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# Influence of Urea and Ammonium Sulfate on Soil Acidity Indices in Lowland Rice Production

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*Urea and ammonium sulfate are principal nitrogen (N) sources for crop production. Two field experiments were conducted during three consecutive years to evaluate influence of urea and ammonium sulfate application on grain yield, soil pH, calcium (Ca) saturation, magnesium (Mg) saturation, base saturation, aluminum (Al) saturation, and acidity (H + Al) saturation in lowland rice production. Grain yield was significantly influenced by urea as well as ammonium sulfate fertilization. Soil pH linearly decreased with the application of N by ammonium sulfate and urea fertilizers. However, the magnitude of the pH decrease was greater by ammonium sulfate than by urea. The Ca and Mg saturations were decreased at the greater N rates compared to low rates of N by both the fertilizer sources. The Al and acidity saturation increased with increasing N rates by both the fertilizer sources. However, these acidity indices were increased more with the application of ammonium sulfate compared with urea. Rice grain yield had negative associations with pH, Ca saturation, Mg saturation, and base saturation and positive associations with Al and acidity saturation. This indicates that rice plant is tolerant to soil acidity.*

**Keywords** Acidity saturation, base saturation, calcium saturation, *Oryza sativa* L., soil pH

## Introduction

Lowland and upland are two main rice production ecosystems. Lowland is also known as flooded rice, and in Brazil this system of rice culture is designated as irrigated rice. On a global basis, about 76% of the rice is produced from an irrigated lowland rice system (Fageria, Slaton, and Baligar 2003). Nitrogen is usually the most yield-limiting nutrient in lowland rice production. Intensive agricultural production systems have increased the use of nitrogen (N) fertilizer in an effort to produce and sustain high crop yields. Nitrogen fertilizers are mostly applied in bands or broadcast. Urea and ammonium sulfate are the two main sources of inorganic N fertilizer for lowland rice (Fageria, Slaton, and Baligar 2003). Urea has about 46% of N, and ammonium sulfate N content is about 21%. In addition, ammonium sulfate also contains about 24% sulfur (S). Fertilizers with more N content are preferred over low-N fertilizers because of the lower cost of transport and application.

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Nitrogen content is an important criterion; however, other factors should also be taken into consideration when choosing a fertilizer carriers. These factors include the content of nutrients other than the principal one, price of the fertilizer, chemical reactions in the soil, and nutrient availability to plants.

Recovery of N in crop plants is usually less than 50% worldwide (Fageria and Baligar 2005). Worldwide, N recovery efficiency for cereal production (rice, wheat, sorghum, millet, barley, corn, oat, and rye is approximately 33% (Raun and Johnson 1999). Fageria and Baligar (2001) reported N recovery efficiency of 39% for lowland rice under Brazilian conditions. Low recovery of N in annual crops is associated with its loss by volatilization, leaching, surface runoff, denitrification, and plant canopy. Nowadays, the environmental as well as financial impact of N fertilizer use deserves increased attention. Field data on changes of soil acidity indices such as pH, calcium (Ca), and magnesium (Mg) saturation, base saturation, aluminum (Al) saturation, and acidity (H + Al) saturation with the application of ammonium sulfate and urea, two major N sources, are scarce for lowland rice under Brazilian conditions. The objective of this study was to evaluate influence of ammonium sulfate and urea on grain yield and soil acidity indices in lowland rice production.

## Materials and Methods

Two field experiments involving lowland rice (*Oryza sativa* L.) were conducted during three consecutive years to evaluate influence of urea and ammonium sulfate application on grain yield and soil acidity indices in lowland rice grown on Inceptisols (sandy-clay loam, isothermic, mesic Typic Haplaquepts). The initial chemical and physical properties of these two experimental areas are presented in Table 1. Soil pH was measured in a 2:2.5 soil–water suspension. Phosphorus (P), potassium (K), copper (Cu), zinc (Zn), iron (Fe), and manganese (Mn) were extracted by the Mehlich 1 extracting solution [0.05 M

**Table 1**
Soil chemical and physical properties of two experimental areas (0–20 cm deep) before the application of N treatments

| Soil property | Ammonium sulfate experiment | Urea experiment |
|---|---|---|
| pH in $H_2O$ | 5.5 | 4.8 |
| Organic matter (g kg$^{-1}$) | 26 | 9 |
| P (mg kg$^{-1}$) | 19.2 | 24.5 |
| K (mg kg$^{-1}$) | 38 | 34 |
| Ca (cmol$_c$ kg$^{-1}$) | 3.7 | 1 |
| Mg (cmol$_c$ kg$^{-1}$) | 1.7 | 0.5 |
| Al (cmol$_c$ kg$^{-1}$) | 0.3 | 1.5 |
| Cu (mg kg$^{-1}$) | 2.9 | 5.1 |
| Zn (mg kg$^{-1}$) | 2.9 | 4.9 |
| Fe (mg kg$^{-1}$) | 227 | 462 |
| Mn (mg kg$^{-1}$) | 60 | 14 |
| Clay (g kg$^{-1}$) | 305 | 332 |
| Silt (g kg$^{-1}$) | 225 | 140 |
| Sand (g kg$^{-1}$) | 470 | 538 |

hydrochloric acid (HCl) + 0.0125 M sulfuric acid ($H_2SO_4$)]. Phosphorus was determined colorimetrically, and K, Cu, Zn, Fe, and Mn were found by atomic absorption spectroscopy. Calcium, Mg, and Al were extracted with 1 M potassium chloride (KCl). Aluminum was determined by titration with sodium hydroxide (NaOH), and Ca and Mg were determined by titration with ethylenediaminetetraacetic acid (EDTA). Organic matter was determined by the Walkley–Black method, and soil texture was found by the pipette method. Soil analysis methods used in this study are described in a soil analysis manual published by EMBRAPA (1997).

In the ammonium sulfate experiment, the N rates used were 0, 30, 60, 90, 120, 150, 180, and 210 kg ha$^{-1}$, whereas in the urea experiment, N rates were 0, 50, 100, 150, and 200 kg ha$^{-1}$. One third of N in the ammonium sulfate experiment was applied at sowing, and the remainder was topdressed twice, at equal rates, at 45 and 70 days after sowing (DAS). In the urea experiment, half of the N was applied at sowing and the remaining was topdressed at 45 DAS. In the ammonium sulfate experiment, treatments were replicated four times in a randomized block design. In the urea experiment, treatments were replicated three times in a randomized bloc design. Plot size was 5 by 4 m in ammonium sulfate experiment and 9.6 by 5 m in the urea experiment. In both the experiments, 52 kg P ha$^{-1}$ as triple superphosphate and 100 kg K ha$^{-1}$ as potassium chloride were applied as basal fertilizers in bands at the time of sowing each year. In the urea experiment, initial pH, Ca, and Mg contents were low. Hence, 4 Mg dolomitic lime ha$^{-1}$ was applied and incorporated 4 weeks before sowing the first crop.

Flooded rice cultivar Metica 1 was sown in the ammonium sulfate experiment, and 12 genotypes were sown in the urea experiment, with 4 rows of 5 m each for each genotype. Sowing was done manually at a spacing of 20 cm between rows, using 90 seeds per meter row. Rice plots were flooded about 30 DAS to a depth of 10 to 15 cm of standing water, remained flooded during the crop growth period, and drained 1 week before harvest. Experiments were repeated for 3 years in the same areas, and after the harvest of the third rice crop, soil samples were taken at 0–20 cm deep from each plot to determine chemical properties. About 30 cores were taken from each plot to make one composite sample. Soil samples were dried and ground, and chemical properties were determined by methods described in the manual of soil analysis of EMBRAPA (1997). Relative grain yield and soil acidity indices were calculated using following formulas:

$$\text{Relative grain yield } (\%) = (\text{Grain yield at a determined N rate}/\text{ Maximum grain yield at a determined N rate}) \times 100$$

$$\text{Ca saturation } (\%) = (\text{Ca}^{2+}/\text{ CEC}) \times 100, \quad \text{where CEC is cation exchange capacity in cmol}_c\text{ kg}^{-1} = [\Sigma(\text{Ca}^{2+}, \text{Mg}^{2+}, \text{K}^{+}, \text{H}^{+}, \text{Al}^{3+})]$$

$$\text{Mg saturation } (\%) = (\text{Mg}^{2+}/\text{CEC}) \times 100$$

$$\text{Base saturation } (\%) = [\Sigma(\text{Ca}^{2+}, \text{Mg}^{2+}, \text{K}^{+})/(\text{CEC})] \times 100$$

$$\text{Al saturation } (\%) = [(\text{Al})/\Sigma(\text{Ca}^{2+}, \text{Mg}^{2+}, \text{K}^{+}, \text{Al}^{3+})] \times 100$$

$$\text{Acidity saturation } (\%) = (\text{H}^{+} + \text{Al}^{3+}/\text{CEC}) \times 100$$

Regression analysis was used to test treatment effects. Appropriate regression equations were selected on the basis of probability level significance and greater $R^2$ values.

## Results and Discussion

### Grain Yield

Grain yield expressed in relative yield was significantly increased by urea as well as ammonium sulfate fertilization, and the increase was in a quadratic fashion (Figure 1). In fertilizer experiments, 90% of the relative yield is considered as an economic index, and this index was used to calculate adequate N rate (Figure 1). Ninety percent of the relative yield (which corresponds to 5750 kg grain ha$^{-1}$) was obtained with the application of 84 kg N ha$^{-1}$ in the case of ammonium sulfate. Similarly, in the case of urea, 90% of the relative grain yield (corresponds to 4811 kg grain ha$^{-1}$) was obtained with the application of 130 kg N ha$^{-1}$. Singh et al. (1998) reported that the maximum average grain yield of 7700 kg ha$^{-1}$ of 20 lowland rice genotypes was obtained at 150 to 200 kg N ha$^{-1}$ at the International Rice Research Institute in the Philippines. Aulakh et al. (2000) reported that flooded rice responded to N rates up to 120 kg N ha$^{-1}$ on sandy loam soils in India. In the Philippines, Dobermann et al. (2000) reported 80 to 100 kg N ha$^{-1}$ was used for maximal yields in the field experiments during the wet season (rainy period) and 120 to 150 kg N ha$^{-1}$ was used during the dry season. These authors also reported that N fertilization rates in Philippines for irrigated lowland rice, from 1992 onward, were increased from 108 to 120 kg N ha$^{-1}$ during the wet season and from 190 to 216 kg N ha$^{-1}$ during the dry season. Fageria and Baligar (1996) also reported significant increases in grain yields of lowland rice grown on an Inceptisol in the central part of Brazil. These authors reported that an average yield of 3 years (5523 kg ha$^{-1}$) of lowland rice was achieved with the application of 100 kg N ha$^{-1}$. Hence, results of this study are comparable with the results reported in the literature for N requirements of lowland rice.

### Soil Acidity Indices

Soil pH was decreased linearly with increasing N rate by ammonium sulfate (0 to 210 kg N ha$^{-1}$) and urea (0 to 200 kg N ha$^{-1}$) (Table 2). The decrease in pH with ammonium sulfate was from 5.8 at 0 N ha$^{-1}$ rate to 5.2 at 210 kg N ha$^{-1}$. This means that the decrease

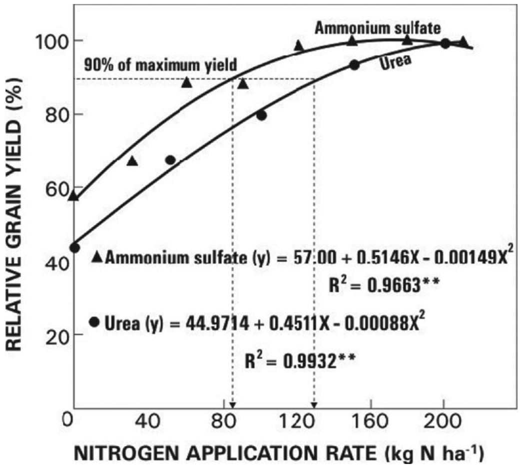

**Figure 1.** Relative grain yield of lowland rice as influenced by ammonium sulfate and urea sources.

**Table 2**

Influence of N rate applied by ammonium sulfate and urea on soil pH after harvest of three lowland rice crops

| N rate (kg $ha^{-1}$) $NH_4(SO_4)_2$ | pH in $H_2O$ | N rate (kg $ha^{-1}$) Urea | pH in $H_2O$ |
|---|---|---|---|
| 0 | 5.8 | 0 | 5.7 |
| 30 | 5.8 | 50 | 5.6 |
| 60 | 5.5 | 100 | 5.7 |
| 90 | 5.4 | 150 | 5.5 |
| 120 | 5.4 | 200 | 5.5 |
| 150 | 5.4 | | |
| 180 | 5.3 | | |
| 210 | 5.2 | | |
| Average | 5.5 | | 5.6 |

$^{*}$, $^{**}$Significant at the 5% and 1% probability levels, respectively.

*Notes*. Regression analysis: N rate, ammonium sulfate ($X$) vs pH ($Y$): $Y = 5.7187 - 0.0026X$, $R^2 = 0.3969^{**}$; and N rate, urea ($X$) vs pH ($Y$): $Y = 5.6927 - 0.00092X$, $R^2 = 0.2601^{*}$.

at the greatest N rate applied with ammonium sulfate was 12% compared with the lowest N rate for the same fertilizer. Similarly, the decrease in pH with urea fertilizer was 5.7 at the 0 rate $ha^{-1}$ to 5.5 at 200 kg N $ha^{-1}$. This decrease corresponds to 4% at the greatest N rate compared with the lowest N rate. Hence, the decrease in soil pH was greater with ammonium sulfate compared to urea. Ammonium sulfate fertilization accounted for about 40% variation in soil pH, and urea fertilization accounted for 26% variation in soil pH. Both the N fertilizer sources are acidic and their acid equivalencies [kg calcium carbonate ($CaCO_3$) required to neutralize acidity produced by 100 kg of fertilizers] are 110 for ammonium sulfate and 80 for urea (Fageria 1989). Decrease in soil pH has been reported by use of ammonium sulfate and urea (Hetrick and Schwab 1992). Stumpe and Vlek (1991) reported that a decrease in pH of tropical acid soils (Oxisols, Ultisols, and Alfisols) due to use of three N fertilizers was in the order of ammonium sulfate > urea > ammonium nitrate. These two fertilizer sources can acidify the soil by following reactions (Fageria 1989; Bolan and Hedley 2003):

$$(NH_4)_2\,SO_4 \Leftrightarrow 2NH_4^+ + SO_4{}^{2-}$$

$$NH_4^+ + 2O_2 \Leftrightarrow NO_3^- + 2H^+ + H_2O$$

$$CO(NH_2)_2 + 3H_2O \Leftrightarrow 2NH_4^+ + 2OH^- + CO_2$$

$$NH_4^+ + 2O_2 \Leftrightarrow NO_3^- + 2H^+ + H_2O$$

According to these equations, the ammonium ($NH_4{}^+$) ions are oxidized to yield nitrate ($NO_3{}^-$) ions or nitrification, which results in the release of $H^+$ ions, leading to soil acidification. Another reason for soil acidification by ammonium sulfate and urea is leaching of $NO_3{}^-$ ions. During leaching of $NO_3{}^-$ ions, they are accompanied by positively charged basic cations, such as $Ca^{2+}$, $Mg^{2+}$, and $K^+$, to maintain the electric charge on the soil particles. During the leaching of these basic cations from soil particles, their sites are replaced by $H^+$ ions, which accelerates the acidification process (Bolan and Hedley 2003).

Calcium as well as Mg saturation decreased with increasing N rates by ammonium sulfate and urea fertilizers (Tables 3 and 4). The decrease in Ca saturation at 210 kg N ha$^{-1}$ supplied by ammonium sulfate was 23%, and with urea application at 200 kg N ha$^{-1}$ it was 33% compared with the control treatment. Similarly, the decrease in Mg saturation was 2% at the greatest N application rate using ammonium sulfate as compared with the

**Table 3**

Influence of N rate applied by ammonium (AS) and urea on Ca saturation after harvest of three lowland rice crops

| N rate<br>$NH_4(SO_4)_2$ | Ca saturation (%) | N rate (kg ha$^{-1}$)<br>$CO(NH_2)_2$ | Ca saturation (%) |
|---|---|---|---|
| 0 | 22.7 | 0 | 31.6 |
| 30 | 24.4 | 50 | 26.8 |
| 60 | 21.0 | 100 | 28.0 |
| 90 | 18.6 | 150 | 27.1 |
| 120 | 20.3 | 200 | 23.8 |
| 150 | 19.9 | | |
| 180 | 19.6 | | |
| 210 | 18.4 | | |
| Average | 20.6 | | 27.4 |

*, **Significant at the 5% and 1% probability levels, respectively.

*Notes.* Regression analysis: N rate AS ($X$) vs. Ca sat. ($Y$): $Y = 23.5510 - 0.0421X + 0.000094X^2$, $R^2 = 0.234^{**}$ ; and N rate urea ($X$) vs. Ca saturation ($Y$): $Y = 30.5133 - 0.0306X$, $R^2 = 0.3684^{*}$.

**Table 4**

Influence of N rate applied by ammonium sulfate (AS) and urea on Mg saturation after harvest of three lowland rice crops

| N rate<br>$NH_4(SO_4)_2$ | Mg saturation (%) | N rate (kg ha$^{-1}$)<br>$CO(NH_2)_2$ | Mg saturation (%) |
|---|---|---|---|
| 0 | 9.1 | 0 | 11.7 |
| 30 | 10.4 | 50 | 9.5 |
| 60 | 9.0 | 100 | 9.7 |
| 90 | 8.0 | 150 | 9.0 |
| 120 | 7.9 | 200 | 8.1 |
| 150 | 8.8 | | |
| 180 | 7.8 | | |
| 210 | 8.9 | | |
| Average | 8.7 | | 9.6 |

**, NSSignificant at the 1% probability level and nonsignificant, respectively.

*Notes.* Regression analysis: N rate AS ($X$) vs. Mg saturation ($Y$): $Y = 9.8208 - 0.0211X + 0.000073X^2$, $R^2 = 0.1077^{NS}$; and N rate urea ($X$) vs. Mg saturation ($Y$): $Y = 11.3723 - 0.0242X + 0.000043X^2$, $R^2 = 0.6205^{**}$.

control treatment. The decrease in Mg saturation at the greatest N rate with urea application was 44% compared with the control treatment. The decrease in Ca and Mg saturation at greater N rates may be associated with increase in acidity at greater N rates and decrease in concentration of these elements. An increase in acidity decreases the concentrations of Ca and Mg in Brazilian Inceptisols (Fageria and Baligar 1999).

Base saturation is an important soil acidity index for predicting fertility behavior of tropical acidic soils (Fageria and Baligar 2001). Base saturation decreased linearly with increasing N rates by both the sources of N fertilizer (Table 5). The decrease in base saturation with application of 210 kg N ha$^{-1}$ with ammonium sulfate was 27.8% compared with 32.2% at the control treatment. Similarly, the base saturation at the control treatment of urea was 44.4%, which decreased to 32.5% at the greatest N rate. The decrease in base saturation at the greater N rate was associated with decreases in Ca and Mg saturation (Tables 3 and 4). At the greater N rates, pH was than the pH at low N rates under both the N sources. At low pH, $Al^{3+}$ is the predominant exchangeable cation on clay minerals. As the pH is raised, the $Al^{3+}$ hydrolyzes, freeing the exchangeable sites for $Ca^{2+}$ and $Mg^{2+}$, and results in an increase of base saturation (Thomas and Hargrove 1984).

The Al saturation increased linearly with the increasing N rates by ammonium sulfate as well as urea fertilization (Table 6). The increase in Al saturation was about twofold at the 210 kg N ha$^{-1}$ supplied by ammonium sulfate compared with control treatment. The increase in Al saturation with the application of 200 kg N ha$^{-1}$ by urea was about fourfold compared with the control treatment of this fertilizer. Similarly, the increase in acidity saturation was significant and quadratic with increasing N rates by both the fertilizer sources (Table 7). The increase in Al saturation and acidity saturation was associated with a decrease in base saturation with increasing N rates. Another reason for increase of these acidity indices was a decrease in pH with increasing N rates. The release of Al and Al + H from various minerals is greatly dependent on pH, and these elements significantly increased in the soil solution with decreasing soil pH (Mengel et al. 2001).

**Table 5**

Influence of N rate applied by ammonium sulfate and urea on base saturation after harvest of three lowland rice crops

| N rate (kg ha$^{-1}$) $NH_4(SO_4)_2$ | Base saturation (%) | N rate (kg ha$^{-1}$) $CO(NH_2)_2$ | Base saturation (%) |
|---|---|---|---|
| | 32.2 | 0 | 44.4 |
| 30 | 35.3 | 50 | 36.9 |
| 60 | 30.5 | 100 | 38.4 |
| 90 | 27.0 | 150 | 36.7 |
| 120 | 28.5 | 200 | 32.5 |
| 150 | 29.2 | | |
| 180 | 27.9 | | |
| 210 | 27.8 | | |
| Average | 29.8 | | 37.7 |

$^{*}$, $^{**}$Significant at the 5% and 1% probability level, respectively.

*Notes.* Regression analysis: N rate ammonium sulfate ($X$) vs. base saturation ($Y$): $Y = 32.7292 - 0.0280X$, $R^2 = 0.1945^{*}$; and N rate urea ($X$) vs. base saturation ($Y$): $Y = 42.5666 - 0.0479X$, $R^2 = 0.4529^{**}$.

**Table 6**
Influence of N rate applied by ammonium sulfate and urea on aluminum saturation after harvest of three lowland rice crops

| N rate $NH_4(SO_4)_2$ | Al saturation (%) | N rate (kg ha$^{-1}$) $CO(NH_2)_2$ | Al saturation (%) |
|---|---|---|---|
| 0 | 6.4 | 0 | 1.7 |
| 30 | 5.9 | 50 | 3.7 |
| 60 | 5.1 | 100 | 3.8 |
| 90 | 6.7 | 150 | 4.5 |
| 120 | 4.2 | 200 | 6.8 |
| 150 | 8.4 | | |
| 180 | 10.3 | | |
| 210 | 11.2 | | |
| Average | 7.3 | | 4.1 |

**Significant at the 1% probability level.

*Notes.* Regression analysis: N rate ammonium sulfate ($X$) vs. Al saturation ($Y$): $Y = 4.6604 + 0.0248X$, $R^2 = 0.2162^{**}$; and N rate urea ($X$) vs. Al saturation ($Y$): $Y = 1.93 + 0.0217X$, $R^2 = 0.5476^{**}$.

**Table 7**
Influence of N rate applied by ammonium sulfate (AS) and urea on acidity saturation after harvest of three lowland rice crops

| N rate $NH_4(SO_4)_2$ | Acidity saturation (%) | N rate (kg ha$^{-1}$) $CO(NH_2)_2$ | Acidity saturation (%) |
|---|---|---|---|
| 0 | 67.8 | 0 | 55.6 |
| 30 | 64.7 | 50 | 63.1 |
| 60 | 69.5 | 100 | 61.6 |
| 90 | 73.0 | 150 | 63.3 |
| 120 | 71.5 | 200 | 67.5 |
| 150 | 70.8 | | |
| 180 | 72.1 | | |
| 210 | 72.2 | | |
| Average | 70.2 | | 62.2 |

*Significant at the 5% probability level.

*Notes.* Regression analysis: N rate AS ($X$) vs. acidity saturation ($Y$): $Y = 66.1739 + 0.0646X – 0.00017 X^2$, $R^2 = 0.2216^*$; and N rate urea ($X$) vs. acidity saturation ($Y$): $Y = 56.9714 + 0.0664X – 0.000092X^2$, $R^2 = 0.4586^*$.

### *Relationship between Soil Acidity Indices and Grain Yield*

In ammonium sulfate as well as urea experiments, grain yield was negatively and significantly associated with pH, base saturation, Ca saturation, and Mg saturation, but Mg saturation in the ammonium sulfate experiment was not significant (Table 8). Aluminum saturation and acidity saturation had positive and significant association with grain yield, except that the Al saturation in the ammonium sulfate was not significant. The negative

**Table 8**
Relationship between soil acidity indices ($X$) and grain yield ($Y$) of ammonium sulfate and urea experiments

| Soil property | Regression equation | $R^2$ |
|---|---|---|
| | Ammonium sulfate experiment | |
| pH in $H_2O$ | $Y = 1577.61 – 1863.3680X$ | 0.2621** |
| Base saturation (%) | $Y = 8711.6960 – 104.9912X$ | 0.1901* |
| Ca saturation (%) | $Y = 8342.7040 – 133.8276X$ | 0.1739* |
| Mg saturation (%) | $Y = 7618.8560 – 232.3198X$ | $0.1122^{NS}$ |
| Al saturation (%) | $Y = 5432.0290 + 20.9815X$ | $0.0272^{NS}$ |
| Acidity saturation (%) | $Y = –1787.1090 + 104.9868X$ | 0.1901* |
| | Urea experiment | |
| pH in $H_2O$ | $Y = 27332.72 – 4149.7830X$ | 0.2070** |
| Base saturation (%) | $Y = 9259.0960 – 136.7193X$ | 0.3881** |
| Ca saturation (%) | $Y = 8678.0870 – 166.9514X$ | 0.2905** |
| Mg saturation (%) | $Y = 9825.5170 – 596.5399X$ | 0.5776** |
| Al saturation (%) | $Y = 2673.6630 + 346.2711X$ | 0.4238** |
| Acidity saturation (%) | $Y = –4412.9740 + 136.7215X$ | 0.3881** |

*,**,$^{NS}$ Significant at the 5% and 1% probability levels and nonsignificant, respectively.

association with pH, base saturation, and Ca and Mg saturation, as well as positive association with Al saturation and acidity saturation, indicates tolerance of rice crop to acidity. Fageria and Baligar (1999) reported that among important annual crops such as wheat, corn, soybean, and dry bean, rice is the most tolerant to soil acidity. Fageria and Santos (1998) reported that lowland rice grain significantly increased with increasing Al concentration in the range of 0 to 3.83 $\text{cmol}_c\ \text{kg}^{-1}$ of soil. Similarly, these authors also reported linear increase in lowland rice yield, when Al saturation in the soil was increased from 0 to 30%. The exact mechanism by which some plant species tolerate a high level of acidity is still debated. Several hypotheses have been suggested, but much research remains to be done to verify these hypothesis. Some important hypotheses are that (1) tolerant plants either prevent excess Al absorption by roots or detoxify Al after it has been absorbed (Foy 1984) and (2) acid-tolerant species or cultivars increase the growth medium pH and thus reduce Al solubility and toxicity. In contrast, acid-sensitive species or cultivars lower the pH of the growth medium, thereby increasing Al solubility and toxicity (Foy 1974), Al-tolerant species may control excess Al in roots and restrict its transport to shoots (Fageria and Carvalho 1982), and Al-tolerant plant species contain high levels of organic acids that chelate and detoxify Al within the plant (Foy 1974; Fageria, Baligar, and Wright 1988). Mendonça et al. (2005) reported that Al-tolerant rice cultivar showed a greater ability to adjust its cations balance, changing the pH to values that favored less Al uptake and greater tolerance to Al.

A genetic basis for acidity tolerance has been reported for many annual crops, including rice (Yang et al. 2004). Acidity tolerance in rice is reported to be controlled by multiple genes (Nguyen et al. 2002; Ma et al. 2002). Nguyen et al. (2001) detected a total of 20 QTLs, distributed over 10 of 12 rice chromosomes, that control root growth under Al stress, whereas Ma et al. (2002) found three putative quantitative trait locuses (QTLs) that control Al tolerance in Japonica rice on chromosomes 1, 2, and 6.

## Conclusions

Relative grain yield of lowland rice increased significantly by application of N by ammonium sulfate and urea. Grain yield had quadratic responses from both sources of N. Increasing N rates by both ammonium sulfate and urea fertilizers have a tendency to decrease soil pH, Ca and Mg saturation, and base saturation and increase Al saturation and acidity (H + Al) saturation. This means that both the fertilizers increase soil acidity. However, the magnitude of acidity increase was greater with the application of ammonium sulfate than with urea. Grain yield was significantly and negatively associated with pH, base saturation, and Ca saturation and significantly and positively associated with Al and acidity saturation. This indicates tolerance of rice plants to soil acidity.

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