

## Elemental Sulphur Effects on Nitrogen Loss in Malaysian High pH Bintang Series Soil

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### ABSTRACT

Amendment of high pH soils with elemental sulphur (S) can result in a reduction of ammonia (NH<sub>3</sub>) emissions following a local decrease in the soil ammonium concentration and pH. Two laboratory experiments were conducted to determine how the application rates of elemental S impacted urea transformations. Urea was surface applied at a rate of 1652 mg per kg of Bintang Series soil that was incubated with different rates of elemental S (0, 0.5, 1 and 2 g S kg<sup>-1</sup> of soil) for three months. The results showed that with the application of elemental S, volatilisation losses decreased quadratically to 30.42% of applied nitrogen (N), for the highest S rate, indicating that as more elemental S was added to the soil, a lesser fraction was lost as NH<sub>3</sub>. Cumulative NH<sub>3</sub>-N emissions were closely related to initial soil pH ( $r=0.62^{**}$ ) and ammonium concentration ( $r = 0.74^{**}$ ). NH<sub>3</sub> volatilisation was the major pathway for the loss of N from surface applied urea and sulphur coated urea in Bintang Series soil. However, acidification of the soil by elemental S reduced NH<sub>3</sub> volatilisation by 50% as compared to the control. The NH<sub>3</sub> volatilisation pattern in soil treated with different rates of S was the same, but the addition of 2 g S kg<sup>-1</sup> soil delayed NH<sub>3</sub> volatilisation for four days. It should be noted that NH<sub>3</sub> hydrolysis in Bintang Series soil was fast and only 1.6 days were needed for the disappearance of 50% of of the urea.

**Keywords:** Ammonia loss, soil acidification, soil incubation study

### INTRODUCTION

Nitrogen (N) is known as the most limiting factor for crop production and this fact is fully understood by farmers and fertiliser producers. The Food and Agriculture Organisation of the United Nations (FAO) (2012) estimates that more than 115 million tonnes of N fertilisers will be used worldwide in 2016. Unfortunately, the inevitable fact is that the applied N fertilisers are not fully recovered or taken up by plants as 20 to 80% of the applied N fertiliser is lost through leaching and volatilisation (Bruce *et al.*, 1990; Jianga *et al.*, 2010). This situation seems to be worse in high pH soils. For instance Karimizarchi, (2011) found that in the wheat

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farms of Yazd province in Iran, N use efficiency was low and varied from 0 to 75%. The results also showed that the application of N fertilisers, according to farmers' experiences, did not positively and significantly affect plant growth and production, in half of studied farms in comparison with control treatment. This unfavorable situation increases the potential of environmental contamination with increased N use by farmers.

Depending on the soil and climatic conditions, ammonia ( $\text{NH}_3$ ) volatilisation can contribute greatly to N loss. Pacholski *et al.* (2006) reported that around 48% of applied urea ( $200 \text{ kg ha}^{-1}$ ) was volatilised as  $\text{NH}_3$  under the conditions of the studied fields in China. A likelihood of  $\text{NH}_3$  volatilisation of up to 80% from added urea under field conditions was reported by Gould *et al.* (1986). Following the application of urea to the soil surface, it may be lost through  $\text{NH}_3$  volatilisation (Jones *et al.*, 2007; Mikkelsen, 2009). Theoretically, a high soil pH increases soil concentrations of  $\text{NH}_3$  dissolved in soil water, causing higher  $\text{NH}_3$  volatilisation. It has been documented that the proportion of dissolved  $\text{NH}_3$  gas is near zero when the pH is below 7.5, but as it rises above 7.5, the dissolved  $\text{NH}_3$  gas increases dramatically (Jones *et al.*, 2007). Additionally, the rate of  $\text{NH}_3$  volatilisation depends on the rate of urea hydrolysis (conversion of urea to ammonium), weather conditions following application, and several soil properties. Multiple, and often interrelated factors make volatilisation difficult to predict; however, soil pH plays an over-riding role (Watson *et al.*, 1994).

Palm oil mill effluent (POME), peat, humic acid and fulvic acid are proposed as materials that can decrease  $\text{NH}_3$  volatilisation from urea fertilisers in the soil (Aminuddin, 1994; Reeza *et al.*, 2009; Rosliza *et al.*, 2009). Rosliza *et al.*, (2009) found that applying humic and fulvic acids completely stopped volatilisation of  $\text{NH}_3$ , reduced soil pH, and slowed urea hydrolysis. Latifah *et al.*, (2011) and Siva *et al.*, (1999) found a decrease in  $\text{NH}_3$  volatilisation in alkaline and acidic soils of Malaysia due to other acidifying materials such as sago waste water and humic acid, respectively. Soaud *et al.*, (2011) found the positive effect of elemental S, as an acidifying soil amendment, on  $\text{NH}_3$  volatilisation reduction in two soils from the United Arab Emirates. It should be noted that urea is the main source of N fertiliser worldwide (Glibert *et al.*, 2006) and an estimated 159 million or more tonnes of urea will be used in 2018 (Heffer and Prud'homme, 2014).

In the light of the above discussion, the importance of  $\text{NH}_3$  volatilisation in soils, and the role of soil pH cannot be ignored. However, there is no information on the role of soil pH on  $\text{NH}_3$  loss from Bintang Series soil (Karimizarchi *et al.*, 2014b). Therefore, this study aimed to investigate the effect of elemental S application rate and soil pH on N transformation and  $\text{NH}_3$  volatilisation of Bintang Series soil. Understanding the role of elemental S on N volatilisation is important for improving N fertiliser management, minimising environmental impacts, and helping farmers being more economical.

## MATERIALS AND METHODS

Alkaline Bintang series soil was used in this study. It was obtained from Taman Anggur, Bukit Bintang, Perlis, West Malaysia ( $6^{\circ} 31' 01.61''$  N and  $100^{\circ} 10' 12.43''$  E). The soil was air dried, ground to pass through a 2-mm sieve, and stored for analysis and experimentation. To provide a wide range of soil pH, the Bintang Series soil was incubated with different rates of elemental S (0.5, 1 and 2 g S kg<sup>-1</sup> soil) for three months under laboratory conditions at 25°C. Each incubation unit consisted of 2 kg of soil in a plastic pot, 26 cm in diameter and 10cm in height. The plastic containers were sealed with perforated plastic sheets to minimise water loss whilst maintaining aeration. Water content of the soils was maintained at 60% field capacity throughout the incubation by weighing and adding the required amount of water every week. The added water was mixed thoroughly with the soil. The experiment was carried out at the Department of Land Management, Universiti Putra Malaysia.

### *Ammonia Volatilisation Measurement*

After the three batches of soil were incubated with different rates of elemental S for three months, they were transferred to a modified closed-dynamic air flow system (Fenn and Kissel, 1973;1974) and daily amounts of NH<sub>3</sub> loss from the following five treatments were determined:

- T<sub>1</sub> : Soil treated with S coated urea
- T<sub>2</sub> : Soil treated with urea
- T<sub>3</sub> : Soil treated with 0.5 g S kg<sup>-1</sup> soil and urea
- T<sub>4</sub> : Soil treated with 1 g S kg<sup>-1</sup> soil and urea
- T<sub>5</sub> : Soil treated with 2 g S kg<sup>-1</sup> soil and urea

Urea or S coated urea, provided by Petroliaam Nasional Berhad (PETRONAS), were both applied at the same rate of 380 mgN per experimental unit. This rate of N was equal to 120 kg N per hectare. The system comprised of an aquarium pump, humidifying unit, soil air chamber and NH<sub>3</sub> trapper unit. Compressed air from a commercial aquarium pump was first humidified by bubbling through 200 ml of distilled water before entering the gas exchange chamber. An air flow rate of 2.5 litres per minute per cylinder was used for NH<sub>3</sub> removal. Each soil air chamber consisted of a 500 ml Erlenmeyer flask with 230 g of Bintang Series soil that was moistened and maintained, at 60% field water capacity during the experiment. Humidified water prevents the soil from becoming dry. The chambers were weighed daily and any deficits from the original weight was considered to represent moisture loss. Distilled water was added on a daily basis, where required, to maintain the moisture contents of the soils. Volatilised ammonium was collected in 20 ml of 2% boric acid indicator solution and was titrated with 0.01 N HCl (Page, 1982). The incubation chambers were maintained at laboratory conditions (25°C).

*Quantification of Urea Transformation*

Another experiment was conducted with the same treatments and conditions as stated in the previous section, and the urea changes as a function of elemental S application rate during the experiment is elucidated in the following paragraphs. Soil samples were taken four times (1, 3, 4 and 9 days after urea application) and immediately frozen at  $-20^{\circ}\text{C}$ . Soil sampling was based on the results of the previous section. The remaining urea and ammonium content in each sample was determined as stated by Page (1982). Exchangeable ammonium and remaining urea were extracted with a 2N KCl-PMA solution. Ammonium content was determined using the steam distillation method. Remaining urea was determined by colorimetric technique (Page, 1982). Soil acidity was determined on soil-water suspension (10 g soil to 25 ml distilled water) using a 24-hour glass electrode after shaking it for 30 minutes on a reciprocal shaker (Jones, 2001).

*Statistical Analysis*

Data were analysed using SAS (SAS Institute, 2003) commands through either completely randomised or split plot design with three replications. Tukey’s test at  $\alpha = 0.05$  was employed to determine the significant differences among the treatments. To model the relationship between soil pH and  $\text{NH}_3$  volatilisation as well as urea hydrolysis over time, the data were subjected to different regression models at a probability level of 0.05 with the help of Sigmaplot software.

**RESULTS AND DISCUSSION**

*Effect of Elemental S on Daily  $\text{NH}_3$  Volatilisation*

The  $\text{NH}_3$  volatilisation trends for the treatments under the conditions of this study were rather similar as shown in Figure 1. However, the starting day of

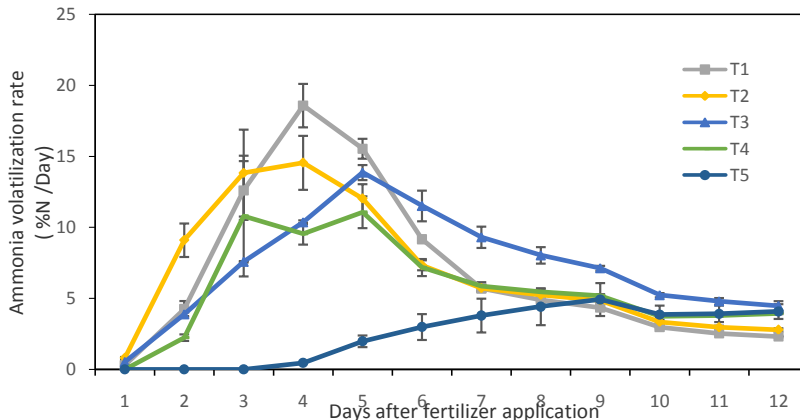


Figure 1: Effect of different treatments ( $T_1$ : sulphur coated urea,  $T_2$ : urea,  $T_3$ : soil treated with 0.5 g S kg<sup>-1</sup> soil and urea,  $T_4$ : soil treated with 1 g S kg<sup>-1</sup> soil and urea and  $T_5$ : soil treated with 2 g S kg<sup>-1</sup> soil and urea) on ammonia volatilisation rate from Bintang Series soil over time. Bars show the standard error.

NH<sub>3</sub> loss, the value and the day of volatilisation peak for Bintang Series soil treated with different rates of elemental S were different. In the untreated soil, NH<sub>3</sub> volatilisation started on the first day of urea application, with 0.8% of total N, followed by a steep rise and reached a volatilisation rate peak of 14.55% on the fourth day. However, in soils treated with 2 g S kg<sup>-1</sup> soil, NH<sub>3</sub> volatilisation was negligible during the first 4 days, followed by a gradual increase that reached a peak of 4.92% on the day 9 of urea addition. Likewise for untreated soil, NH<sub>3</sub> volatilisation for Bintang Series soil which received 0.5 g S kg<sup>-1</sup> started on day 1 of urea addition, whilst the application of 1 g S kg<sup>-1</sup> delayed NH<sub>3</sub> volatilisation by just only 24 hours (*Figure 1*).

The rates of NH<sub>3</sub> volatilisation for all treatments, except that of the highest S application rate, were at a maximum during the first 3 to 5 days and declined thereafter, with a little volatilisation occurring towards the end of day 10. Being around one-third of untreated soil, the addition of 2 g S kg<sup>-1</sup> soil resulted in a volatilisation peak of 4.92% being shifted by 5 days to day 9 after NH<sub>3</sub> application. Significant differences in NH<sub>3</sub> volatilisation rates were found between elemental S application rates and days after urea application (Table 1), with the highest S application rate showing the lowest NH<sub>3</sub> volatilisation rate. The highest volatilisation rate for the highest S application rate was 18.76 mg N per day on day 9 after the urea application, whilst the volatilisation rate for soils treated with 0, 0.5, and 1 g S kg<sup>-1</sup> soil were 55.44, 39.48, and 41.16 mg N per day, respectively.

In other words, it appeared that acidification of Bintang Series soil with applications of 1 and 2 g S kg<sup>-1</sup> soil stretched the duration of cumulative losses of N. This could be attributed to the over-riding influence of the initial soil acidity on NH<sub>3</sub> volatilisation (Jones *et al.*, 2007; Mikkelsen, 2009; Siva *et al.*, 1999). The negligible loss of NH<sub>3</sub> during the first four days in soil treated with 2 g S kg<sup>-1</sup> soil might also be due to the coincidence of this period with that of urea hydrolysis: therefore urea was not subjected to NH<sub>3</sub> volatilisation until it is first transformed into NH<sub>3</sub>.

TABLE 1

Effect of different treatments (T<sub>1</sub>: sulphur coated urea, T<sub>2</sub>: urea, T<sub>3</sub>: soil treated with 0.5 g S kg<sup>-1</sup> soil and urea, T<sub>4</sub>: soil treated with 1 g S kg<sup>-1</sup> soil and urea and T<sub>5</sub>: soil treated with 2 g S kg<sup>-1</sup> soil and urea) and days after urea application on daily ammonia volatilisation rate (mg nitrogen per day) in Bintang Series soil.

Treatment	Days after urea application				Mean
	1	3	4	9	
T <sub>1</sub>	1.12Cc	48.02Ab	70.79Aa	16.56Bc	34.12A
T <sub>2</sub>	3.08Ab	52.68Aa	55.44Ba	18.48Bb	32.42A
T <sub>3</sub>	2Bd	28.88Ab	39.48C	27.16Ac	24.38B
T <sub>4</sub>	Tr <sup>a</sup>	41.16Aa	36.4Ca	19.78Bb	24.33B
T <sub>5</sub>	Tr	Tr	1.7Db	18.76Ba	5.12C

<sup>a</sup> Traces

Means within column followed by the same capital letter and within rows followed by the same small letters are not significant at the 0.05 level, according to Tukey's test

To determine the role of initial soil acidity on maximum NH<sub>3</sub> volatilisation rate, the relationship between these two factors was studied. There was a linear and upward trend between soil pH and the maximum NH<sub>3</sub> volatilisation rate,  $Y = -22.84 + 11.51 \text{ pH}$ ,  $R^2 = 0.79^{**}$ . In other words, with each unit decrease in soil pH, the NH<sub>3</sub> volatilisation rate from Bintang Series soil decreased 11.51 mg per day.

*Effect of Elemental S on Cumulative NH<sub>3</sub> Volatilisation*

As can be seen from Figure 2, the cumulative NH<sub>3</sub> volatilisation increased progressively for all treatments. Whilst the NH<sub>3</sub> volatilisation for the highest S rate started on day 5 after urea application, it started on day 1 after urea application for other treatments. At the end of the experiment, there was no significant difference in total NH<sub>3</sub> volatilised between untreated soil and those that received 0.5 and 1 g S kg<sup>-1</sup> soil (Table 2). However, the application of 2 g S kg<sup>-1</sup> soil significantly decreased NH<sub>3</sub> volatilisation from 82.56% of added urea for untreated soil to 30.42%. As the only difference between soils treated with elemental S was their pH, the relationship between soil acidity and total volatilised urea was modelled by  $Y = -237.03 + 101.32X - 7.81 X^2$ ,  $R^2 = 0.86^{**}$ . There was an upward trend in NH<sub>3</sub> volatilisation from the lowest pH value of 3.77, to a pH value of 6.5, before levelling, indicating the overriding effect of soil acidity. The findings agreed with those of Soaud *et al.*, (2011) who found a reduction in ammonia volatilisation from 30% to 15% due to the application of elemental S at a rate of 10 tonnes per hectare. However, they did not relate this reduction in NH<sub>3</sub> volatilisation to soil pH reduction. Jones *et al.* (2007) have documented the importance and role of soil acidity in NH<sub>3</sub> volatilisation.

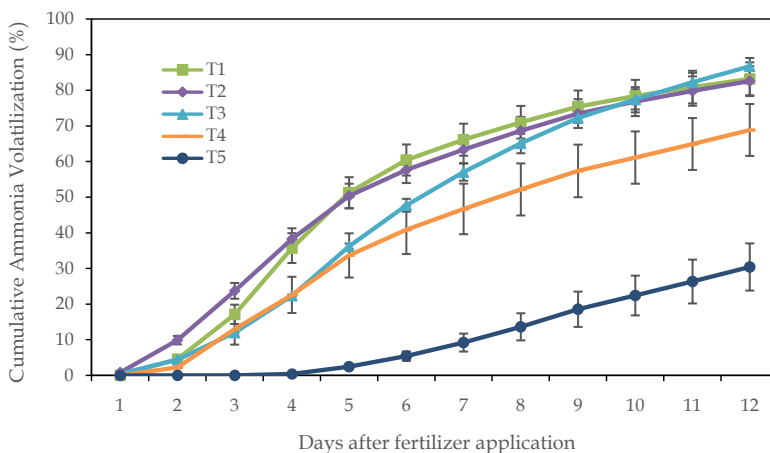


Figure 2: Effect of different treatments ( $T_1$ : sulphur coated urea,  $T_2$ : urea,  $T_3$ : soil treated with 0.5 g S kg<sup>-1</sup> soil and urea,  $T_4$ : soil treated with 1 g S kg<sup>-1</sup> soil and urea and  $T_5$ : soil treated with 2 g S kg<sup>-1</sup> soil and urea) on cumulative ammonia volatilisation from Bintang Series soil treated with urea and sulphur coated urea over time. Bars show the standard error.

TABLE 2  
Effect of different treatments on total ammonia volatilised from Bintang Series soil treated with urea or sulphur coated urea.

Treatment	Total ammonia volatilised within 12 days	
	mg nitrogen	Percent
T <sub>1</sub> ( sulphur coated urea)	313.27A	82.22A
T <sub>2</sub> (urea)	314.58A	82.56A
T <sub>3</sub> (soil treated with 0.5 g S kg <sup>-1</sup> soil and urea)	330.35A	86.70A
T <sub>4</sub> (soil treated with 1 g S kg <sup>-1</sup> soil and urea)	262.36A	68.86A
T <sub>5</sub> (soil treated with 2 g S kg <sup>-1</sup> soil and urea)	115.92B	30.42B

Means within column followed by the same capital letter and within rows followed by the same small letters are not significant at the 0.05 level, according to Tukey's test

#### *Effect of Elemental S on Ammonium Production Over Time*

The role of elemental S application rate on urea hydrolysis and ammonium concentration is shown in Table 3. Our results showed that application of elemental S at rates of 1 and 2 g kg<sup>-1</sup> soil significantly decreased ammonium production until day 4 after urea application. With 50.66 and 41.33 mg kg<sup>-1</sup> soil, the lowest concentration of ammonium at day 1 was found for elemental S rates of 1 and 2 g kg<sup>-1</sup> soil and the highest ammonium concentration of 97.73 mg kg<sup>-1</sup> soil was found in Bintang Series soil treated with 0.5 g S kg<sup>-1</sup> soil, which was not significantly different from untreated soil which received urea and sulphur coated urea.

TABLE 3  
Effect of different treatments (T<sub>1</sub>: sulphur coated urea, T<sub>2</sub>: urea, T<sub>3</sub>: soil treated with 0.5 g S kg<sup>-1</sup> soil and urea, T<sub>4</sub>: soil treated with 1 g S kg<sup>-1</sup> soil and urea and T<sub>5</sub>: soil treated with 2 g S kg<sup>-1</sup> soil and urea) and days after urea application on ammonium concentration (mg kg<sup>-1</sup> soil) in Bintang Series soil.

Treatment	Days after urea or SCU addition				Mean
	1	3	4	9	
T <sub>1</sub>	83.33Ab	506.33Aa	546Aa	492.33Aa	407.00A
T <sub>2</sub>	78.66Ac	560Aa	613.66Aa	340.66Bb	398.25A
T <sub>3</sub>	97.33Ac	471.33Aab	380.33Bb	492.33Aa	360.33AB
T <sub>4</sub>	50.66Bb	375.66ABa	396.66Ba	478.33Aa	325.33B
T <sub>5</sub>	41.33Bc	130.66Bb	198.33Cb	494.66Aa	216.25C
Mean	70.27b	408.8a	427a	459.67a	

Means within column followed by the same capital letter and within rows followed by the same small letters are not significant at the 0.05 level, according to Tukey's test

Ammonium concentration was significantly affected by the lapsed time after urea application. The ammonium concentration for T1, T2, T3, T4 and T5 treatments significantly increased from 83.33, 78.66, 97.33, 50.66 and 41.33 mg kg<sup>-1</sup> soil, respectively, on day 1 after urea addition to 506.33, 560, 471.33, 375.66 and 130.66 mg kg<sup>-1</sup> soil, respectively, on day 3 of urea addition (Table 3). In other words, the concentration of ammonium in untreated soils increased six times within three days whilst that of the soils treated with 2 g S kg<sup>-1</sup> soil increased 3.16 times. This finding agreed with those of Soaud *et al.*, (2011) who stated that faster urea hydrolysis occurs in alkaline soils than in acidic soils.

*Effect of Elemental S on Urea Disappearance*

Nitrogen fertilisers such as urea, applied at different rates, undergo transformations in Bintang Series soil. In order to derive a method for predicting the time taken for complete hydrolysis of urea in Bintang Series soil, the time courses between urea concentrations in Bintang Series soil treated with different rates of elemental S and time were modeled. Urea disappearance for all treatments followed a non-linear regression, exponential decay model with two parameters:

$$A = A_0 e^{-kt}$$

The *r* square for all treatments was highly significant at levels of less than 0.01 with a range of 0.79 to 0.95 (Table 4). This exponential decay model shows that urea disappearance follows a first order reaction, a reaction that proceeds at a rate

TABLE 4  
Urea (U) or sulphur coated urea (SCU) disappearance equations and coefficients of determinations for Bintang Series soil treated with different rates of elemental sulphur with half-life.

Treatment	Regression equation	R <sup>2</sup>	Half-life (days) ( $t_{\frac{1}{2}}$ )
T <sub>5</sub> (soil treated with 2 g S kg <sup>-1</sup> soil and urea)	U = 72.5 e <sup>-0.21t</sup>	0.79**	1.75
T <sub>4</sub> (soil treated with 1 g S kg <sup>-1</sup> soil and urea)	U = 85.36 e <sup>-0.38t</sup>	0.86**	1.4
T <sub>3</sub> (soil treated with 0.5 g S kg <sup>-1</sup> soil and urea)	U = 170.42 e <sup>-0.74t</sup>	0.94**	1.6
T <sub>2</sub> (urea)	U = 158.47 e <sup>-0.72t</sup>	0.82**	1.6
T <sub>1</sub> ( sulphur coated urea)	SCU = 165.05 e <sup>-0.68t</sup>	0.95**	1.7

Means within column followed by the same capital letter and within rows followed by the same small letters are not significant at the 0.05 level, according to Tukey's test



that depends linearly only on one reactant concentration. The integrated forms of the rate law allow the population of reactant to be found at any time after the start of the reaction. Plotting  $\ln A$  with respect to time for a first-order reaction gives a straight line with the slope of the line equal to  $-k$ . It should be noted that urea hydrolysis rate depends on the S application rate as well as time. As 'k' values for all treatments were negative, the remaining urea in soil decreased with an increase in time. Accordingly, it is expected that 50% of urea applied at Bintang Series soil with different levels of elemental S would disappear very quickly (within 1.4 to 1.7 days). It should be noted that, based on these models, for all but soils treated with the highest amounts of elemental S (where 10% of the urea remained), after day 9 almost all of the urea applied totally disappeared (Table 4). Warner (1942) also stated that urea hydrolysis follows a first order reaction. The dependency of urea hydrolysis rate on soil pH and urea concentration in both experiments were previously studied by Cabrera *et al.*, (1991) and they stated that increasing urea concentration and soil pH cause the urea hydrolysis rate to increase.

#### *Effect of Urea on Soil pH Over Time*

This study showed that the addition of urea and S coated urea to Bintang Series soil treated with different rates of elemental S significantly increased soil pH, but the degree and pattern of soil pH change depended on initial soil pH and time (Table 5). For instance, the addition of urea to Bintang Series soil treated with 0, 0.5 and 1 g S kg<sup>-1</sup> soil, increased soil pH from the background values of 7.65, 6.33 and 4.56 to the maximums of 8.99, 8.31 and 7.79 three days after the application, respectively. This maximum pH coincided with the highest NH<sub>3</sub> volatilisation rate recorded from day 2 to 4 (Figure 2). Thereafter, soil acidity values for soil treated with 0, 0.5 and 1 g S kg<sup>-1</sup> soil tended to marginally reduce from the maximum of 8.99, 8.31 and 7.79, respectively, at day 3 to 8.47, 8.24 and 7.8, respectively, after 9 days of urea addition. However, there was a progressive and upward trend in soil pH over time for Bintang Series soil treated with 2 g S kg<sup>-1</sup> soil. It should be noted that the highest pH value recorded for the highest S application rate, 6.05, was less

TABLE 5

Effect of sulphur application rate and incubation time on soil pH in Bintang Series soil.

Treatment	Incubation days					Mean
	0 <sup>a</sup>	1	3	4	9	
T <sub>1</sub>	7.65Ac	7.93Ac	8.75Aa	8.61Ba	8.3Bb	8.4B
T <sub>2</sub>	7.65Ad	8.16Ac	8.99Aa	8.9Aa	8.47Ab	8.63A
T <sub>3</sub>	6.33Bc	7.4Bb	8.31Ba	8.16Ca	8.24Ba	8.03C
T <sub>4</sub>	4.56Cc	5.57Cb	7.79Ca	7.72Da	7.8Ca	7.22D
T <sub>5</sub>	3.77Dd	3.91Dc	4.44Db	4.37Eb	6.05Da	4.66E
Mean		6.59c	7.63b	7.55b	7.7a	

<sup>a</sup> soil pH before addition of urea fertiliser.

Means within column followed by the same capital letter and within rows followed by the same small letters are not significant at the 0.05 level, according to Tukey's test

than that of other treatments. This shows that the effectiveness of elemental S on soil pH changes over time due to urea application and supports the role of soil pH on daily NH<sub>3</sub> volatilisation rate and cumulative NH<sub>3</sub> volatilisation as observed in the conditions of this study (Figures 2 and 3). This fact was also highly supported by the significant and positive correlation between soil pH and NH<sub>3</sub> volatilisation rate as well as ammonium concentration in soil (Table 6). The increase in soil pH due to urea application agreed with the findings of Singh and Beauchamp (1988) who stated that application of urea increases soil pH of Conestogo and Brookston soils from the background levels of 7.65 and 5.7 to 9. They also reported that due to the soil pH of Conestogo soil being close to that of urea, there were few changes over 35 days but the pH of Brookston soil fell below 9, but not less than 8.5 after 20 days.

TABLE 6

Pearson correlation coefficients among soil pH, different forms of nitrogen and ammonia volatilisation rates in Bintang Series soil treated with different rates of elemental sulphur.

	pH	Ammonium	Urea	Volatilisation rate
pH	1	0.61**	-0.38**	0.62**
Ammonium		1	-0.72**	0.74**
Urea			1	-0.55**
Volatilisation rate				1

Values of r followed by \*\* or \* are significant at  $\alpha=0.01$  and  $\alpha=0.05$  respectively.

ns: non- significant

### CONCLUSIONS

As outlined above, NH<sub>3</sub> volatilisation was the major pathway of N loss of surface applied urea and S coated urea in Bintang Series soil. However acidification of the soil by elemental S reduced the NH<sub>3</sub> volatilisation from the background of 82% in untreated soil to 30% in S amended soil. In addition, as a high rate of N loss through NH<sub>3</sub> volatilisation was recorded in this study, it can be concluded that urea is an unsuitable form of N fertiliser for calcareous soils and it is recommended that the efficiency of other N fertiliser sources, such as ammonium sulphate, be studied to develop new directions.

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