

(wileyonlinelibrary.com) DOI 10.1002/jsfa.8525

# Nitrogen release from urea with different coatings

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## Abstract

**BACKGROUND:** Coatings or urease inhibitors are designed to reduce losses of ammonia [ $\text{NH}_{3(\text{g})}$ ] from urea fertilizers. However, nitrogen (N) release and its effects on soil solution have not previously been evaluated under standardized conditions in soils. In this study, the urea fertilizers were incubated in chambers filled with sandy loam soil, adapted for the collection of  $\text{NH}_{3(\text{g})}$  and soil solution by centrifugation.

**RESULTS:** In the fast-release N fertilizers, around 93% and 100% of urea-N applied was recovered within the first hours of incubation. In contrast, in the slow-release N fertilizers, less than 40% of urea-N applied, was recovered at 19 days of incubation. The maximum N release from the fertilizers followed the order: UP1 (106%)  $\approx$  UNBPT (102%)  $\approx$  urea (93%)  $>$  USP2 (57%)  $\approx$  USP3 (57%)  $>$  USP4 (31%)  $\approx$  USP5 (18%).  $\text{NH}_{3(\text{g})}$  volatilization accounted for only 3% of the applied N in the slow-release fertilizers, which corresponded to about 88% less than the  $\text{NH}_{3(\text{g})}$  loss from prilled urea.

**CONCLUSION:** This study demonstrated distinct N release patterns, which changed the N dynamics in the soil. Some coatings effectively delayed urea release from granules and reduced  $\text{NH}_{3(\text{g})}$  gas losses, while other were not efficient.

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**Keywords:** hydrolysis; *N*-(*n*-butyl) thiophosphoric triamide; slow-release fertilize; volatilization

## INTRODUCTION

Urea production has increased worldwide as a result of the increase in more affordable and low-cost raw materials, such as nitrogen gas ( $\text{N}_2$ ) and natural gas.<sup>1</sup> However, nitrogen (N) losses from urea potentially reduce the agronomic efficiency of urea fertilizers.

Adequate soil moisture is needed to dissolve the applied urea fertilizer granules and allow the conversion of urea into ammonium carbonate ( $\text{NH}_4\text{HCO}_3$ ) by urease, resulting in the release of ammonium ( $\text{NH}_4^+$ ) into the soil.<sup>2</sup> This process promotes a temporary pH increase around the granules or within the entire application area. However,  $\text{NH}_4^+$  is relatively unstable at high pH, and the N is lost as gas if converted into ammonia [ $\text{NH}_{3(\text{g})}$ ]. N loss in the form of  $\text{NH}_{3(\text{g})}$  may reach up to 77% of the N applied when using urea.<sup>3–5</sup> Accordingly, a rapid increase in urea concentration in the soil solution, arising from a fast-release source application, could be a key factor in reducing the fertilizer agronomic efficiency,<sup>6,7</sup> strongly impeding the use of urea.

Consequently, fertilizer companies have been seeking alternatives other than urea to reduce N losses. Some developed products, containing urease/nitrification inhibitors or coatings with substances that are able to reduce dissolution in the soil, such as elemental sulfur ( $\text{S}^0$ ) and hydrophobic polymers, have shown slower nutrient release.<sup>8</sup>

Among the urease inhibitors, *N*-(*n*-butyl) thiophosphoric triamide (NBPT) is one of the most efficient and widely available substances and is generally used at doses varying from 400 to 1000 mg  $\text{kg}^{-1}$  urea.<sup>8–10</sup> Once in contact with the soil, NBPT is converted to its analog *N*-(*n*-butyl) phosphoric triamide (NBPTO),<sup>11</sup> which has an inhibitory action on urease, thereby ensuring urea longevity in its applied chemical form.

Polymers and/or elemental sulfur are used in coated fertilizers to act as a physical barrier to water permeability. Such products delay the release and diffusion of urea out of the granule, thereby altering the dynamics of N forms.<sup>8,12,13</sup> Thus, recognizing the patterns of nutrient release is important for the prediction of soil reactions, as well as plant N availability and absorption.

N release from slow release fertilizers has been estimated by dissolution in water or acidic solutions.<sup>8</sup> Such tests provide important information on nutrient release rates. However, this test does not permit the effects of the release rate on the N dynamics in soil to be distinguished, particularly regarding urea hydrolysis, volatilization of N and changes in the pH of the application region.

The objectives of the present work were to evaluate N release and dynamics using sandy loam soil samples with slow-release urea fertilizers.

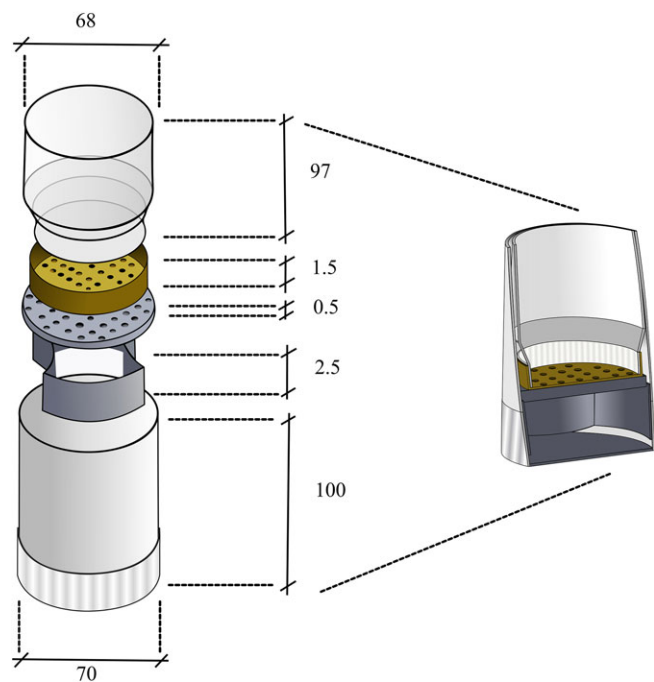
## MATERIAL AND METHODS

The soil was collected at Três Marias, in Minas Gerais State, Brazil, from the top layer (0–30 cm), then air-dried and sieved to  $<2$  mm before use. The soil was a Red–Yellow Latosol (Oxisol) and had the following physical and chemical properties: clay 190 g  $\text{kg}^{-1}$ ; water retention capacity 170 g  $\text{kg}^{-1}$ ; cation exchange capacity 4.8  $\text{cmol}_c \text{ dm}^{-3}$ ; pH 4.8 in water and organic carbon 15 g  $\text{kg}^{-1}$ .

Soil samples (180 g) were placed into incubation chambers adapted to separate the soil solution by centrifugation (Fig. 1). The

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**Figure 1.** The soil solution collecting system consists of a soil incubator and a soil-solution collector. The soil incubator and soil solution collector internal parts are shown in the diagram on the left side and a sectional view of structure on right side. It was made of PVC pipe, an inner ring and a perforated Tecnil plate. The measures are shown in millimeters.

low  $\text{NH}_4^+$  adsorption is a crucial process in the soil N dynamics. Because of this, the N release from the fertilizers could be assessed in an easier way with sandy textured soils.

The incubation chambers were constructed of 70-mm PVC pipes and a perforated plate (3 mm) placed at the bottom. A slow-filtering paper (JP42,  $\Phi$ pores  $\approx 8 \mu\text{m}$ ) was positioned at the end of the incubation chamber to avoid mixing clay and soil solution. The incubation chambers were kept in static collectors of  $\text{NH}_3(\text{g})$  made of PVC tubes ( $\Phi \approx 8 \text{ cm}$ ). Foam discs saturated with a solution of glycerine and  $\text{H}_2\text{SO}_4$  ( $1 \text{ mol L}^{-1}$ ) were placed inside the collectors to capture  $\text{NH}_3(\text{g})$  as  $\text{NH}_4^+$ , according to the models of Cabezas *et al.*<sup>14</sup> The N in the foams was determined by Kjeldahl distillation. A portion of the soil solution was removed by centrifuging the samples at  $2500 \times g$  at  $25^\circ\text{C}$  in a centrifuge containing four buckets of 400 mL. A soil solution sampler was assembled as proposed by Miranda *et al.*<sup>15</sup> with some adaptations (Fig. 1).

The experiment consisted of a randomized block design with four replications. Treatments were arranged in a  $(7 + 1) \times 9$  factorial scheme, comprising seven fertilizers and a control without N, plus nine incubation times, which ranged from 1 h to 54 days. The maximum evaluation period was set in compliance with the N release of the tested fertilizers, reaching less than 54 days for fast-release ones.

The four commercially available coated urea fertilizers (USP2, USP3, USP4 and USP5), a non-commercial coated urea fertilizer (UP1), a urea fertilizer with urease inhibitor (UNBPT) and a prilled urea (U) were evaluated. A control without N was also included. Both UNBPT and U contained 45% N each.

Regarding the coated fertilizers, UP1 (37% N) was coated with polyolefins and USP2 (34% N, 24% S), USP3 (39% N, 16% S), USP4 (39% N, 13% S), and USP5 (37% N, 11% S) were coated with  $\text{S}^0$ , polyolefins and ethylene-vinyl acetate co-polymers. Polymers

were accounted for 1–3% of coated fertilizers weight according to their release rate. Both  $\text{S}^0$  and polymers had a hydrophobic character. Even though NBPT urease inhibitor loses efficiency with storage time,<sup>9</sup> UNBPT was stored for 60 days before use because storing is a common practice.

Fertilizers were applied at a  $2 \text{ g kg}^{-1}$  rate of N in the center of the incubator and 0.5 cm into the soil, allowing it be fully immersed in the soil. After application of fertilizer, the incubators with  $\text{NH}_3$  collectors were placed in a greenhouse where the minimum and maximum air temperature measured were  $25$  and  $30^\circ\text{C}$ , respectively.

The pH of the soil solution extracts (SS) was determined and solutions were treated with 0.05 mL phenylmercuric acetate (PMA) solution ( $500 \text{ mg L}^{-1}$ ), which is sufficient to inhibit urease. The total-N and  $\text{NH}_4^+$ -N concentrations,<sup>16</sup> as well as urea-N concentration<sup>17</sup> in the soil and the soil solution, were measured. The percentage of N recovered, which was regarded as released N, was calculated using the following equation:

$$N_{\text{Released}} = \left( \frac{\sum N_{\text{Fertilized treatments}} - \sum N_{\text{Control}}}{N_{\text{Applied}}} \right) \times 100$$

where  $\sum N$  is the sum of the total N forms in soil, soil solution and  $\text{NH}_3$ -N and  $N_{\text{Applied}}$  is the amount of urea-N with reference rate of  $2 \text{ g kg}^{-1}$ . The percentage of volatilized N ( $N_{\text{Vol}}$ ) was calculated by:

$$N_{\text{Vol}} = \left( \frac{N_{\text{NH}_3(\text{g})\text{Fertilized treatments}} - N_{\text{NH}_3(\text{g})\text{Control}}}{N_{\text{Applied}}} \right) \times 100$$

The rate of N in different forms (urea-N or  $\text{NH}_4^+$ -N) in the soil solution was calculated by:

$$N_x = \left( \frac{N_{x\text{Cumulative}} \times \text{Volume}_{\text{SS}}}{N_{\text{Applied}}} \right) \times 100$$

where  $N_x$  is the concentration ( $\text{g L}^{-1}$ ) of N as urea-N or  $\text{NH}_4^+$ -N forms in soil solution after removal of the treatment control effect and  $\text{Volume}_{\text{SS}}$  is the volume of water in soil (liters), based on water retention capacity of the soil ( $170 \text{ g kg}^{-1}$ ).

The rate of N in different forms (urea-N or  $\text{NH}_4^+$ -N) in the soil system was calculated using the following equation:

$$N_x = \left[ \frac{\left( N_{x \text{ in SS}} \times \text{Volume}_{\text{SS extracted}} \right) + \left( N_{x \text{ in soil}} \times \text{Volume}_{\text{Soil sample}} \right)}{N_{\text{Applied}}} \right] \times 100$$

where  $N_{x \text{ in SS}}$  is the concentration ( $\text{g L}^{-1}$ ) of N as urea-N or  $\text{NH}_4^+$ -N forms in soil solution after removal of the treatment control effect,  $N_{x \text{ in soil}}$  is the concentration ( $\text{g dm}^{-3}$ ) of N as urea-N or  $\text{NH}_4^+$ -N forms in soil sample after removal of the treatment control effect,  $\text{Volume}_{\text{SS}}$  is the volume of water in soil (liters), based on water retention capacity of the soil and  $\text{Volume}_{\text{soil sample}}$  is the volume of the soil sample ( $0.18 \text{ dm}^3$ ).

Data underwent variance and regression analyses for response variables according to incubation time by using SAS 9.1 statistical software (SAS Institute, Inc., Cary, NC, USA). Non-linear models were fitted to release ( $N_{\text{released}}$ ) and volatilization ( $N_{\text{Vol}}$ ) patterns, through which maximum released N was estimated. Results of N forms ( $N_x$ ) were displayed in graphs with mean values and standard deviations, showing N form dynamics in the soil solution.

**Table 1.** Equations used to estimate nitrogen release from urea fertilizers, percentage of released nitrogen ( $\hat{y}$ ) and respective estimated time ( $x$ ) used in sandy loam soil samples (Oxisol)

Fertilizer	Equation	$R^2$	$N_{\text{released}}$ (%)	Time (days)
UNBPT	$\hat{y} = \frac{61.48 - 34.24^{***}x + 5.11^{***}x^2}{1 - 0.5863^{***}x + 0.081101^{***}x^2 + 0.002838^{***}x^3}$	0.99	102.2	3
UP1	$\hat{y} = \frac{55.36 - 27.32^{**}x + 3.962^{**}x^2}{1 - 0.595669^{***}x + 0.094866^{**}x^2 + 0.0008^{*}x^3}$	0.96	106.2	3
U	$\hat{y} = \frac{55.92 - 58.30^{***}x^{0.5} + 15.60^{***}x}{1 - 1.00299^{***}x^{0.5} + 0.19084^{**}x + 0.03542^{*}x^{1.5}}$	0.99	93.0	3
USP2	$\hat{y} = \frac{26.17 - 2.68^{**}x^{0.5}}{1 - 0.30088^{***}x^{0.5} + 0.02983^{***}x}$	0.93	56.8	18
USP3	$\hat{y} = \frac{20.27 - 11.59^{**}x^{0.5} + 2.061^{**}x}{1 - 0.56978^{***}x^{0.5} + 0.088173^{***}x}$	0.96	57.4	12
USP4	$\hat{y} = \frac{9.789 + 0.3458^{*}x}{1 - 0.03923^{***}x + 0.000919^{**}x^2}$	0.87	31.3	27
USP5	$\hat{y} = \frac{19.37 - 8.88^{**}x^{0.5} + 1.236^{**}x}{1 - 0.4626^{***}x^{0.5} + 0.05931^{***}x}$	0.93	37.4	18

The two right columns show the maximum percentage of released N and the related time to maximum released N. <sup>o</sup>, <sup>\*</sup>, <sup>\*\*</sup>, <sup>\*\*\*</sup>, coefficients, statistically significant at 10, 5, 1 and 0.1% of probability by the *t* test.

## RESULTS

### Nitrogen release

Based on the results, the fertilizers could be divided into three groups according to their N-release patterns (Table 1). Group 1 (G1) comprised U, UNBPT and UP1 sources with a fast-release rate, which had full dissolution (100% on average) at 3 days incubation. Group 2 (G2) was represented by USP2 and USP3 with an intermediary-release rate (57% on average), requiring 18 and 12 days, respectively, to reach maximum released N. Group 3 (G3), represented by USP4 and USP5, had the slowest release rate (34% on average) and the longest time to reach maximum released N, of 27 and 18 days, respectively, in a sandy loam soil texture.

### Soil solution characteristics

The soil solution showed distinct characteristics that depended solely on the fertilizer used (Fig. 2). The solution acidity was reduced according to the ability of the fertilizer to release urea. Therefore, maximum pH values for U and UP1 (G1) were 8.6 and 8.8, respectively, while NBPT had a maximum pH of 9.0. Yet, in G2, the USP2 and USP3 fertilizers reached a maximum pH of 7.8 and 7.7, respectively. Moreover, for G3, maximum pH values of 5.9 and 5.6 were found for USP4 and USP5, respectively.

On the fourth day, around 22% and 11% of the added N was in urea form when using U and UP1, respectively. For such fertilizers, urea form availability peaks occurred before the  $N-NH_4^+$  ones, which corresponded to 16% and 14%, respectively, of the applied N (Fig. 2).

### Nitrogen forms and dynamics in the soil system

In the fast-release N fertilizers (U, UP1 and UNBPT), around 93% and 100% of the urea-N applied were recovered within the first incubation hours (Fig. 3). However, significant reductions in urea-N concentration were noted after 1 h for U and after 1 and 2 days for UP1 and UNBPT, respectively (Fig. 3). Urea in the soil system was reduced to zero rate within the first week, which demonstrates a fast-release and conversion of the amidic form of these fertilizers by urease activity (Fig. 3). Concurrent with the decline in urea concentrations,  $NH_4^+$ -N concentrations increased in the soil, accounting for 62% and 67% of the applied N on the fourth day after U and UP1 application, respectively. Afterward,  $NH_4^+$ -N concentrations in the soil decreased, representing, on average, 23% of the applied N at 32 d incubation for G1 fertilizers (Fig. 3).

The G2 fertilizers (USP2 and USP3) presented low concentrations of urea-N; however, concentrations were even lower for G3 fertilizers (USP4 and USP5). Thus, it was assumed that dissolution rates decreased based on granule coating type (Fig. 3). Additionally, the rates of recovered  $NH_4^+$ -N were low compared to G1, i.e. 48% at 12 days for USP2, 45% at 16 days for USP3, 36% at 19 days for USP4, and 32% at 19 days for USP5 (Fig. 3).

### $NH_{3(g)}$ volatilization

Volatilization of  $NH_3$  represented, on average, 24% of the applied N for G1 fertilizers (Fig. 4). NBPT urease inhibitor reduced volatilization by less than 3% compared to U.

Volatilization rates were 20% and 11% for USP2 and USP3, respectively (Fig. 4). These rates were equivalent to 15% and 54% reductions in N volatilization when compared with U, respectively. Furthermore, the time to reach a maximum volatilization value was increased up to 13 days compared to the time needed for prilled urea.

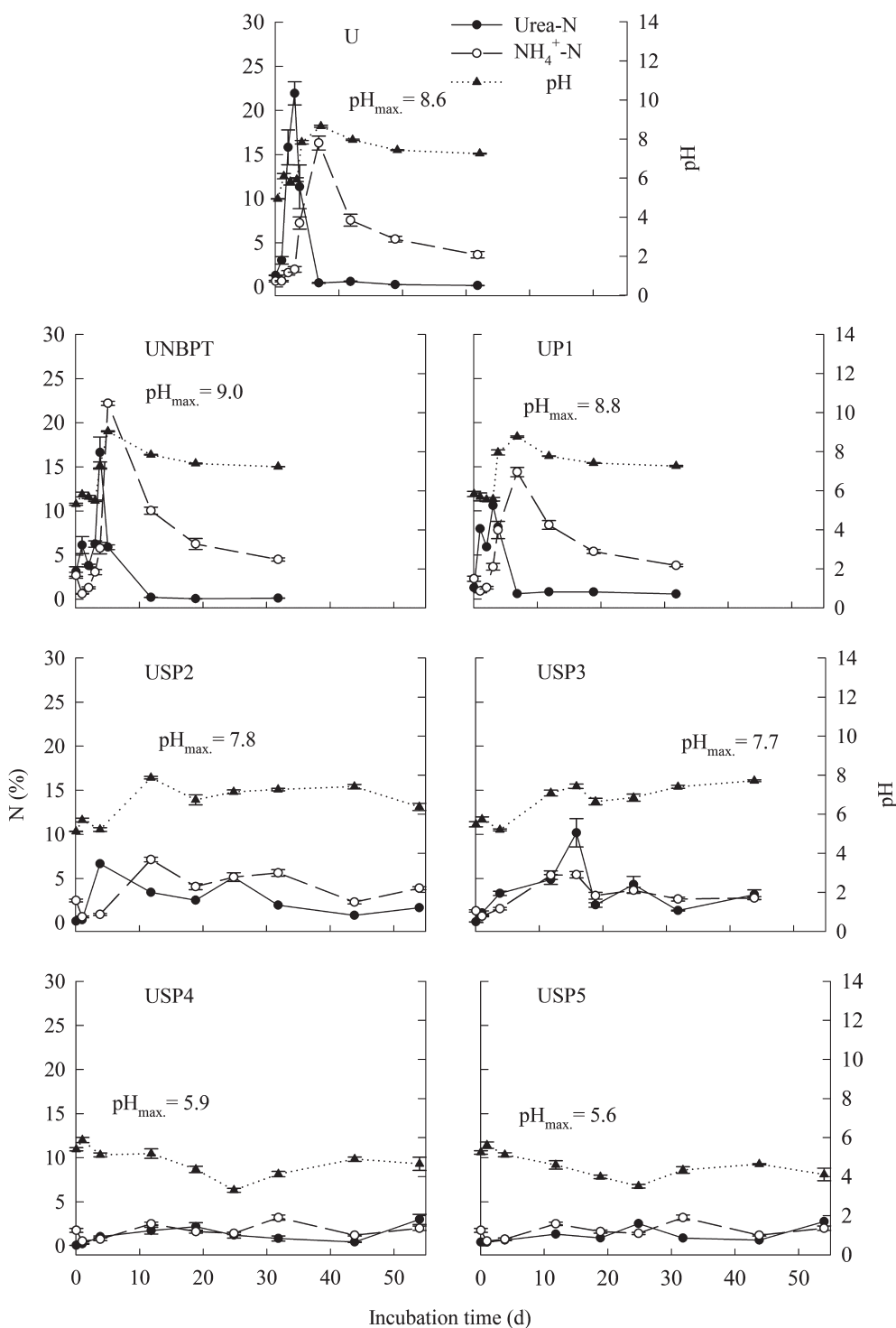
For G3 fertilizers,  $NH_{3(g)}$  volatilization accounted for only 3% of the applied N, being about 88% lower than  $NH_{3(g)}$  loss from prilled urea (Fig. 4).

## DISCUSSION

Evaluating the N released from fertilizers into the soil is crucial in determining the most effective release patterns and chemical reactions that affect N use efficiency of urea fertilizers under field conditions. Soil solution sampling and analysis, besides being rapid procedures, may provide the most reliable results with the advantage of requiring less dilution compared to the use of extractant solutions and direct pH evaluations using soil suspensions in water.

The coated fertilizers presented varied patterns of release, loss and forms of N in the soil. The results showed that some coatings were effective (G3) at delaying granule dissolution, hence, proved the importance of low permeability coating materials. The rate of urea release affects N dynamics in the soil and the reactions that lead to volatilization and leaching losses. Moreover, the residual N effect should be higher than that of non-coated fertilizers.<sup>18,19</sup> Nevertheless, fertilizers with low N release ability should be used cautiously to avoid the supply of nutrients below that required by plants,<sup>20</sup> mainly for short cycle crops.

Most  $NH_{3(g)}$  volatilization observed in G1 was associated with high soil solution pH values. Rapid dissolution of granules and urea release into the soil solution is followed by urea hydrolysis and



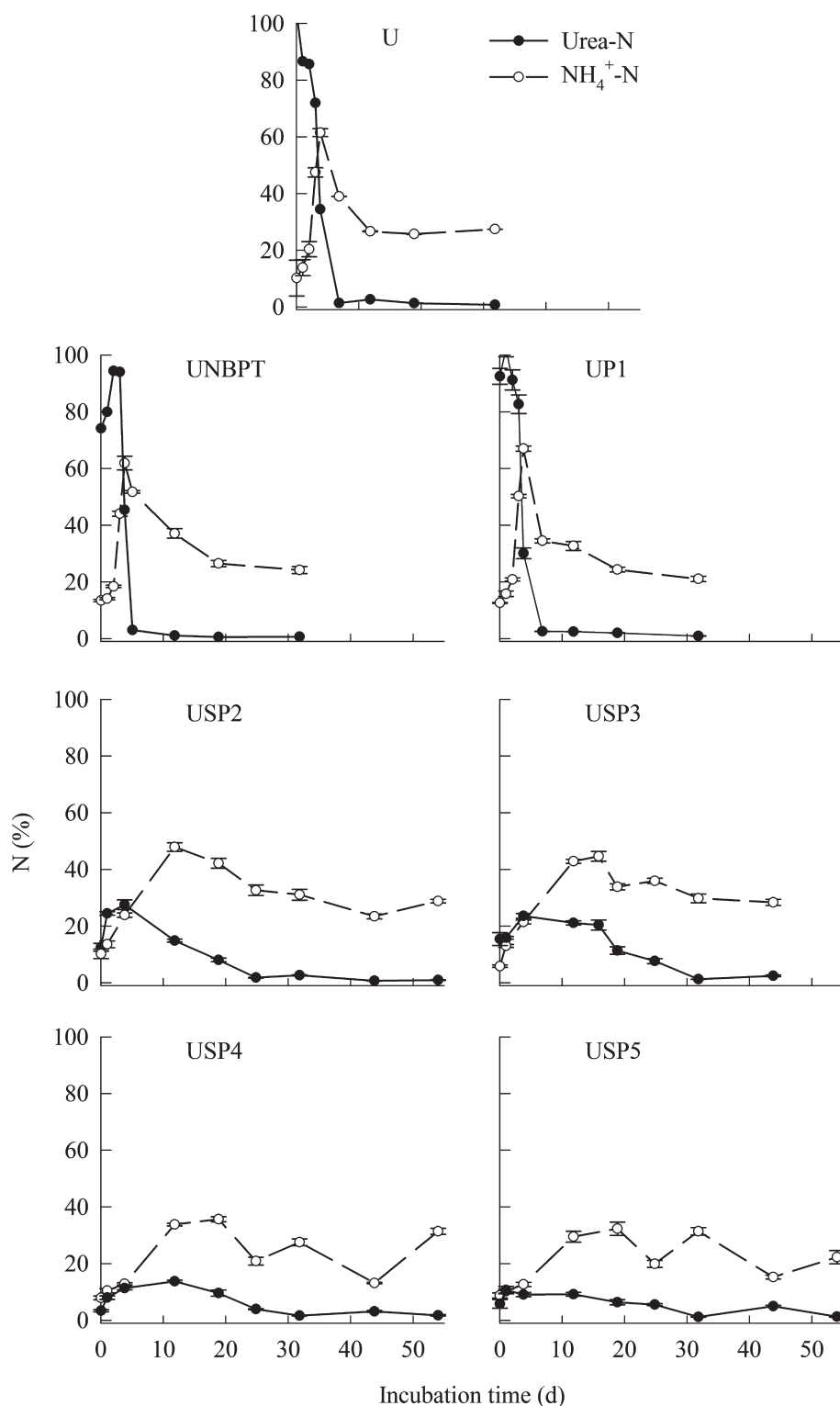
**Figure 2.** Soil solution pH and percentage of recovered nitrogen as urea-N and  $\text{NH}_4^+$ -N forms in soil solution after application of fertilizer. U, pearly urea; UP1, urea coated with polymer 1; USP2, urea coated with  $\text{S}^0$  and polymer 2; USP3, urea coated with  $\text{S}^0$  and polymer 3; USP4, urea coated with  $\text{S}^0$  and polymer 4; USP5, urea coated with  $\text{S}^0$  and polymer 5.

subsequent  $\text{NH}_4^+$  formation, a process that consumes hydrogen protons.<sup>6,7</sup> Given the instability of  $\text{NH}_4^+$  in alkaline conditions, it is converted to  $\text{NH}_3$ , which is lost in gas form.<sup>21,22</sup> Therefore,  $\text{NH}_{3(\text{g})}$ -N losses are more pronounced in fast-release fertilizers, such as G1, compared to G2 and G3 (Fig. 3).

The NBPT inhibitor maintains urea in its chemical form for a long time, thus reducing volatilization.<sup>4,7,23</sup> However, the current results

showed that when stored for 60 days, UNBPT had similar reactions in soil compared to prilled urea. Urease inhibitor loses efficiency with storage time. Therefore, long-term storage is not advisable, as recommended by Watson *et al.*,<sup>9</sup> especially when temperatures are high, as in Brazil.

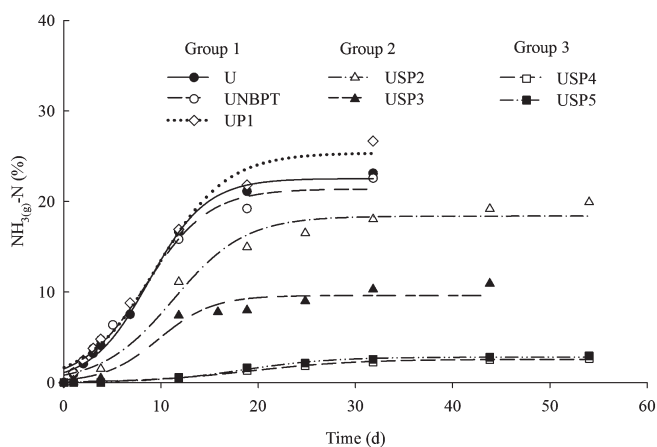
Soil solution characteristics may indicate the release capacity and behavior of fertilizers in the soil. Concentrations of urea-N



**Figure 3.** Percentage of nitrogen recovered as urea and  $\text{NH}_4^+$  form in soil after application of fertilizer. U, pearly urea; UP1, urea coated with polymer 1; USP2, urea coated with  $\text{S}^0$  and polymer 2; USP3, urea coated with  $\text{S}^0$  and polymer 3; USP4, urea coated with  $\text{S}^0$  and polymer 4; USP5, urea coated with  $\text{S}^0$  and polymer 5.

and  $\text{NH}_4^+$ -N, as well as soil solution pH at field conditions, can be very similar to those found in the current experiment, particularly considering the formation of microenvironments with high concentrations of N around the fertilizers granules. Although N dissolution tests in water or acidic solutions provide

a method to rapidly gain information about coating effectiveness, soil incubation methods are essential for assessing N dynamics from slow- or controlled-release fertilizers. In contrast, some fertilizers, with characteristics similar to prilled urea, were no longer feasible as slow-release fertilizers. Moreover, the



**Figure 4.** Volatilization of  $\text{NH}_3$  after application of fertilizer. U, pearly urea; UPI1, urea coated with polymer 1; USP2, urea coated with  $\text{S}^0$  and polymer 2; USP3, urea coated with  $\text{S}^0$  and polymer 3; USP4, urea coated with  $\text{S}^0$  and polymer 4; USP5, urea coated with  $\text{S}^0$  and polymer 5.

current results are in agreement with the results from similar studies.<sup>13,24–26</sup>

## CONCLUSIONS

The current work verified distinct release patterns of N, which changed the N dynamics in the soil. The maximum N released from the fertilizers followed the order: UP1 (106%)  $\approx$  UNBPT (102%)  $\approx$  urea (93%) > USP2 (57%)  $\approx$  USP3 (57%) > USP4 (31%)  $\approx$  USP5 (37%). Fast-release urea fertilizers had complete dissolution in soil at 3 days incubation, while the slowest release fertilizer only released 31% N at 27 days incubation. The increase in soil pH with urea hydrolysis, combined with high  $\text{NH}_4^+$  concentrations as a result of fast-release urea, results in higher  $\text{NH}_3(\text{g})$  losses.

## ACKNOWLEDGEMENTS

This work was supported by funding from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and Produquímica-UFV/50128263910. We thank Dr Richard Bell for his useful review and suggestions.

## REFERENCES

- International Fertilizer Industry Association (IFA), *Fertilizer indicators*, 3rd edition. [Online]. International Fertilizer Industry Association (IFA), Paris, France (2013). Available: <http://www.fertilizer.org> [20 April 2015].
- Behera SN, Sharma M, Aneja VP and Balasubramanian R, Ammonia in the atmosphere: a review on emission sources, atmospheric chemistry and deposition on terrestrial bodies. *Environ Sci Pollut Res* **20**:8092–8131 (2013).
- Cabezas WARL and Souza MA, Ammonia volatilization, leaching of nitrogen and corn yield in response to the application of mix of urea and ammonium sulphate or gypsum. *Rev Bras Ciênc Solo* **32**:2331–2342 (2008).
- Cantarella H, Trivelin PCO, Contín TLM, Dias FLF, Rossetto R, Marcelino R et al. Ammonia volatilisation from urease inhibitor-treated urea applied to sugarcane trash blankets. *Sci Agric* **65**:397–401 (2008).
- Viero F, Bayer C, Fontoura SMV and de Moraes RP, Ammonia volatilization from nitrogen fertilizers in no-till wheat and maize in southern Brazil. *Rev Bras Ciênc Solo* **38**:1515–1525 (2014).
- Longo RM and Melo WJ, Urea hydrolysis in Oxisols: effects of substrate concentration, temperature, pH, incubation time and storage conditions. *Rev Bras Ciênc Solo* **29**:651–657 (2005).

- Dawar K, Zaman M, Rowarth JS, Blennerhasset J and Turnbull MH, Urea hydrolysis and lateral and vertical movement in the soil: effects of urease inhibitor and irrigation. *Biol Fertil Soils* **47**:139–146 (2010).
- Trenkel ME, *Slow- and Controlled-release and Stabilized Fertilizers: An Option for Enhancing Nutrient Efficiency in Agriculture*, 2nd edition. [Online]. International Fertilizer Industry Association (IFA), Paris, France (2010). Available: <http://www.fertilizer.org> [6 September 2012].
- Watson CJ, Akhonzada NA, Hamilton JTG and Matthews DI, Rate and mode of application of the urease inhibitor N-(n-butyl) thiophosphoric triamide on ammonia volatilization from surface-applied urea. *Soil Use Manag* **24**:246–253 (2008).
- Soares JR, Cantarella H and de C Menegale ML, Ammonia volatilization losses from surface-applied urea with urease and nitrification inhibitors. *Soil Biol Biochem* **52**:82–89 (2012).
- Creason GL, Schmitt NMR, Douglass EA and Hendrickson LL, Urea-inhibitory activity associated with N-(n-butyl)thiophosphoric triamide is due to formation of its oxon analog. *Soil Biol Biochem* **22**:209–211 (1990).
- Xiaoyu N, Yuejin W, Zhengyan W, Lin W, Guannan Q and Lixiang Y, A novel slow-release urea fertiliser: Physical and chemical analysis of its structure and study of its release mechanism. *Biosyst Eng* **115**:274–282 (2013).
- Azeem B, KuShaari K, Man ZB, Basit A and Thanh TH, Review on materials and methods to produce controlled release coated urea fertilizer. *J Controlled Release* **181**:11–21 (2014).
- Cabezas WARL, Trivelin PCO, Bendassolli JA, Santana DG and Gascho GJ, Calibration of a semi-open static collector for determination of ammonia volatilization from nitrogen fertilizers. *Commun Soil Sci Plant Anal* **30**:389–406 (1999).
- Miranda J, da Costa LM, Ruiz HA and Einloft R, Chemical composition of soil solution under different land cover and soluble organic carbon in water from small creeks. *Rev Bras Ciênc Solo* **30**:633–647 (2006).
- Bremner JM and Mulvaney CS, Nitrogen – total, in *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*, ed. by Page AL, Miller RH and Keeney DR. American Society of Agronomy, Soil Science Society of America, Madison, pp. 595–624 (1982).
- Douglas LA and Bremner JM, Extraction and colorimetric determination of urea in soils, in *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*, ed. by Page AL, Miller RH and Keeney DR. American Society of Agronomy, Soil Science Society of America, Madison, pp. 702–703 (1982).
- Cartagena MC, Vallejo A, Díez JA, Bustos A, Caballero R and Roman R, Effect of the type of fertilizer and source of irrigation water on N use in a maize crop. *Field Crops Res* **44**:33–39 (1995).
- Guan Y, Song C, Gan Y and Li F-M, Increased maize yield using slow-release attapulgite-coated fertilizers. *Agron Sustain Dev* **34**:657–665 (2013).
- Arrobas M, Parada MJ, Magalhães P and Rodrigues MA, Nitrogen-use efficiency and economic efficiency of slow-release N fertilisers applied to irrigated turfs in a Mediterranean environment. *Nutr Cycl Agroecosystems* **89**:329–339 (2010).
- Turner DA, Edis RE, Chen D, Freney JR and Denmead OT, Ammonia volatilization from nitrogen fertilizers applied to cereals in two cropping areas of southern Australia. *Nutr Cycl Agroecosystems* **93**:113–126 (2012).
- Petersen V, Markfoged R, Hafner SD and Sommer SG, A new slurry pH model accounting for effects of ammonia and carbon dioxide volatilization on solution speciation. *Nutr Cycl Agroecosystems* **100**:189–204 (2014).
- Suter H, Sultana H, Turner D, Davies R, Walker C and Chen D, Influence of urea fertiliser formulation, urease inhibitor and season on ammonia loss from ryegrass. *Nutr Cycl Agroecosystems* **95**:175–185 (2013).
- Medina LC, Sartain JB, Obreza TA, Hall WL and Thiex NJ, Evaluation of a soil incubation method to characterize nitrogen release patterns of slow- and controlled-release fertilizers. *J AOAC Int* **97**:643–660 (2014).
- Medina LC, Sartain JB, Obreza TA, Hall WL and Thiex NJ, Optimization and validation of an accelerated laboratory extraction method to estimate nitrogen release patterns of slow- and controlled-release fertilizers. *J AOAC Int* **97**:661–676 (2014).
- Medina LC, Sartain JB, Obreza TA, Hall WL and Thiex NJ, Statistical correlation of the soil incubation and the accelerated laboratory extraction methods to estimate nitrogen release rates of slow- and controlled-release fertilizers. *J AOAC Int* **97**:677–686 (2014).