Nitrogen Fertilizer Sources and Timing before Flooding Dry-Seeded, Delayed-Flood Rice

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Urea is the primary N source used for the large prefl ood N application in delayed-flood rice (Oryza sativa L.) production in the southern United States. Urea is prone to substantial NH$_3$ volatilization losses, however, if fields are not flooded quickly. Most delayed-flood rice fields require 5 to 10 d to flood. Consequently, a study was conducted to evaluate the use of less NH$_3$-volatile N sources for the prefl ood N application. The objectives were to evaluate the NH$_3$ volatilization loss and impact on N uptake and rice yield when urea, urea plus the urease inhibitor N-(n-butyl)thiophosphoric triamide (NBPT), (NH$_4$)$_2$SO$_4$ or a urea-(NH$_4$)$_2$SO$_4$ (UAS) blend were applied prefl ood and a fl ood established 1, 5, or 10 d after N application. When fl ooding was delayed for 5 or 10 d after N application, NH$_3$ volatilization was the least for urea + NBPT (2–10%) and (NH$_4$)$_2$SO$_4$ (4–5%) and they produced the highest rice N uptake and yield. The UAS blend that had NH$_3$ volatilization losses (11–15%) at 5 and 10 d after application that were intermediate between urea (17–24%) and (NH$_4$)$_2$SO$_4$ or urea + NBPT also had N uptake and grain yield intermediate between these N sources. Urea should only be used if ~2 d are required to flood a field. If 3 to 5 d are required to flood a field, then UAS has some merits but it is not as consistent as (NH$_4$)$_2$SO$_4$ or urea + NBPT. When >5 d are required to flood, (NH$_4$)$_2$SO$_4$ or urea + NBPT should be used.

Abbreviations: NBPT, N-(n-butyl)thiophosphoric triamide; UAS, urea–ammonium sulfate.

The early N fertilizer application in the dry-seeded, delayed-flood rice culture system should be applied as an NH$_4^+$ or NH$_4^+$–forming N source onto dry soil immediately before fl ooding, termed prefl ood N application, at around the four- to five-leaf growth stage (Norman et al., 2003). Once the prefl ood N fertilizer has been applied, flooding should be completed as quickly as possible, preferably within a few days. The fl oodwater moves the N fertilizer down into the soil profile and thus minimizes losses via NH$_3$ volatilization and nitrification–denitrification as long as a fl ood is maintained (De Datta and Patrick, 1986; Savin et al., 2007). The fl ood should be maintained for at least 3 to 4 wk to achieve maximum uptake of the prefl ood-applied N fertilizer (Wilson et al., 1989; Norman et al., 1992; Guindo et al., 1994).

Urea (460 g N kg$^{-1}$) is the primary N source used in the delayed-flood rice cultural system practiced in the southern United States (Norman et al., 2003). This is because of its high N analysis, ease of handling, and lower cost relative to other N sources. Although urea has many fine qualities, it also has the undesirable characteristic in that its rapid hydrolysis to NH$_4^+$ can lead to substantial NH$_3$ volatilization losses if not soil incorporated within a couple of days after surface application (Mikkelsen et al., 1978; Vlek and Craswell, 1979; Griggs et al., 2007). Most rice farmers cannot fl ood their fields within a few days following the prefl ood urea fertilizer application. Typically, 5 to 10 d are required to get the fl oodwater across the field. In a situation where a farmer cannot fl ood in a timely manner after the prefl ood N application, it would seem prudent to use an N source less prone than urea to NH$_3$ volatilization loss.

Ammonium sulfate (210 g N kg$^{-1}$) is an excellent N source that has slightly acidic properties and thus is less prone to NH$_3$ volatilization loss than urea (Vlek and Craswell, 1979). Bufogle et al. (1998) demonstrated that urea was equally effective as (NH$_4$)$_2$SO$_4$ as a prefl ood N source in supplying N to delayed-
Aly et al., 2001) with some measuring a significant grain
yield increase (Chaiwanakupt et al., 1996) while others mea-
sured no significant yield increase (Buresh et al., 1988; Freney et al., 1995; Aly et al., 2001). None of these rice studies evalu-
atuated urea applied with and without NBPT to an unsaturated soil surface at an unsaturated soil surface before flooding such as is practiced in delayed-flood rice. The only study with some similar-
ities to delayed-flood rice where NBPT has been evaluated was a greenhouse study with transplanted rice (Soliman and Abdel Monem, 1996). Soliman and Abdel Monem (1996) applied urea with and without NBPT to an unsaturated soil surface at an undesigned time before flooding and transplanting rice. They reported significantly greater N uptake by the transplanted rice when urea was applied with NBPT than when it was applied without NBPT.

A review of the refereed literature regarding the NH$_3$ volatilization loss of N fertilizer applied pre flood and the impact on the N uptake and grain yield of dry-seeded, delayed-flood rice found only the field study conducted by Griggs et al. (2007) evaluating urea and (NH$_4$)$_2$SO$_4$ applied pre flood. Griggs et al. (2007) indicated that substantial NH$_3$ volatilization loss of urea can occur even if the flood is delayed for just 5 d following urea application and that (NH$_4$)$_2$SO$_4$ is a viable substitute for urea when the flood cannot be established in <5 d. The minimal knowledge concerning NH$_3$ volatilization loss from the large pre flood application of urea in dry-seeded, delayed-flood rice coupled with the considerable knowledge of NBPT to mini-

Yield and Nitrogen Uptake Experiments

The short-statured, long-grain rice cultivar Wells (Moldenhauer et al., 2007) was chosen for use in both years of the study due to its high yield potential, N responsiveness, and widespread use in Arkansas. Rice was seeded at 120 kg ha$^{-1}$ in nine-row-wide plots (18-cm spacing) of 4.6 m in length on 16 Apr. 2003 and 26 Apr. 2004. The rice was grown upland until the four- to five-leaf growth stage and then a permanent flood (5–10-cm depth) was established on 4 June 2003 and 13 June 2004 and maintained until maturity. Weed growth was controlled by use of a tank mixture of 0.30 kg ha$^{-1}$ clomazone (2-[(2-chlorophenyl) methyl]-4,4-dimethyl-3-isoxazolidinone) plus 0.40 kg ha$^{-1}$ quinclorac (3,7-dichloro-8-quinolinocarbonyl acid) applied to the soil surface before rice emergence followed by a tank mixture of 4 kg ha$^{-1}$ propanil (N-(3,4-dichlorophenyl)propanamide) plus 0.04 kg ha$^{-1}$ bensulfuron methyl (methyl 2-[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl][amino]sulfonyl]methyl)benzoate) at the four-leaf stage and just before flooding.

Fertilizer N sources were: (i) urea; (ii) urea + NBPT; (iii) (NH$_4$)$_2$SO$_4$; and (iv) UAS. The UAS was a 1:1 urea-(NH$_4$)$_2$SO$_4$ blend on an N weight basis. Agrotain solution contains the NBPT urease inhibitor at a concentration of 200 g kg$^{-1}$ (Agrotain International, St. Louis, MO). The urea + NBPT source was prepared by blending 1 kg of prilled urea with 4.2 mL of Agrotain solution. Fertilizer N rates applied were 0 (control), 67, and 134 kg N ha$^{-1}$. The application times for the N fertilizers were 10, 5, and 1 d pre flood. All N fertilizers were applied by hand to a dry soil surface with no mechanical incorporation. The soil gravimetric water content at the time of N application averaged 0.18 and 0.23 kg water kg$^{-1}$ soil in 2003 and 2004, respectively.

Plant samples were collected from each plot by hand cutting the total aboveground biomass from a 1-m length of a second inside row at heading for determination of total N uptake. Plant samples were collected at heading for total N uptake because previous research has shown that maximum total N uptake in rice typically occurs at heading.

MATERIALS AND METHODS

Site Description

The study was conducted in 2003 and 2004 at the University of Arkansas Pine Tree Branch Experiment Station on a Calloway silt loam (a fine-silty, mixed, active, thermic Aquic Fraglossudalf) in fields that have been in a rice–soybean [Glycine max (L.) Merr.] rotation for the past few decades. The experimental site in 2003 had an average soil pH (1:2 soil/water suspension) of 7.3, Mehlich-3-extractable P of 26 mg P kg$^{-1}$, and Mehlich-3-extractable K of 126 mg K kg$^{-1}$, and the experimental site in 2004 had an average soil pH (1:2 soil/water suspension) of 7.6, Mehlich-3-extractable P of 24 mg P kg$^{-1}$, and Mehlich-3-extractable K of 119 mg K kg$^{-1}$. Since soil analyses indicated that soil P and K concentrations were sufficient for optimum rice growth for both experimental sites, no P and K fertilizer was applied (Slaton, 2001). Due to high soil pH, 10 kg Zn ha$^{-1}$ as granular ZnSO$_4$ was applied to the experimental sites immediately before seeding.
Two foam sorbers were used in each chamber. The first sorber was placed 15 cm below the top of the chamber to trap the NH₃ volatilized from the NH₃ source. The washed foam sorbers were impregnated with 20 mL of a 0.73 mol L⁻¹ H₃PO₄–33% glycerine (v/v) solution to trap the NH₃. This volume was sufficient to saturate the foam sorber evenly but not drip from the sorber or leach down the sides of the chamber. Foams sorbers were washed with deionized water and randomly extracted with 100 mL of 2 mol L⁻¹ KCl solution overnight and extracted by hand squeezing each sorber. A 50-mL aliquot of the 2 mol L⁻¹ KCl extract was steam distilled for determination of NH₄⁺–N by acidimetric titration according to Mulvaney (1996). The volatilization data were analyzed for each year separately. For each year, the design was a split plot in which the whole plot was a randomized complete block with three blocks and four N sources. The split-plot factor was sampling time. Ammonia volatilization means were separated using a LSD at \( P = 0.05 \) following a significant \( F \) test in the analysis of variance. All analyses were performed using SAS 9.1.

### RESULTS AND DISCUSSION

The weather in both years of the study was quite conducive during the 10 d before flooding for measuring and comparing the NH₃ volatilization potential of N fertilizer sources under field conditions. No measurable precipitation occurred to incorporate the N fertilizers and minimize NH₃ volatilization during the 10 d before flooding in either year and the air temperature appeared typical. The air temperatures during the 20-d NH₃ volatilization measurement period in 2003 consisted of lows ranging from 16 to 24°C and highs ranging from of 27 to 34°C, which resulted in an average air temperature range of 22 to 29°C. In 2004, the air temperatures during the 20-d measurement period had lows ranging from 13 to 23°C and highs ranging from 24 to 32°C, with an average temperature range of 19 to 27°C.

### Ammonia Volatilization

The N source \( \times \) sampling time interaction was significant \( (P < 0.0001) \) in both years of the study (Table 1). Significant amounts of NH₃ volatilization were measured from all the N sources except urea + NBPT by the first sampling time, 2 d after N fertilization, in both years. Initially, urea and UAS lost similar amounts of NH₃ and significantly more than urea + NBPT. Generally, hydrolysis of urea when applied without a urease inhibitor requires just a few days to exceed the ability of the soil to buffer the NH₃ formed through conversion to the stable NH₄⁺ ion (Beyrouty et al., 1988; Clay et al., 1990; Griggs et al., 2007). The use of NBPT has been shown to minimize NH₃ volatilization of urea for at least a week after application to the soil (Bremner and Chai, 1989; Clay et al., 1990). Use of NBPT in combination with urea significantly decreased volatilization, compared with urea alone.

### Table 1. Cumulative NH₃ volatilization losses from urea, urea + UAS, urea + NBPT (N-(n-butyl)thiophosphoric triamide), (NH₄)₂SO₄ (AS), and a urea–AS (UAS) blend applied to a silt loam soil in 2003 and 2004.

<table>
<thead>
<tr>
<th>Time after application</th>
<th>Cumulative NH₃ volatilization losses</th>
<th>2003†</th>
<th>2004‡</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Urea</td>
<td>Urea + NBPT</td>
</tr>
<tr>
<td>d</td>
<td>% of applied N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>8.1</td>
<td>0.1</td>
<td>3.2</td>
</tr>
<tr>
<td>5</td>
<td>20.7</td>
<td>2.2</td>
<td>4.7</td>
</tr>
<tr>
<td>10§</td>
<td>24.4</td>
<td>9.8</td>
<td>5.3</td>
</tr>
<tr>
<td>15</td>
<td>25.6</td>
<td>12.0</td>
<td>5.5</td>
</tr>
<tr>
<td>20</td>
<td>25.6</td>
<td>12.0</td>
<td>5.6</td>
</tr>
</tbody>
</table>

† LSD(0.05) for 2003 to compare means between days within the same N source = 0.7% and to compare means from different N sources = 3.1%.

‡ LSD(0.05) for 2004 to compare means between days within the same N source = 0.9% and to compare means from different N sources = 2.8%.

§ Permanent flood was established.
Within the first 2 d of application, (NH₄)₂SO₄ volatilized about one-half of the total NH₃ lost from this N source during the 20-d sampling period, which agrees with Griggs et al. (2007). Ammonia volatilization from (NH₄)₂SO₄ after 2 d was numerically about one-half that of urea and the UAS blend in both years. Unlike urea, which requires a few days to hydrolyze, the reaction of (NH₄)₂SO₄ is immediate on dissolution. Thus, it is not unusual for most of the NH₃ volatilized from (NH₄)₂SO₄ to be measured within the first few days after application as the (NH₄)₂SO₄ dissolves and acidifies the soil around the granule. Griggs et al. (2007), in a similar study, measured soil surface pH values ranging from 6.6 to 8.4 in the area where urea had been applied, but measured lower soil surface pH values of 5.0 to 5.9 where (NH₄)₂SO₄ had been applied.

Ammonia volatilization from urea and the UAS blend increased substantially between 2 and 5 d after application (Table 1). By 5 d after application, urea volatilized about one-third more NH₃ than the UAS blend, which lost three and six times more than (NH₄)₂SO₄ and urea + NBPT, respectively, in both years. Urea + NBPT and (NH₄)₂SO₄ lost <5% of the N due to NH₃ volatilization by 5 d after application. Cumulative NH₃ losses from (NH₄)₂SO₄ 5 d after application were not significantly higher than urea + NBPT. Most (81–85% of total volatilized NH₃) of the NH₃ volatilized from the N sources during the 20-d monitoring period occurred within the first 5 d of application in both years, the only exception being urea + NBPT.

Ammonia volatilization from the N sources essentially ended at 10 d after N fertilizer application due to the establishment of the permanent flood. Griggs et al. (2007) determined that NH₃ volatilization from urea and (NH₄)₂SO₄ applied to a similar silt loam soil was basically over by 10 d after application and ended when the flood was established at 14 d after application. By 10 d after application, urea had cumulative NH₃ volatilization losses of 24.4% in 2003 and 20.5% in 2004, which were significantly greater than losses from the other N sources (Table 1). The loss of N from the UAS blend was about equidistant between the losses measured from urea and (NH₄)₂SO₄. The addition of NBPT to the urea delayed most of the NH₃ volatilization loss until 5 to 10 d after application but also resulted in significantly less total N loss via NH₃ volatilization than urea alone or the UAS blend. Ammonium sulfate lost the least amount of N, with cumulative NH₃ volatilization losses during the 10 d before flooding of about one-half that of urea + NBPT and one-fifth that of urea. Mikkelsen (1987) reported that (NH₄)₂SO₄ was much less susceptible to NH₃ volatilization than urea. Griggs et al. (2007) measured little loss of (NH₄)₂SO₄ and substantial losses of urea via NH₃ volatilization from a silt loam soil before flooding.

During the 10 d that NH₃ volatilization was monitored after flooding, no significant increase in loss was measured from (NH₄)₂SO₄ or UAS in either year or urea in 2004 (Table 1). The NH₃ volatilized after flooding from urea + NBPT, however, although significant, was only 2.2 and 1.2% of the applied N in 2003 and 2004, respectively, and 1.2% of the applied N from urea in 2003. Griggs et al. (2007) measured no significant NH₃ volatilization loss from urea and (NH₄)₂SO₄ after the flood was established. Savin et al. (2007) demonstrated, using intact soil cores, that the floodwater could incorporate (NH₄)₂SO₄ and especially urea several centimeters below the soil surface and terminate NH₃ volatilization when the N fertilizers were applied to a dry silt loam soil.

Table 2. Influence of the N rate and N source interaction, averaged across preflod N application time, on N uptake by rice sampled at heading in 2003.

<table>
<thead>
<tr>
<th>N rate kg N ha⁻¹</th>
<th>N uptake</th>
<th>N rate kg N ha⁻¹</th>
<th>N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urea</td>
<td>98</td>
<td>Urea + NBPT</td>
<td>116</td>
</tr>
<tr>
<td>67</td>
<td>141</td>
<td>116</td>
<td>164</td>
</tr>
<tr>
<td>134</td>
<td>164</td>
<td>(NH₄)₂SO₄</td>
<td>163</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UAS blend</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LSD(0.05)</td>
<td>9</td>
</tr>
</tbody>
</table>

† NBPT, N-(n-butyliithiophosphoric triamide; AS, (NH₄)₂SO₄; UAS, urea–(NH₄)₂SO₄.
10 kg N ha\(^{-1}\) was obtained at the 134 kg N ha\(^{-1}\) rate, however, when the flood was delayed from 1 to 5 d and from 5 to 10 d.

No significant difference in N uptake by rice occurred among the four N sources when they were applied 1 d before flooding (Table 4). When the time between the N application and flooding was increased from 1 to 5 d, a significant decrease in N uptake was measured for urea, but not for urea + NBPT, (NH\(_4\))\(_2\)SO\(_4\) or UAS. A further delay between N application and flooding from 5 to 10 d caused a significant decrease in N uptake when urea and UAS were the N sources, but not when urea + NBPT or (NH\(_4\))\(_2\)SO\(_4\) were used.

A significant interaction of N rate × N source × N application time for N uptake by rice was obtained in 2004 (Table 5). Also, a higher native soil N availability in 2004 than 2003 (Tables 2–4), as indicated by N uptake when no N was applied, caused all of the treatments to have numerically higher N uptake in 2004 (Table 5). Similar to 2003, rice N uptake in 2004 increased as the N rate increased for all N sources at each of the three application times. In addition, N uptake was not significantly different among the N sources when they were applied 1 d before flooding at each of the application rates in 2004. When the flood was delayed until 5 d after the N fertilizer application, urea + NBPT and (NH\(_4\))\(_2\)SO\(_4\) resulted in similar N uptake compared with when the flood was delayed only 1 d after N application at each of the N rates. Urea and the UAS blend, however, had significantly less N uptake when they were applied 5 d before flooding compared with 1 d at the 134 kg N ha\(^{-1}\) rate, but not at the 67 kg N ha\(^{-1}\) rate. Urea + NBPT and (NH\(_4\))\(_2\)SO\(_4\) had greater N uptake than urea when applied 5 d before flooding at each of the N application rates. The UAS blend applied 5 d before flooding resulted in an N uptake by rice not significantly greater than urea or lower than urea + NBPT or (NH\(_4\))\(_2\)SO\(_4\) when 67 kg N ha\(^{-1}\) was applied. When 134 kg N ha\(^{-1}\) was applied 5 d before flooding, the UAS blend resulted in less N uptake than urea + NBPT.

### Table 5. Influence of the N source, N rate, and prefluood N application time interaction on N uptake by rice sampled at heading in 2004.

<table>
<thead>
<tr>
<th>N source†</th>
<th>67 kg N ha(^{-1})</th>
<th>134 kg N ha(^{-1})</th>
<th>N uptake‡</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 d prefluood</td>
<td>5 d prefluood</td>
<td>10 d prefluood</td>
</tr>
<tr>
<td>Urea</td>
<td>145 133</td>
<td>125 194</td>
<td>158 153</td>
</tr>
<tr>
<td>Urea + NBPT</td>
<td>148 144</td>
<td>192 185</td>
<td>172</td>
</tr>
<tr>
<td>AS</td>
<td>150 146</td>
<td>187 189</td>
<td>177</td>
</tr>
<tr>
<td>UAS blend</td>
<td>149 137</td>
<td>185 164</td>
<td>161</td>
</tr>
</tbody>
</table>

† NBPT, N-(\(\text{n-butyl}\))thiophosphoric triamide; AS, (NH\(_4\))\(_2\)SO\(_4\); UAS, urea–(NH\(_4\))\(_2\)SO\(_4\).
‡ N uptake was 105 kg N ha\(^{-1}\) when no N fertilizer was applied.

Grain Yield

The N rate × N source × N application time interaction for rice grain yield was significant in 2003 (\(P = 0.0476\)) and 2004 (\(P = 0.0043\)). The much larger grain yields in 2004 compared with 2003 (Table 6) can be attributed to the higher native soil N availability in 2004 (Tables 2, 3, and 5). Rice grain yields increased as N fertilizer rate increased for all of the N sources at each application time in both years (Table 6). Grain yield results for the different...
N sources, rates, and application times reflected the total N uptake results (Tables 2–5) quite well. Grain yield was similar for the different N sources within each application rate when the N sources were applied 1 d before flooding (Table 6). Significant grain yield differences were measured between some of the N sources when they were applied 5 and 10 d before flooding, which matched the N uptake differences between the N sources at these application times. Ammonium sulfate and urea + NBPT had the highest grain yield when the flood was delayed for 5 or 10 d and these two N sources almost always resulted in the highest N uptake by rice when the flood was delayed for 5 or 10 d. The UAS blend usually had a grain yield intermediate between urea and (NH₄)₂SO₄ or urea + NBPT and typically resulted in an intermediate N uptake by rice that at times could rival the N uptake produced when urea + NBPT was the N source and at times was not significantly better than urea. Urea applied 5 and 10 d before flooding always resulted in rice with significantly lower N uptake and grain yield compared with (NH₄)₂SO₄ and urea + NBPT, and was frequently lower than UAS but not always. Similarly, Griggs et al. (2007), working in delayed-flood rice, reported that (NH₄)₂SO₄ applied 14 d before flooding resulted in N uptake and grain yield by rice comparable to urea applied 1 d before flooding and significantly greater than urea applied 14 d before flooding. Studies evaluating urea with and without NBPT applied into the floodwater of transplanted, lowland rice have reported measuring a significant grain yield increase when urea was applied with NBPT (Chaiwanakupt et al., 1996), while others measured no significant yield increase (Buresh et al., 1988; Freney et al., 1995; Aly et al., 2001).

CONCLUSIONS

The N uptake and grain yield of rice were at a maximum and similar among the four N sources when the flood was applied 1 d after N application. This indicates that a flood applied quickly after N application minimizes NH₃ volatilization loss and maximizes the N uptake and grain yield potential of delayed-flood rice. Ammonia volatilization of urea increased substantially between 2 and 5 d after application and usually resulted in significantly less N uptake and grain yield than the less volatile (NH₄)₂SO₄ or urea + NBPT when the flood was delayed for 5 or more d. The UAS blend, which had NH₃ volatilization losses intermediate between urea and (NH₄)₂SO₄ or urea + NBPT when the flood was delayed for 5 and 10 d, also had N uptake and grain yield intermediate between these N sources for these flood establishment times. The practical conclusions and recommendations that can be drawn from this study to minimize NH₃ volatilization loss and maximize uptake of N applied pre flood to delayed-flood rice are: (i) urea is very prone to NH₃ volatilization loss when applied to a silt loam soil and to minimize this loss a permanent flood should be applied in ~2 d after urea application; (ii) if 3 to 5 d are required to flood a field, then the UAS blend has some merits but it is not as consistent as (NH₄)₂SO₄ or urea + NBPT; and (iii) if >5 d are required to flood a field, then (NH₄)₂SO₄ or urea + NBPT should be used.

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REFERENCES


Campbell, C.R. 1992. Determination of total nitrogen in plant tissue by


