



Urease inhibitor reduces ammonia volatilization and increases rice grain yield under irrigation delay

Filipe Selau Carlos · Roberta Jeske Kunde · Rogerio Oliveira de Sousa · Cristiano Weinert · André da Rosa Ulguim · Fernando Viero · Iuri Rossi · Marina Patel Buchain · Cacio Luiz Boechat · Flávio Anastácio de Oliveira Camargo

Received: 23 May 2021 / Accepted: 25 March 2022 / Published online: 31 March 2022
© The Author(s), under exclusive licence to Springer Nature B.V. 2022

Abstract Nitrogen is the most limiting element for the development of rice. However, under irrigated rice growing conditions, there is a recurrent delay in irrigation, which increases ammonia losses. Additionally, there is a gap between the effect of urease inhibitors and the delay of irrigation, affecting agronomic efficiency and rice yields. The objective of this work was to evaluate the ammonia volatilization and the grain yield of medium and short cycle cultivars when combining urease inhibitors and irrigation delay. The experiment was based on a double factorial, where factor 1 consisted of type of N fertilizer, urea and urea + N-(n-Butyl) thiophosphoric

triamide (NBPT) and factor 2 consisted in irrigation establishing times: V3 (third leaf fully expanded), V3+7, V3+14 and V3+21 days. The experiment was conducted in 2016/17 and 2017/18. The accumulated volatilization, in the average of the irrigation times, was 7% and 4% to urea and urea + NBPT, respectively. In each day of irrigation delay, there was a grain yield loss of 158 and 83 kg day⁻¹ ha⁻¹, with urea and urea + NBPT, respectively. The grain yield loss of the short cycle cultivar due to irrigation delay was 12% larger than the one observed for the medium cycle and even larger when urea was used. Thus, the use of NBPT is a relevant strategy to mitigate the volatilization of ammonia, increase agronomic efficiency and grain yield of the crop when there is a delay in the irrigation.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10705-022-10203-7>.

F. S. Carlos (✉) · R. J. Kunde · R. O. de Sousa · C. Weinert
Federal University of Pelotas, Pelotas, Brazil
e-mail: filipeselaucarlos@hotmail.com

A. da Rosa Ulguim
Federal University of Santa Maria, Santa Maria, Brazil

F. Viero · F. A. de Oliveira Camargo
Federal University of Rio Grande Do Sul, Porto Alegre, Brazil

I. Rossi · M. P. Buchain
Lutheran University of Brazil, Canoas, Brazil

C. L. Boechat
Federal University of Piau, Bom Jesus, Brazil

Keywords Nitrogen loss · Agronomic efficiency · Irrigation management · *Oryza sativa*

Introduction

Nitrogen (N) is the most limiting element in the development of rice plants due to the low organic matter level of most soils cultivated with rice (Martins et al. 2017; Carlos et al. 2021). Also, this element is subjected to many loss processes such as volatilization, leaching and denitrification (Zhao et al. 2013; Nash et al. 2015). Some studies have observed ammonia volatilization losses of 10–14% (Pan et al. 2016),

however in more extreme conditions losses can be up to 25% (Misselbrook et al. 2014; Adhikari et al. 2020). Ammonia volatilization can be even higher depending on the N source, such as urea, a high N content and low effective cost fertilizer (Minato et al. 2020). After its application to the soil, urea is immediately hydrolyzed by the enzyme urease which results in the formation of ammonium carbonate, which rapidly decomposes into ammonium, bicarbonate and hydroxyls, significantly increasing pH values around the fertilizer granules (8.5 to 8.8) (Phongpan et al. 1995; Pan et al. 2016). The increase in pH around the granule accelerates the conversion of this ammonium to ammonia, which can be volatilized into the atmosphere (Viero et al. 2015; Ke et al. 2017).

In irrigated rice, flooding is a strategy that reduces N losses and improves the efficiency of N fertilization (Carlos et al. 2021). When applying urea to the dry soil and establishing the water layer immediately afterwards, the downward movement of the water incorporates N into the soil, reducing losses due to volatilization (Liu et al. 2020b). However, it is not always possible to establish the water layer in the entire crop in a timely manner, in order to avoid N losses through ammonia volatilization, since irrigation should occur three to five days after the application of N fertilization (Xu et al. 2012). After this period, the urea deposited on the soil surface is exposed to losses, which may contribute to a reduction in grain yield (Liu et al. 2020a). One way to get around this problem is to use urea formulations plus urease inhibitors (Zaman et al. 2008; Chatterjee 2018). Several chemical compounds have been evaluated for their effectiveness in reducing ammonia emissions from N fertilizers by inhibiting the urea hydrolysis process (Rose et al. 2018) and the consequent impacts on grain yield (Abalos et al. 2014; Rose et al. 2018). Thus, urease inhibitors have been used as promising chemical additives in reducing urease activity by delaying urea hydrolysis for 7 to 10 days (Puga et al. 2020), and therefore decreasing losses through ammonia volatilization (Chatterjee 2018; Abed et al. 2020). In the case of irrigated rice, the delay in urea hydrolysis by the action of inhibitors contained in the fertilizer would allow a longer time for the establishment of the water layer in the entire crop, resulting in a reduction of N losses, an increase in the efficiency of use of the N and grain yield (Scivittaro et al. 2010). In addition, the length

of the cultivar cycle may have an influence on the use of urease inhibitors and the delay in irrigation (Silva et al. 2017). The ill combination of irrigation delay and the use of conventional urea can be more effectively detected in short rather than medium cycle cultivars. However, there is still a great knowledge gap regarding the losses due to ammonia volatilization under irrigation delay in rice cultivation with the use of short and medium cycle cultivars.

The hypothesis of this work is that losses from ammonia volatilization, due to the delay in the establishment of the water layer in rice, is reduced by the use of urease inhibitor N- (n-butyl)thiophosphoric triamide (NBPT) which provides greater availability of mineral N in the soil and provides greater rice grain yield. Thus, the objective of this work was to evaluate the volatilization of ammonia and the grain yield of rice grains under the use of urea + NBPT under different times of establishment of the irrigation for two seasons.

Material and Methods

Site description

The experiment was conducted at the Rio Grande do Sul Rice Institute experimental station. The experimental area is located at 29°57'02" S and 51°05'02" W at 7 m elevation. The soil was classified as Entisol (Endoaquent) (US Soil Taxonomy 1999) which has 200 g kg⁻¹ of clay; pH (1:1 soil:water ratio) 5.3; 10 mg kg⁻¹ of P; 42 mg kg⁻¹ of K; 3.1 cmol_c kg⁻¹ of Ca, 1.2 cmol_c kg⁻³ of Mg and 17 g kg⁻¹ organic matter in the 0–0.20 m layer.

Experimental Design

The experimental design was random blocks in split-plot design with the treatments arranged in a 4×2 factorial scheme. Factor 1 consisted of different irrigation start times, V3 (third leaf fully expanded) (Counce et al. 2000), V3+7 days, V3+14 days and V3+21 days. Irrigation times (factor 1) were allocated to the main plots. Factor 2 consisted of two N fertilizers, urea and urea + N- (n-butyl)thiophosphoric triamide (NBPT). These nitrogen sources were allocated in the sub-plot. The first application of N in top dressing was carried out at the three fully expanded

leaf stage, which represents the V3 stage (Counce et al. 2000). The experimental units were plots with a width of 9 rows with 0.17 m spacing, totaling a width of 1.53 m. The length of the plot was 5 m, totaling an area of 7.65 m². The design used was randomized blocks with 4 replications. The sowing method used was in dry soil with a tractor-tractioned plot seeder. In 2017/18, the experiment was conducted in the same location and similarly to the 2016/17 crop season. However, a short cycle cultivar, IRGA 430 (120 days), was inserted, in addition to the cultivar IRGA 424 RI (135 days), which was also used during the first year of the experiment.

The seeding density used was 100 kg ha⁻¹. The fertilizer application throughout the cycle was of 166, 30 and 90 kg ha⁻¹ of N, P and K, respectively. N fertilization, using urea and urea plus NBPT, was divided in applications of 16 kg N ha⁻¹ at the time of sowing, and 100 and 50 kg ha⁻¹ of N in top dressing at the phenological stages V3 and R0 (beginning of floral primordium differentiation) (Counce et al., 2000), respectively.

Ammonia collection and analysis

Ammonia volatilization collections were carried out in the 2016/17 and 2017/18 crop seasons according to the methodology proposed by Viero et al. (2015) using static semi-open collectors. The collectors were composed of PVC columns 150 mm in diameter, with circular sponges 150 mm in diameter and 20 mm in height, which were allocated internally in the PVC column at heights of 0.25 and 0.30 m, both being saturated with 60 mL of phosphoric acid solution (50 ml L⁻¹) and glycerin (40 ml L⁻¹). The sponge allocated at 0.25 m was used to capture volatile NH₃ and the sponge allocated at 0.30 m was used to prevent the entry of ammonia outside the PVC chamber (Supplementary online material). As 9 collections were carried out over time, 9 PVC bases were used in the soil with 0.05 m in height where the NH₃ capture chambers were positioned (Supplementary online material). Nitrogen at an equivalent dose of 100 kg N ha⁻¹ was applied on the same day at stage V3 in all bases. At each collection, the sponge was replaced with a new solution containing phosphoric acid and glycerin. The amount of volatilized ammonia was determined by steam entrainment in a Kjeldahl semi-micro device (Tedesco et al. 1995). Ammonia

collections were performed at 1, 2, 3, 4, 7, 9, 11, 14 and 16 days after N fertilization. The ammonia contents were expressed as daily volatilization rates and the amount of accumulated volatilization that results from the sum of the daily ammonia volatilization rates. Ammonia volatilization collections were made in the first application of N, where the highest proportion of N (67%) is applied in the soil with moisture in the field capacity. The meteorological data of rainfall that influence ammonia volatilization are shown in Fig. 1. The average temperatures in November 2016 and 2017 were 20.9 and 20.7 °C, respectively.

Plant biomass, chlorophyll index, grain yield and agronomic efficiency (AE)

To determine the amount of plant biomass, plants were collected above the soil surface in an area of 0.5 × 0.5 m (0.25 m²) in each experimental plot in the phenological stage of full flowering, R4 (Counce et al. 2000). The material was dried in an oven at 50°C until reaching constant weight, subsequently, the weight measurement was made. The chlorophyll content was determined using the Falker chloroFILOG model CFL 1030 equipment. The chlorophyll content of the central region of the flag leaf of 4 plants per plot was quantified at the end of the crop season, at the phenological stage of R0 (Counce et al. 2000).

To quantify the grain yield data in each plot, an area of 1.2 × 4 m was collected, totaling 4.8 m². Afterwards, these samples were traced, impurities were removed by ventilation and weight and humidity measures were used to determine the grain yield at 13% humidity.

To calculate the Agronomic Efficiency (AE), the grain yield in the respective irrigation time and type of N fertilizer was calculated and subtracted from the control treatment dose (0 N), divided by the N dose used, Eq. 1. A control treatment without nitrogen application (0 kg N ha⁻¹) was used at all times of irrigation establishment to calculate the Agronomic Efficiency.

$$AE = \frac{Yeldf - Yeld0}{FertilizerN} \quad (1)$$

where, Yeldf: grain yield in the N dose used, Yeld0: grain yield in the control treatment and Fertilizer N: N dose used.

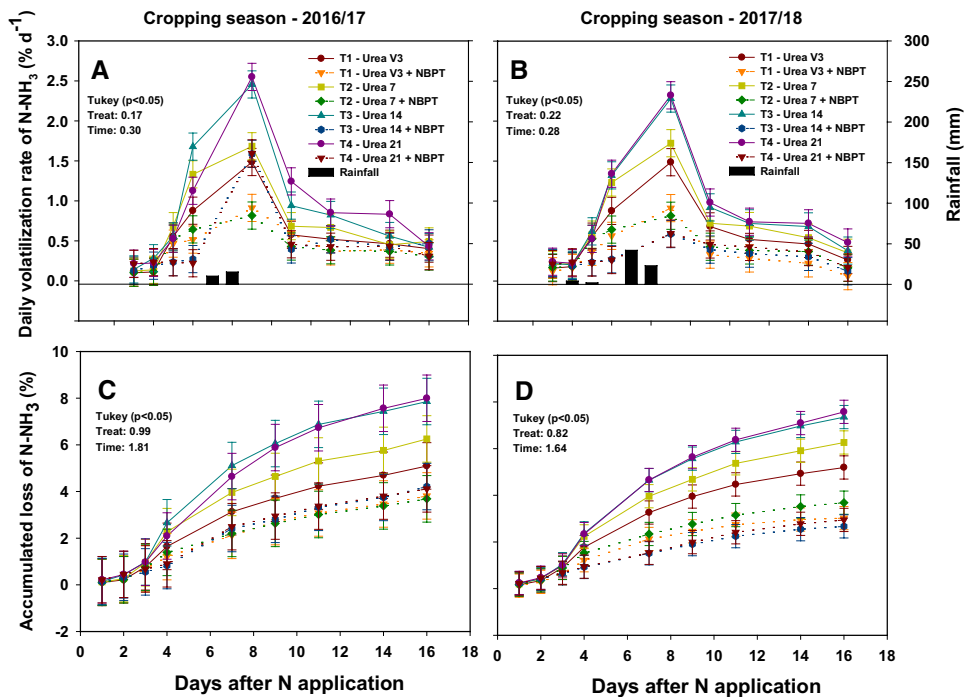


Fig. 1 Daily volatilization rate of N-NH_3 **a** and **b** and accumulated loss of N-NH_3 **c** and **d** under irrigation delay and urea+NBPT in medium and short cycle cultivars in the crop seasons 2016/17 and 2017/18. Vertical bars indicate

the minimum significant difference. Treat: treatment. Tukey ($p < 0.05$). (—) continued line: urea and (---) dashed line: urea+NBPT. Vertical bars indicate standard deviation

Statistical analysis

Levene's test was used to assess the homogeneity of variances. The normality of the data was assessed by the Shapiro–Wilk test and subsequently, following the assumptions of normality, the data on ammonia emission and grain yield were subjected to analysis of variance (ANOVA), and when significant ($p < 0.05$) the data were fitted to the linear regression model with significance evaluation at $p < 0.05$. When used, the average test was performed with the tukey test ($p < 0.05$). All data analysis was conducted in the R statistical environment with particular use of the packages *nlme* and *ggplot2* (R Core Team 2020). Principal component analysis was carried out where all the attributes and parameters of the analyzed plants were vectored to better understand the variations observed regarding the cultivar cycle and the N dose. For PCA analysis, the statistical software R was used.

Results

Ammonia volatilization

The irrigation delay and the use of conventional urea increased the daily rate of volatilization of ammonia (Table 1) (Fig. 1A and B) and consequently affected the accumulated loss of ammonia (Fig. 1C and D). Both the daily rate and the accumulated loss were higher when fertilization with conventional urea was carried out. In addition, the highest losses of ammonia occurred on the 7th day after the application of N fertilizers, reaching peaks of up to $2.5 \text{ kg ha}^{-1} \text{ day}^{-1}$, in both growing seasons (Fig. 1A and B). Considering that the applied rate of N as top dressing was 100 kg ha^{-1} until the moment of water flow into the system, it was verified that the periods of establishment of the irrigation layer and the type of N fertilizer used had a significant effect on the proportion loss of accumulated ammonia (Fig. 1B and D). In

Table 1 Accumulated nitrogen losses on the 16th day after the application of nitrogen fertilization using urea and urea+NBPT in irrigated rice under irrigation delay in the 2016/17 and 2017/18 crop seasons

Accumulated ammonia volatilization (%)					
Crop Season 2016/17					
Days of irrigation delay after nitrogen fertilization in V3					
	1	7	14	21	\bar{X}
Urea	5.1 Ac	6.3 Ab	7.9 Aa	7.9 Aa	6.8 A
Urea+NBPT	3.8 B ^{ns}	4.2 B	4.1 B	3.9 B	4.2 B
Crop Season 2017/18					
	1	7	14	21	\bar{X}
Urea	5.2 Ac	6.2 Ab	7.3 Aa	7.6 Aa	6.6 A
Urea+NBPT	3.0 B ^{ns}	3.6 B	2.7 B	3.3 B	3.2 B

* Uppercase letters compare in the column and lowercase in the row. Tukey test ($p < 0.05$). ^{ns}: no statistical difference

the 2016/2017 growing season, conventional urea under 14 and 21-days delay had average accumulated losses of about 8 kg ha⁻¹, which is equivalent to 8% of the applied N. On the other hand, when establishing the irrigation layer immediately after the application of N fertilizer in stage V3 and V3+7 days, the average losses of ammonia from conventional urea were 5.1 and 6.3% of the applied N, respectively. In the 2017/2018 growing season, treatments with conventional urea under 14 and 21-days delay showed average accumulated losses of 7.6 kg ha⁻¹, which are equivalent to 7.5%. The accumulated losses of urea+NBPT were not influenced by the delay in irrigation in both crop seasons. Under the delay of 21 days from the establishment of the water layer, the losses resulting from the use of urea+NBPT were less than half compared to conventional urea. The average losses in the two agricultural years, regardless of delay time, was 6.7% with conventional urea and 3.7% with urea+NBPT (Table 1).

Plant biomass, chlorophyll index, grain yield and Agronomic Efficiency (AE)

The shoot plant biomass content of rice plants was influenced by N fertilizer and irrigation delay. When irrigation was carried out in V3, the biomass production of rice plants was at the level of 20 Mg ha⁻¹. On the other hand, with delay in establishing irrigation by 14 and 21 days, more extreme conditions, 15 Mg ha⁻¹ biomass was observed (Fig. 2a). In the delays in

establishing irrigation between 7 and 14 days, a clear difference was observed between the higher production of plant biomass in the rice shoots due to the use of urea+NBPT (Fig. 2a). The chlorophyll index followed the trend observed in plant biomass (Fig. 2b). In the most pronounced irrigation delays of 7 and 14 days, lower levels of chlorophyll were observed (Fig. 2b). When urea was used in the fertilization of rice and irrigation delay of 21 days, a reduction of 10% in the chlorophyll index was observed in comparison to irrigation in V3 (Fig. 2a). When fertilizing with urea+NBPT, this reduction was only 5%.

The delay in establishing the irrigation layer negatively influenced the grain yield in the two growing seasons (Table 2). However, it was found that the reduction in grain yield was lower when urea+NBPT was used, with a decrease of 79.9 to 103.6 kg ha⁻¹ of grains per day of delay (Fig. 3). On the other hand, with the application of urea, this reduction ranged from 88.3 to 257 kg ha⁻¹ of grains per day of irrigation delay. In other words, with the use of urea, there is a daily loss of 157.5 kg day⁻¹ and using urea+NBPT this loss is 82.7 kg day⁻¹. This corresponds to a 47.5% reduction in losses due to the use of the NBPT inhibitor. For the short cycle cultivar, regardless of the use of urease inhibitor, the daily grain yield losses due to the irrigation delay were 180 kg day⁻¹ of grains, while in the medium cycle cultivar the grain yield loss was 72 kg day⁻¹ of grains. This condition means that after a period of irrigation delay of 21 days the losses of grain yield

Fig. 2 Dry matter **a** and chlorophyll index **b** of rice irrigated under urea and urea + NBPT and irrigation delay in crop seasons 2016/17 and 2017/18. Bands indicate a 95% confidence interval

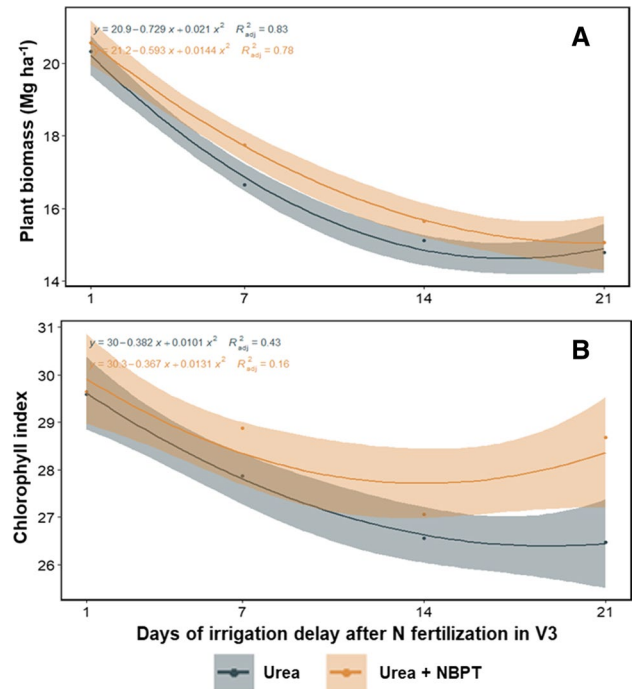
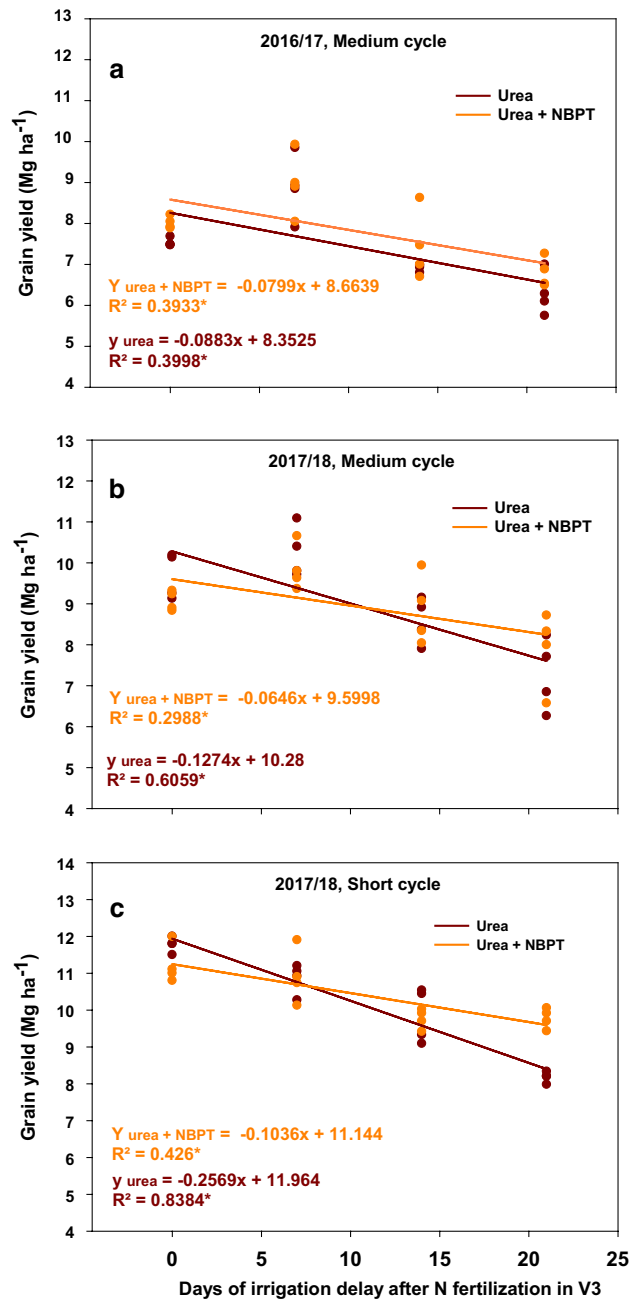


Table 2 Rice grain yield after application of nitrogen fertilization with urea and urea + NBPT under irrigation delay in the 2016/17 and 2017/18 crop seasons

	Grain yield (Mg ha ⁻¹)			
	Crop Season 2016/17 – Medium cycle			
	Days of irrigation delay after nitrogen fertilization in V3			
	1	7	14	21
Urea	7.5 b*	8.9 a	6.9 bc	6.3 c
Urea + NBPT	8.0 b	9.0 a	7.4 bc	6.8 c
	Crop Season 2017/18 – Medium cycle			
	Days of irrigation delay after nitrogen fertilization in V3			
		1	7	14
Urea	9.7 ab	10.2 a	8.6 b	7.3 c
Urea + NBPT	9.1 ab	9.9 a	8.9 b	7.9 c
	Crop Season 2017/18 – Short cycle			
	Days of irrigation delay after nitrogen fertilization in V3			
		1	7	14
Urea	11.8 a	10.8 b	9.9 c	8.2 d
Urea + NBPT	11.2 a	10.9 a	9.8 b	9.7 b

*Tukey test ($p < 0.05$)

Fig. 3 Grain yield of irrigated rice under irrigation delay and use of urea and urea + NBPT in medium and short cycle cultivars in the crop seasons 2016/17 and 2017/18. * Indicate statistical difference at the level of $p < 0.05$



under irrigation delay are 32.8 and 20.5% in the short and medium cycle cultivars, respectively.

The AE was affected by the use of urea + NBPT and by the delay in irrigation (Fig. 4). When irrigation was established in V3, AE was similar to 26 and 24 kg grains kg N⁻¹ for urea and urea + NBPT, respectively. However, with the delay in irrigation, the reduction in AE decreased significantly with the

sole use of urea. AE is not influenced by the days of delayed irrigation with the use of urea + NBPT. Per day of delayed irrigation using conventional urea, a reduction of 0.48 kg of grains was observed per kg of N used in fertilization (Fig. 4).

Pearson’s correlation showed a positive relationship between AE, plant biomass and chlorophyll with the yield of irrigated rice grains (Fig. 5). On the other

Fig. 4 Agronomic efficiency in irrigated rice under nitrogen fertilization with urea and urea + NBPT under irrigation delay after nitrogen fertilization in stage V3. Averages of three experiments in the crop seasons 2016/17 and 2017/18

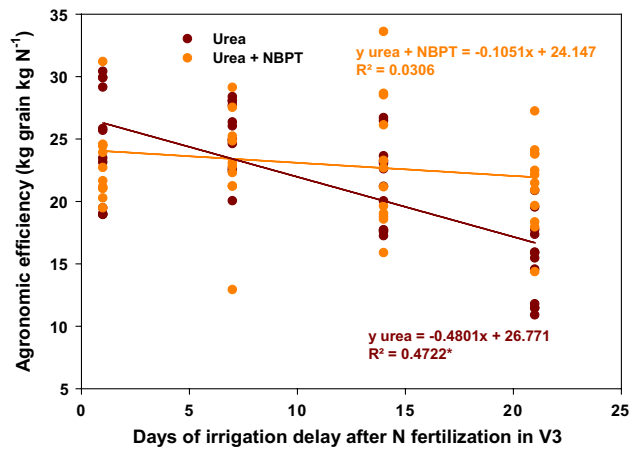
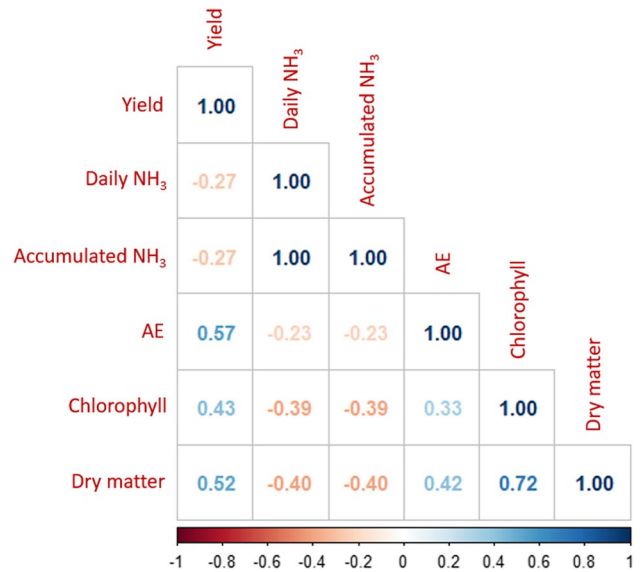


Fig. 5 Pearson correlation between the attributes evaluated in an experiment using urea and urea + NBPT under different irrigation delays in irrigated rice. Significance at the level of $p < 0.05$. AE: agronomic efficiency



hand, an inverse relationship was observed between grain yield and N losses due to ammonia volatilization. Ammonia volatilization also showed an inverse relationship with plant biomass content, AE and chlorophyll index (Fig. 5).

In the principal component multivariate analysis (PCA), it was observed that 54.9% of the data variation occurred in PC1 and 18.0% of the variation in PC2 (Fig. 6). The sum of PC1 and PC2, 72.9% of all observed variations were obtained. In Fig. 6a, a clear cluster was observed when urea and urea + NBPT were used. Most of the vectors analyzed, such as Yield, AE, plant biomass and chlorophyll, converged to urea + NBPT. However, the ammonia vector converged to the grouping of use of urea as N fertilizer

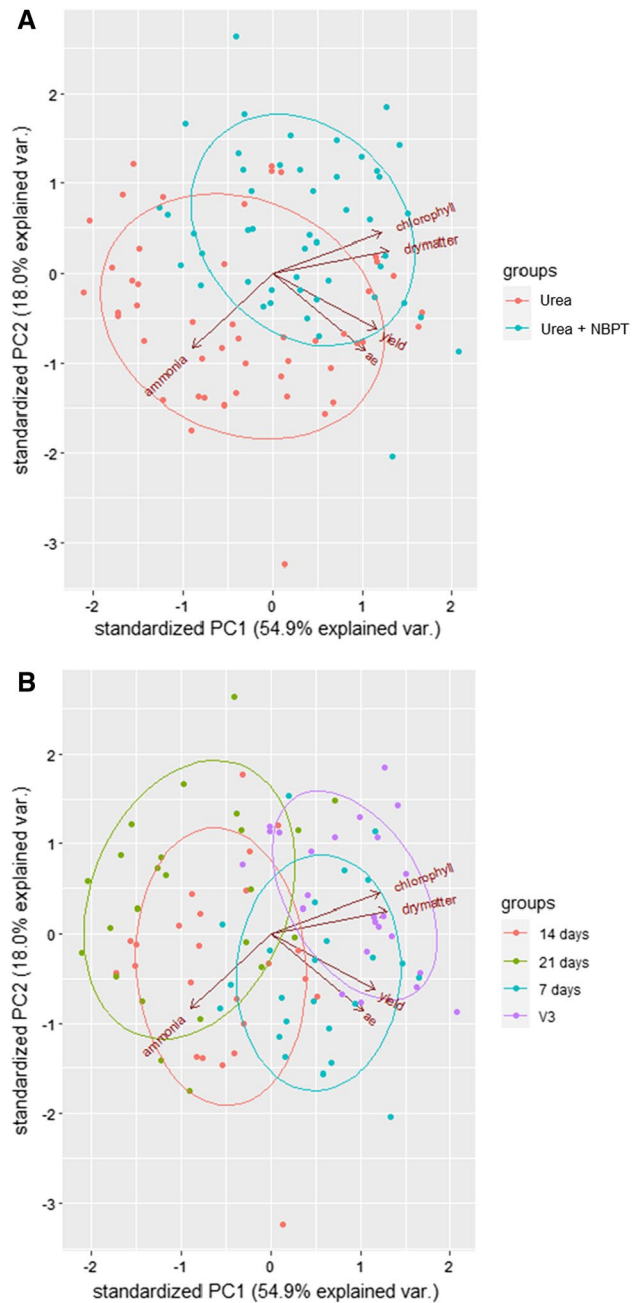
(Fig. 6a). Regarding the groupings by times of establishment of irrigation, it was observed that the vectors of the variables yield, plant biomass, chlorophyll and AE converged to the irrigations established in V3 and with 7 days delay. In the groups with the longest irrigation delay, 14 and 21 days, there was a convergence of the ammonia volatilization vector.

Discussion

Ammonia volatilization

Losses of N by ammonia volatilization increased with the delay of irrigation, due to the urea solubilization

Fig. 6 Principal component analysis of the variables evaluated in rice irrigated using urea and urea + NBPT **a** and under different irrigation delay times **b**. Ammonia: accumulated ammonia loss, ae: agronomic efficiency, yield: grain yield, chlorophyll: chlorophyll index and dry matter: plant biomass



reactions. The N present in urea in the amide form is converted in the soil to ammonium, but the increase in pH that occurs around the urea granule causes part of the ammonium to be converted to ammonia, which volatilizes and is lost to the atmosphere (Viero et al. 2015; Ke et al. 2017). The magnitude of losses was lower than values commonly found in the literature, which are 10–14% N on average (Pan et al. 2016)

and up to 25% of applied N (Misselbrook et al. 2014; Adhikari et al. 2020). Variations in the magnitude of losses reported in the literature are due to factors such as CEC and soil moisture, climatic conditions such as temperature and precipitation, type of fertilizer and fertilizer management (Scivittaro et al. 2010). The wide variation in ammonia losses is due to rainfall after urea application and the most favorable

condition for losses occurs when there is application of urea in moist soil without subsequent rainfall (Ni et al. 2014). Probably, the volume of rainfall observed after N application in the present study helped to incorporate N into the soil, reducing losses. In a study conducted in southern Brazil with irrigated rice, Scivittaro et al. (2010) observed that ammonia losses were 15% in saturated soil and 22% in moist soil. In this experiment, the interval between the application of urea and the beginning of irrigation was 10 days. Soil and temperature conditions observed by Scivittaro et al. (2010) are very similar to the present study, as both experiments were conducted in Southern Brazilian paddy fields. However, possibly the higher soil moisture in the work by Scivittaro et al. (2010) has contributed to higher ammonia losses. Larger soil moisture content has been reported as a factor that increases ammonia losses as it possibly increases the dissolution and activation of enzymatic hydrolysis caused by urease (Ni et al. 2014). On the other hand, the larger loss of ammonia under irrigation delay contributes to a lower availability of mineral N to plants, which impacted a lower chlorophyll index and plant biomass.

Irrigation delay

The current N fertilization recommendation system in Southern Brazil suggests the use of high rates of N (80 to 100 kg N ha⁻¹) at the beginning of tillering in dry soil prior to the establishment of irrigation (SOS-BAI 2018). The high concentration of ammonium in the soil at an short stage of development with less demand, may further favor losses due to ammonia volatilization (Xu et al. 2012). As the delay in irrigation intensifies the process of ammonia volatilization, it can trigger a lower supply of N to the plants and have impact on the reduction of irrigated rice grain yield. On the other hand, delayed soil flooding may also interfere with another important N loss process in flooded soils, denitrification. Maintaining the soil oxidized for a longer time favors the activity of nitrifying bacteria, essentially aerobic organisms, which promote nitrification (transformation of ammonium into nitrate) (Buchen et al. 2016). Thus, the larger amounts of nitrate accumulated in the aerobic period cause a higher loss of N through denitrification after flooding, by reducing the nitrate to N₂O, NO and N₂,

which are easily lost to the atmosphere (Silva et al. 2017).

The urease inhibitor reduces urea hydrolysis, which reduces the rapid increase in NH₄⁺ and pH around the urea granule. In this condition, a reduction in the peak of losses due to ammonia volatilization is observed (Ni et al. 2014). Some authors have observed that the reduction of ammonia losses enables an adequate synchronism of mineral N availability to plants (Soares et al. 2012). In an experiment under similar soil and climate conditions, Scivittaro et al. (2010) observed that wet soil with and 10 days of irrigation delay had losses of 19.7 and 2.4 kg ha⁻¹ of N, using urea and urea+NBPT, respectively. That is, a considerable reduction in ammonia losses due to the use of the urease inhibitor (NBPT) similar to what was observed in the present study. These differences found in this locations may be related to soil characteristics such as pH and CTC, and to climatic conditions, such as temperature and wind speed, in addition to the characteristics of irrigation water (Knoblauch et al. 2012).

However, the impact of NBPT on the grain yield of rice under irrigation delay may be associated with processes other than ammonia volatilization (Silva et al. 2017). As the NBPT molecule inhibits the hydrolysis of urea and the formation of ammonium, there is also a reduction in nitrate synthesis and, thus, a reduction in the intensity of denitrification in a condition of delay of irrigation in rice. Some authors have observed that the use of NBPT reduced the availability of ammonium for nitrification and consequently the rates of N₂O emissions (Singh et al. 2013).

In the context of irrigated rice production in Southern Brazil and many places in the world that use mechanized sowing in rows, the delay of irrigation in rice fields is frequent. This situation affects numerous plant development factors, especially the efficiency of nitrogen utilization by the crop. Thus, the use of NBPT as a urease inhibitor is a relevant strategy to mitigate the losses due to ammonia volatilization, enabling higher plant biomass production, higher amounts of chlorophyll in rice plants under irrigation delay, which is a recurrent condition in paddy fields. Other investigations of ammonia losses in soils with CEC contrast and under different climatic conditions, mainly temperature, must be evaluated in rice cultivation, as there is a great gap of scientific information.

Conclusions

The highest emissions of ammonia from rice cultivation occur when there is a delay in irrigation and this loss of nitrogen is reduced with the use of N-(n-Butyl) thiophosphoric triamide (NBPT). The delay in irrigation causes higher yield grain losses when urea is used in comparison with urea+NBPT. Furthermore, yield losses under irrigation delay are more pronounced in short cycle than medium cycle cultivars. Thus, the use of urea plus the additive with NBPT is an important strategy to increase the agronomic efficiency of nitrogen in irrigated rice production systems, mainly in rice fields that do not have adequate irrigation.

Future research from this study should be carried out in order to compare the ammonia losses and agronomic response of rice with the use of NBPT in relation to new molecules that inhibit urease and nitrification.

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

References

- Abalos D, Jeffery S, Sanz-Cobena A et al (2014) Meta-analysis of the effect of urease and nitrification inhibitors on crop productivity and nitrogen use efficiency. *Agric Ecosyst Environ* 189:136–144. <https://doi.org/10.1016/j.agee.2014.03.036>
- Abed SN, Almuktar SA, Scholz M (2020) Impact of storage time on characteristics of synthetic greywater for two different pollutant strengths to be treated or recycled. *Water Air Soil Pollut* 231:1–18. <https://doi.org/10.1007/s11270-020-04602-1>
- Adhikari KP, Saggari S, Hanly JA (2020) Guinto DF (2020) Urease inhibitors reduced ammonia emissions from cattle urine applied to pasture soil. *Nutr Cycl Agroecosyst* 1173(117):317–335. <https://doi.org/10.1007/S10705-020-10070-0>
- Buchen C, Lewicka-Szczepak D, Fuß R et al (2016) Fluxes of N₂ and N₂O and contributing processes in summer after grassland renewal and grassland conversion to maize cropping on a Plagic Anthrosol and a Histic Gleysol. *Soil Biol Biochem* 101:6–19. <https://doi.org/10.1016/j.soilbio.2016.06.028>
- Carlos FS, Schaffer N, Marcolin E et al (2021) A long-term no-tillage system can increase enzymatic activity and maintain bacterial richness in paddy fields. *L Degrad Dev* 32:2257–2268. <https://doi.org/10.1002/ldr.3896>
- Chatterjee A (2018) Additions of ammonium sulfate and urease inhibitor with urea to improve spring wheat and sugar beet yield. *Arch Agron Soil Sci* 64:1459–1464. <https://doi.org/10.1080/03650340.2018.1436762>
- Counce PA, Keisling TC, Mitchell AJ (2000) A Uniform, objective, and adaptive system for expressing rice development. *Crop Sci* 40:436–443
- Ke J, Xing X, Li G et al (2017) Effects of different controlled-release nitrogen fertilisers on ammonia volatilisation, nitrogen use efficiency and yield of blanket-seedling machine-transplanted rice. *F Crop Res* 205:147–156. <https://doi.org/10.1016/j.fcr.2016.12.027>
- Knoblauch R, Ernani PR, Walker TW et al (2012) Volatilização de Amônia em Solos Alagados Influenciada pela Forma de Aplicação de Ureia. *Rev Bras Cienc Do Solo* 36:813–821. <https://doi.org/10.1590/S0100-06832012000300012>
- Liu L, Zhang X, Xu W et al (2020a) Ammonia volatilization as the major nitrogen loss pathway in dryland agro-ecosystems. *Environ Pollut* 265:114862. <https://doi.org/10.1016/j.envpol.2020.114862>
- Liu X, Chen L, Hua Z et al (2020b) Comparing ammonia volatilization between conventional and slow-release nitrogen fertilizers in paddy fields in the Taihu Lake region. *Environ Sci Pollut Res* 27:8386–8394. <https://doi.org/10.1007/s11356-019-07536-2>
- Martins AP, Denardin LGDO, Borin JBM et al (2017) Short-term impacts on soil-quality assessment in alternative land uses of traditional paddy fields in Southern Brazil. *L Degrad Dev*. <https://doi.org/10.1002/ldr.2640>
- Minato EA, Cassim BMAR, Besen MR et al. (2020) Controlled-release nitrogen fertilizers: Characterization, ammonia volatilization, and effects on second-season corn. *Rev Bras Cienc do Solo* 44: <https://doi.org/10.36783/18069657rbcs20190108>
- Misselbrook TH, Cardenas LM, Camp V et al (2014) An assessment of nitrification inhibitors to reduce nitrous oxide emissions from UK agriculture. *Environ Res Lett* 9:115006. <https://doi.org/10.1088/1748-9326/9/11/115006>
- Nash P, Motavalli P, Nelson K, Kremer R (2015) Ammonia and nitrous oxide gas loss with subsurface drainage and polymer-coated urea fertilizer in a poorly drained soil. *J Soil Water Conserv* 70:267–275. <https://doi.org/10.2489/jswc.70.4.267>
- Ni K, Pacholski A, Kage H (2014) Ammonia volatilization after application of urea to winter wheat over 3 years affected by novel urease and nitrification inhibitors. *Agric Ecosyst Environ* 197:184–194. <https://doi.org/10.1016/J.AGEE.2014.08.007>
- Pan B, Lam SK, Mosier A et al (2016) Ammonia volatilization from synthetic fertilizers and its mitigation strategies: A global synthesis. *Agric Ecosyst Environ* 232:283–289. <https://doi.org/10.1016/j.agee.2016.08.019>
- Phongpan S, Freney JR, Keerthisinghe DG, Chaiwanakupt P (1995) Use of phenylphosphorodiamidate and N-(n-butyl)thiophosphoric triamide to reduce ammonia loss and increase grain yield following application of urea to flooded rice. *Fertil Res* 41:59–66. <https://doi.org/10.1007/BF00749521>
- Puga AP, de Queiroz MCA, Ligo MAV et al (2020) Nitrogen availability and ammonia volatilization in biochar-based

- fertilizers. *Arch Agron Soil Sci* 66:992–1004. <https://doi.org/10.1080/03650340.2019.1650916>
- R Core Team (2020) A Language and Environment for Statistical Computing. R Foundation and Environment for Statistical Computing, Vienna, Austria. - References - Scientific Research Publishing. [https://www.scirp.org/\(S\(351jmbntvnsjt1aadkposzje\)\)/reference/referencespapers.aspx?referenceid=2882118](https://www.scirp.org/(S(351jmbntvnsjt1aadkposzje))/reference/referencespapers.aspx?referenceid=2882118). Accessed 10 May 2021
- Rose TJ, Wood RH, Rose MT, Van Zwieten L (2018) A re-evaluation of the agronomic effectiveness of the nitrification inhibitors DCD and DMPP and the urease inhibitor NBPT. *Agric Ecosyst Environ* 252:69–73. <https://doi.org/10.1016/j.agee.2017.10.008>
- Scivittaro WB, Gonçalves DRN, do Vale MLC, Ricordi VG (2010) Nitrogen losses by ammonia volatilization and lowland rice response to NBPT urease inhibitor-treated urea. *Cienc Rural* 40:1283–1289. <https://doi.org/10.1590/s0103-84782010000600007>
- Silva AGB, Sequeira CH, Sermarini RA, Otto R (2017) Urease inhibitor NBPT on ammonia volatilization and crop productivity: A meta-analysis. *Agron J* 109:1–13
- Singh J, Kunhikrishnan A, Bolan NS, Saggar S (2013) Impact of urease inhibitor on ammonia and nitrous oxide emissions from temperate pasture soil cores receiving urea fertilizer and cattle urine. *Sci Total Environ* 465:56–63. <https://doi.org/10.1016/j.scitotenv.2013.02.018>
- Soares JR, Cantarella H, de Menegale MLC (2012) Ammonia volatilization losses from surface-applied urea with urease and nitrification inhibitors. *Soil Biol Biochem* 52:82–89. <https://doi.org/10.1016/j.soilbio.2012.04.019>
- SOSBAI (2018) Arroz Irrigado - Recomendações técnicas da pesquisa para o Sul do Brasil. Cachoerinha
- Tedesco M, Gianello C, Bissani C et al. (1995) Análises de solo, plantas e outros materiais, 2nd edn. Porto Alegre-RS, Brazil
- US Soil Taxonomy (1999) Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys., 2nd edn. Washington
- Viero F, Bayer C, Costa Beber Vieira R, Carniel E (2015) Management of irrigation and nitrogen fertilizers to reduce ammonia volatilization. *Rev Bras Cienc do Solo* <https://doi.org/10.1590/01000683rbc20150132>
- Xu J, Peng S, Yang S, Wang W (2012) Ammonia volatilization losses from a rice paddy with different irrigation and nitrogen managements. *Agric Water Manag* 104:184–192. <https://doi.org/10.1016/j.agwat.2011.12.013>
- Zaman M, Nguyen ML, Blennerhassett JD, Quin BF (2008) Reducing NH₃, N₂O and NO₃⁻-N losses from a pasture soil with urease or nitrification inhibitors and elemental S-amended nitrogenous fertilizers. *Biol Fertil Soils* 44:693–705. <https://doi.org/10.1007/s00374-007-0252-4>
- Zhao B, Dong S, Zhang J, Liu P (2013) Effects of Controlled-Release Fertiliser on Nitrogen Use Efficiency in Summer Maize. *PLoS ONE* 8:7–10. <https://doi.org/10.1371/journal.pone.0070569>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.