treatment	Rainfall Applied	Initial Manure Urea-N	Synthetic Urea-N Added	Initial + Synthetic	NH_3-N[a]	Final Manure Urea-N	NH_3-N + Final Urea-N	Urea-N Balance[b] (µg g^{-1})	(%)
$NBPT_{0,NR}$	No	154	1838	1992	1529	123	1652	-339	-17
$NBPT_{0,R}$	Yes	154	1838	1992	971	103	1074	-918	-46
$NBPT_{5,NR}$	No	154	1838	1992	454	1624	2078	87	4
$NBPT_{5,R}$	Yes	154	1838	1992	321	1206	1527	-465	-23
$NBPT_{5/40,NR}$	No	154	1838	1992	413	2119	2532	540	27
$NBPT_{5/40,R}$	Yes	154	1838	1992	253	1979	2232	241	12

[a] NH_3-N is based on total N collected in acid traps (NH_3-N is the predominant N compound and includes trace amounts of amines and other N-containing VOCs).

[b] Urea-N balance = [(NH_3-N + final urea-N) - (initial urea-N + synthetic urea-N)]. Positive balance indicates unaccounted gain of urea-N, and negative balance indicates unaccounted loss of urea-N.

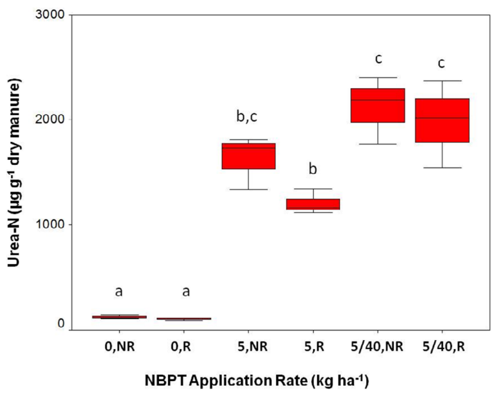

Figure 3. Box plots comparing urea-N concentrations in manure at the completion of the 16-day experiment at various NBPT application rates and rainfall applications. Mean urea-N concentrations with different letters are significantly different using Tukey's HSD test (α = 0.05).

expected, so it appears that some of the nitrogen was transformed. During hydrolysis, urea is initially converted to ammonium, which is then converted to ammonia gas. The potential exists for some of the ammonia produced during urea hydrolysis to be transformed to other forms of organic nitrogen, nitrate (NO_3^-), nitrous oxide (N_2O), or nitrogen gas (N_2). Under anaerobic conditions, the NO_3^- can be converted to N_2O or N_2 gas.

Nitrogen Mass Balance

Nitrogen mass balances for those treatments receiving NBPT ranged from a negative balance of 918 µg g^{-1} to a positive balance of 540 µg g^{-1} (table 4). $NBPT_{5,R}$ had a negative balance, indicating an unaccounted loss of N, while $NBPT_{5,NR}$, $NBPT_{5/40,NR}$, and $NBPT_{5/40,R}$ had positive balances, indicating unaccounted gains of N. Both $NBPT_{0,NR}$ and $NBPT_{0,R}$ had negative balances of 918 and 339 µg g^{-1}, respectively, indicating unaccounted losses of N. Unaccounted losses can be due to nitrogen transformations to other forms of N, such as NH_4^+, N_2, N_2O, or organic N. In this research, we did not quantify these other potential forms of N, with the exception of organic N in the form of urea. Unaccounted gains are more difficult to explain but could have been due to non-representative sampling of the manure at the completion of the experiment, or potential analytical differences in the manure urea analysis due to differences in manure moisture content. Organic nitrogen mineralization could also be a source of ammonia nitrogen gains in these experiments.

While NBPT appears promising for reducing ammonia emissions, additional research is warranted to study its effectiveness under long-term conditions in a feedyard setting. Based on the results reported herein, and those of Shi et al. (2001) and Varel et al. (1999, 2007), it appears that urease inhibitors may play a role in reducing ammonia emissions from open-lot beef feedyards. However, while application to the feedyard surface every 4 to 7 days is feasible in the laboratory, application at such a frequent rate under field conditions is not being embraced by feedyard owners and managers. While ideally the urease inhibitor would stay active for the entire 100+ day feeding period, at a minimum it should stay active for about 30 days to have use in a feedyard setting. The urease inhibitor could then be applied to the surface in the last 30 days of the feeding period, conserving a considerable amount of nitrogen loss prior to land application of the manure. In addition to controlling ammonia emissions, the effects and possible control of nitrous oxide, a potent greenhouse gas, should also be studied in laboratory and feedyard settings.

Conclusions

The following conclusions were drawn from this research:

- Continual addition of urea to a simulated feedyard surface did not require increasing NBPT application over time. There were no differences in ammonia emissions for the NBPT applied at steady or increasing rates. A steady application of NBPT was effective in reducing ammonia emissions over the duration of the experiment.
- For those treatments receiving no NBPT, ammonia emissions were lower when simulated rainfall was added. This same trend was observed for the NBPT treatments, but the differences were not statistically significant. Mean ammonia emission rates for the NBPT treatments were 26% to 33% of the control, demonstrating that the urease inhibitor was effective at reducing emissions from the manure surfaces in both wet and dry conditions.
- Both NBPT application rates effectively retained urea-N in the manure.

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