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Performance of enhanced efficiency nitrogen fertilizers in green-harvesting sugarcane

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Abstract

Enhanced efficiency fertilizers (EEF) are of interest for sugarcane (*Saccharum* spp.) production due to the potential to reduce N losses, and improve crop yield and environmental conditions. This study was conducted to determine the effect of urea with N-(n-butyl) thiophosphoric triamide (NBPT) or dicyandiamide (DCD) on NH_3 volatilization and sugarcane yield. The NH_3 volatilization, the foliar concentration of N and S, and yield of stalk and pol were monitored in two field trials testing six N sources (urea; urea + NBPT; urea + DCD; ammonium sulfate [AS]; ammonium nitrate [AN]; ammonium sulfate nitrate), and three N rates (50, 100, and 150 kg ha^{-1}). The N losses from urea totaled 22 and 18% in Sites 1 and 2, respectively. Treating urea with NBPT reduced NH_3 volatilization by 60%. Sugarcane yield increased 8.8; 11.6; and 16.0 Mg ha^{-1} (Site 1), and 4.5, 9.3, and 14.2 Mg ha^{-1} (Site 2) with the application of 50, 100, and 150 kg ha^{-1} N as compared to control, respectively. All N sources increased yields, demonstrating similar efficiency for sugarcane production. Green harvesting sugarcane cultivated in sandy soils with low organic matter concentration is highly responsive to N, showing similar efficiency between EEF and conventional N fertilizers.

Abbreviations: AN, ammonium nitrate; AS, ammonium sulfate; DCD, dicyandiamide; DM, dry matter; EEF, enhanced efficiency fertilizers; NBPT, N-(n-butyl) thiophosphoric triamide; NI, nitrification inhibitors; NUE, nitrogen use efficiency.

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1 | INTRODUCTION

Core Ideas

- Sugarcane is highly responsive to N fertilization in low-organic matter sandy soils.
- Nitrogen sources increased sugarcane yield compared to control without N fertilization.
- Treating urea with NBPT reduced NH_3 volatilization by 60%.
- Enhanced efficiency N fertilizers and conventional N fertilizers resulted in similar sugarcane yields.

Sugarcane (*Saccharum* spp.) is widely grown along the most Brazilian States making Brazil the largest sugarcane producer in the world with 43% of global production (FAOSTAT, 2020). With the establishment of policies to promote no-burning practices and minimize environmental degradation, the use of pre-harvesting burning is being totally replaced by green-harvested sugarcane. Currently, 84% of the cultivated area in São Paulo State is cultivated using green-harvested sugarcane. São Paulo is the major sugarcane producer in Brazil (São Paulo, 2014).

In mechanical harvesting systems, thick layers of straw remain on the soil surface. The quantity may vary from 10 to 20 Mg ha^{-1} yr^{-1} of dry material. Accumulation of straw on soil promotes soil conservation, maintenance of soil moisture, and nutrient cycling (Ferraz-Almeida et al., 2016; Leal et al., 2013). As possible drawbacks, when trash such as dry leaves, tops, and stalk pieces are left on the soil surface, the incorporation of urea-based fertilizers is limited (Vieira-Megda et al., 2015). This is particularly important if considered that urea represents 53% of N fertilizer consumption in Brazil (FAOSTAT, 2015), with the trend of increasing its share due to current limitations of storage and sale of ammonium nitrate in Brazil.

The preference of urea over ammonium nitrate (AN) or ammonium sulfate (AS) as N source in Brazil is based on the lower cost per unit of N and imposition of transport regulations in AN due to its potential use in manufacturing explosives. Significant ammonia (NH_3) loss may occur with the application of urea in soil due to the rapid hydrolysis of urea to NH_3 by urease activity, an enzyme presents in soil and crop residues produced by bacteria, actinomycetes, and soil fungi (Barth et al., 2020; Cantarella et al., 2008). In mechanical harvesting systems, the presence of sugarcane trash blanket in soil can increase NH_3 loss ranging from 20 to 40% of the applied N (Silva, Sequeira, Sermarini, & Otto, 2017; Gallucci et al., 2019), making ammonia volatilization the main pathway of N loss in sugarcane fields (Otto et al., 2016). The incorporation of fertilizer in soil under straw is an alternative but is considered an expensive and difficult practice by sugarcane growers.

The urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) has been increasingly used to reduce NH_3 loss in soil (Cantarella et al., 2008). The NBPT delays urea hydrolysis and provides more time to rainfall and moves urea deeper into the soil in order to decrease volatilization rates (Fillery & De Datta, 1986; Mira et al., 2017). Preliminary studies under field conditions have shown that urease inhibitors may have a variable period of efficiency, lasting from 3 d (Fillery & De Datta, 1986) to 12–14 d (Bronson, Touchton, Hiltbold, & Hendrickson, 1989; Christianson, Byrnes, & Carmona, 1990). This can be related to soil pH changes (Hendrickson & Douglass, 1993), soil chemical properties (Bremner & Chai, 1986; Watson et al., 1994), temperature, and humidity. In sugarcane fields, Mira et al. (2017) showed that NBPT delayed the peak of volatilization by 2 d, and reduce NH_3 loss by 43% when compared to untreated urea. Silva et al. (2017) showed that NBPT-treated urea has the potential in reducing 52% of the ammonia losses when compared to untreated urea.

Another strategy to improve nitrogen use efficiency (NUE) in several crops is the use of nitrification inhibitors (NI). Dicyandiamide (DCD) is the NI most commercially successful and has been widely used in several commercial formulations as a result of being relatively inexpensive, nonvolatile, water-soluble, and efficient when applied to N fertilizers (Barth et al., 2019; Trenkel, 2010). Application of NI decreases the oxidation of NH_4^+ to NO_2^- minimizing NO_3^- leaching losses (Prasad & Power, 1995). Leaching losses of N in sugarcane fields can be as high as 22% of applied N fertilizer (Ghiberto, Libardi, & Trivelin, 2015), with a loss mean of 6% in sugarcane cultivation (Otto, Zavaschi, Souza-Netto, Machado, & Mira, 2017).

Application of urea treated with NBPT or nitrification inhibitors are classified as enhanced efficiency fertilizers (EEF) due to the potential to reduce N losses and improve crop yields. However, the lack of studies about EEF's performance in sugarcane fields under tropical environments, have been hindering the adoption of this technology by sugarcane growers. Therefore, field experiments are required to provide scientifically validated recommendations to end-users of fertilizers.

We hypothesized that applications of EEF increase NUE with economic gains, reducing environmental impacts in sugarcane areas. Our main goal was to determine the effect of urea with NBPT or DCD on NH_3 volatilization and sugarcane yield as compared to untreated urea.

2 | MATERIALS AND METHODS

2.1 | Soil characterization and experimental design

Two field trials were carried out in Piracicaba, Brazil (22°40′ S, 47°53′ W; 500 m altitude), in the crop seasons of 2005–2006 (Site 1) and 2006–2007 (Site 2). Field trials were located close to each other. The area presents climate classified as Aw (Tropical, Köppen classification), characterized as warm and rainy in the summer, and cold and dry in the winter.

Soil physical and chemical attributes were monitored for 0- to 0.4-m depth (Raij, Andrade, Cantarella, & Quaggio, 2001), Table 1. The soil was classified as a Typic Hapludox according to Soil Taxonomy (Soil Survey Staff et al., 2010), with a sandy texture (pipette method; Camargo, Moniz, Jorge, & Valadares, 2009).

Field trials were laid down under a complete randomized block design using a split-plot arrangement (Site 1) and a factorial arrangement (Site 2), with four replications. The first treatment factor was six N sources (urea; urea + NBPT; urea + DCD; ammonium sulfate; ammonium nitrate; ammonium sulfate nitrate), and the second treatment factor three N rates (50, 100, 150 kg ha^{-1} N), plus a control plot without N fertilization. Each plot consisted of seven sugarcane rows of 13 m length spaced 1.4 m between rows totaling 127.4 m^2 plots.

Sugarcane was planted using the variety SP83-2847 (Site 1) and RB86-7515 (Site 2) after third and second ratoon, respectively, with the conventional system (soil disturbance). In both sites, soil management was performed over sugarcane straw left on the soil after mechanically harvested without previous burning, following the procedures of Espironello et al. (2009).

The N fertilizers were applied manually banded 0.25 m from sugarcane rows on the soil surface in November 2005 (Site 1) and August 2006 (Site 2), encompassing the usual period of fertilizer application in sugarcane fields in São Paulo State. Urea, ammonium sulfate, ammonium nitrate, and ammonium sulfate nitrate present 45, 20, 32, and 26% of N, respectively. The urea was treated with 530 mg kg^{-1} of NBPT, and with DCD that presented 46% of N + 1H-1,2,4-Triazole. The quantity of sugarcane straw collected on the field, in the moment of N application, was approximately 8.7 and 12.7 Mg ha^{-1} of dry matter (DM), in Sites 1 and 2, respectively.

2.2 | Measurements

Volatilization losses of NH_3 were measured periodically over approximately 40 d after N application in both fields. Data of air temperature and precipitation were monitored during the study to correlate with losses of NH_3. Air temperature ranged from 20 to 26 °C (Site 1), and from 12 to 28 °C (Site 2). The precipitation in such periods is shown in combination with volatilization data in Figure 1. The volatilization losses of NH_3 was monitored using semi-open static chambers to trap NH_3 following the method described by Lara Cabezas, Trivelin, Bendassolli, Santana, and Gascho (1999). Foams treated with a 0.75 mol L^{-1} phosphoric acid and 5% of glycerol solution was periodically replaced up to 40 d after fertilizer application. After each foam collection, chambers were moved to another position to ensure the rainfall effect in incorporating fertilizers in the adjacent area. Foams collected were washed with 1 mol L^{-1} KCl solution, and N-NH_4^+ concentration in the extract was quantified by steam distillation procedures (Bremner, 1996). Volatilization losses of NH_3 in control plots were be used as blank, and mean subtracted from N treatments. However, the NH_3 volatilization in control plots was negligible and below the quantification limit of the steam distillation method adopted herein. Because of that, we considered NH_3 volatilization in control plots as zero.

Concentrations of N and S were analyzed in the Top Visible Dewlap (TVD); leaves were collected randomly 4 mo after the last harvest, following the procedures described in Malavolta, Vitti, and Oliveira (1997)). Stalk yield was evaluated in the five central rows in September of the following year for both sites. Sugarcane was mechanically (Site 1) and manually (Site 2) harvested. All stalks were weighted to determine sugarcane yield. Ten stalks per plot were collected to determine pol (%), according to Fernandes et al. (2003).

2.3 | Statistical analysis

The data normality and homogeneity of variance were evaluated using the Shapiro–Wilk test (Sigmaplot Inc.) and the Bartlett test (SPSS Inc.), respectively. Statistical analysis was subjected to ANOVA ($P < .05$), based on the *F* test; considering a split-plot (Site 1) and factorial arrangement (Site 2). When the *F* test was significant, the means were compared by the regression test and the Tukey's HSD test using SAS software (SAS Institute, 2011).

3 | RESULTS

Volatilization losses for ammonium sulfate and ammonium nitrate were negligible at both sites, volatilization losses of surface-applied urea ranged from 17 to 23% (mean 22%) in Site 1, and from 13 to 20% (mean: 18%) in Site 2 (Figure 1). In both sites, urea DCD-treated urea showed a cumulative NH_3 loss comparable to untreated urea, while treating urea with NBPT reduced NH_3 loss by up to 70% (Figure 1; Table 2).

TABLE 1 Chemical and physical attributes of soil in two sugarcane fields in São Paulo, Brazil, prior to trial installation

Depth	pH	SOM	P	S	Ca	Mg	K	Al	H+Al	CEC	BS	Sand	Silt	Clay
m		g dm^{-3}	–mg dm^{-3}–		———mmol$_c$ dm^{-3}———						%	——g kg^{-1}——		
Site 1														
0.0–0.2	4.9	15.0	7.3	13.2	15.1	6.2	1.1	1.0	25.0	48.1	47.4	760	60	180
0.2–0.4	4.4	11.1	3.1	16.3	7.1	4.1	0.2	4.1	28.2	43.4	29.1	760	40	200
Site 2														
0.0–0.2	4.9	15.0	9.0	5.1	21.1	8.3	1.1	1.2	28.1	58.1	52.2	800	30	170
0.2–0.4	4.6	13.2	22.1	5.0	18.2	5.1	0.3	2.1	31.3	56.3	43.1	700	60	240

Note. pH in soil ($CaCl_2$ .01 mol L^{-1}); SOM, soil organic matter; P (extracted by anion-exchange resin); H + Al, hydrogen plus aluminum; CEC, cation-exchange capacity; BS, base saturation. Chemical analysis following Raij et al. (2001).

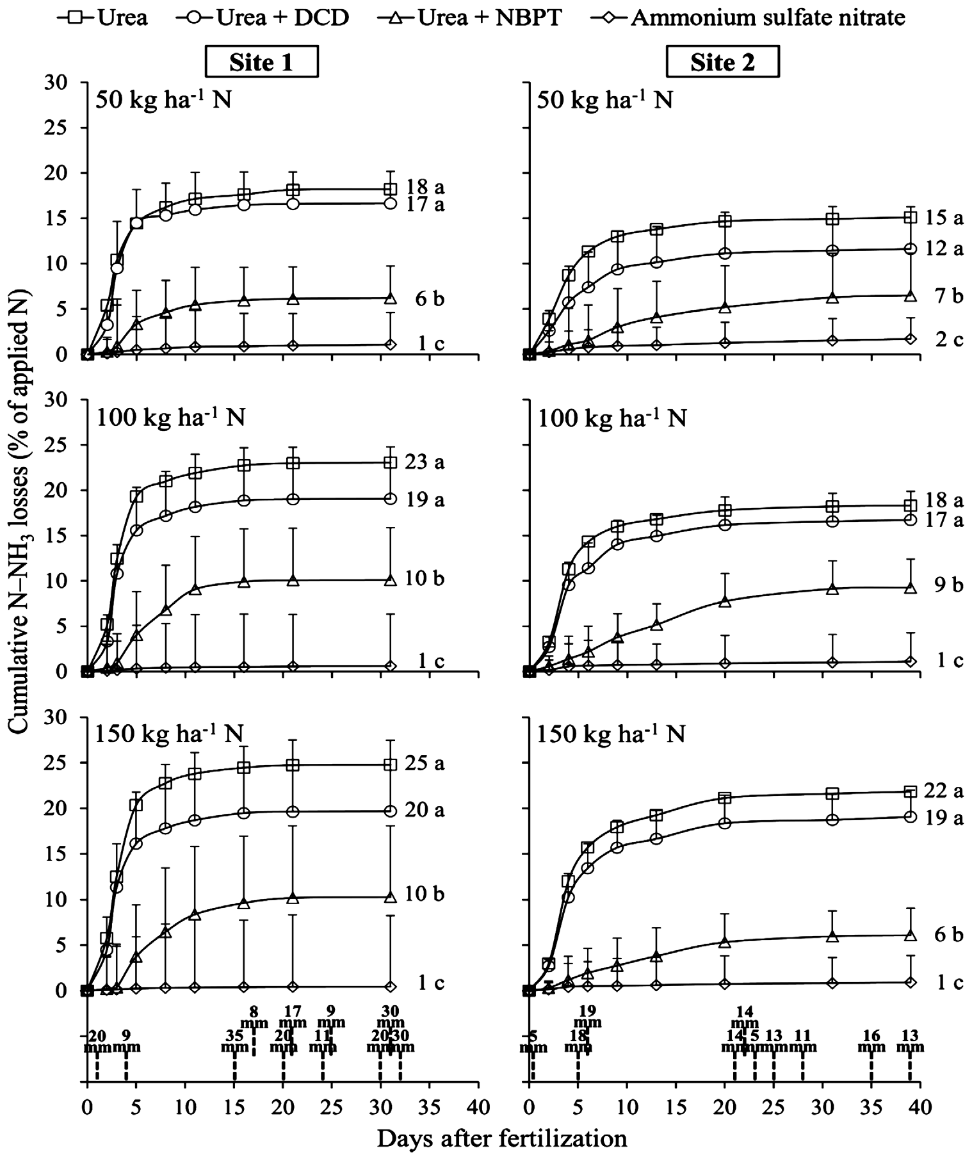

FIGURE 1 Accumulated NH_3 volatilization from four sources and three N rates applied on sugarcane straw blanket in two sites in Brazil. At the last day of evaluation, means followed by the same lower-case letter are not significantly different according to the Tukey's HSD test ($P \geq .05$). Numbers on dashed lines represent rainfall events along the NH_3 volatilization evaluation time. Volatilization losses of control plots, ammonium sulfate and ammonium nitrate were below the quantification limit and not presented

TABLE 2 Forty-days accumulated N–NH_3 volatilization from N sources and rates applied over sugarcane straw blanket in two sites in São Paulo, Brazil

	Site 1					Site 2				
N rates	Urea	Urea + NBPT	Urea + DCD	Ammonium sulfate nitrate	Mean	Urea	Urea + NBPT	Urea + DCD	Ammonium sulfate nitrate	Mean
kg ha^{-1}	% of applied N									
0	0	0	0	0	0	0	0	0	0	0
50	18.2	6.2	16.6	1.1	10.5b	15.1aC	6.5cB	11.6bB	1.7dA	8.7
100	23.1	10.1	19.0	0.6	13.2a	18.3aB	9.2bA	16.7aB	1.1cA	11.3
150	24.8	10.3	19.7	0.4	13.8a	21.8aA	6.1bB	19.0aA	0.9cA	12.0
Mean	22.0A	8.9C	18.5B	0.7d	12.5	18.4	7.3	15.8	1.2	10.7
ANOVA *p* values										
N rate (R)					≤.05					≤.001
N source (S)					≤.001					≤.001
R × S					ns					≤.001
CV, %					21.44					14.91

Note. Means followed by the same lower-case letter within columns, and by the same upper-case letter within rows are not different according Tukey's HSD test ($P \geq .05$). ns, nonsignificant ($P \geq .05$).

Nevertheless, NH_3 volatilization from NBPT-treated urea was still superior to that observed in ASN, which presented NH_3 loss virtually null. In addition, results showed a linear increase in NH_3 loss following N rates for all amidic sources evaluated, except ASN.

Nitrogen rates linearly increased the foliar concentration of N in all cases (Table 3). This result may be a consequence of a low N availability on this soil, considering the low levels of soil organic matter (SOM) presented in both sites (Table 1).

Sulfur concentration in leaves increased in treatments that received AS, because of the 24% of S on this fertilizer. Sulfur concentration in the leaves increased in both sites, even though Site 1 showed adequate levels of soil S (13–16 mg dm^{-3}). Treatments that received ASN showed no increases in S concentration in the leaves, despite the concentration of S on that fertilizer. This can be due to the lower concentration of S in ASN as compared to AS (Table 3).

There was a positive effect of N rates on sugarcane yield for all N sources. However, there was no effect of N sources or interaction between N sources and rates for sugarcane yield (Supplemental Table S1), indicating that all N sources yielded similar. Since there was no interaction between N sources and rates, the yield increase due N fertilization presented for each N rate is the average between all N sources (Table 4). In both sites, yield of stalk and sugar increased linearly with the N rates. The maximum N rate increased yield of stalk and sugar by 30% in Site 1, and by 25% in Site 2, compared to the control.

The yields obtained in both sites are below the average sugarcane yield in Brazil (72 Mg ha^{-1} in 2017/2018), indicating the fields were management with restrictions in the previous years. There was no effect of N sources and rates on pol concentration (Table 4), suggesting that N management did not affect the sugarcane maturation process.

4 | DISCUSSION

Volatilization losses presented a similar range in both sites (22% Site 1; and 18% Site 2), despite the differences in straw amount (8.7 Mg ha^{-1} of DM Site 1; and 12.7 Mg ha^{-1} of DM Site 2) and different period of fertilizer application. Sugarcane straw covering soil surface can enhance NH_3 losses for acting as a barrier between N fertilizer and the soil (Cantarella et al., 2008; Freney, Denmead, Wood, & Saffigna, 1994). Although the potential for losses was greater in Site 2 due to the larger quantities of straw. The occurrence of rainy days shortly after fertilizer application on-Site 2 may have promoted urea incorporation into the soil, consequently reducing volatilization losses.

Despite the overall expectations that 10–20 mm of irrigation or rainfall could be sufficient to stop or reduce NH_3 volatilization from surface-applied urea (Cantarella et al., 2008; Soares, Cantarella, & Menegale, 2012), greater amounts of rainfall may have been required to effectively reduce NH_3 losses in this study. In Site 1, rainfall of 10 and 20 mm occurred over the first week after application, a period in which urea hydrolyses is greater (Trenkel, 2010). Such amount of rain probably was not enough to incorporate urea into the soil, even with lower amounts of trash on the soil surface in comparison to Site 2. Nascimento, Vitti, Faria, Luz, and Mendes (2013) pointed out that 23 mm of rainfall was not sufficient to cause NH_3 reduction, concluding that greater

TABLE 3 Foliar concentration of N and S in sugarcane as effect of N sources (UR, urea; AS, ammonium sulfate; AN, ammonium nitrate; ASN, ammonium sulfate nitrate) and rates applied over sugarcane straw blanket in two sites in São Paulo, Brazil

	Site 1							Site 2						
N rates	UR	UR + NBPT	UR + DCD	AS	AN	ASN	Mean	UR	UR + NBPT	UR + DCD	AS	AN	ASN	Mean
kg ha^{-1}	N foliar concentration, g kg^{-1}													
0	20.5	20.3	20.3	20.8	20.3	21.3	20.6	21.0	21.8	20.8	21.0	20.5	20.9	21.0
50	20.8	20.5	20.3	21.0	21.3	21.0	20.8	21.5	21.8	21.3	22.8	21.9	22.1	21.9
100	22.3	21.3	21.5	21.0	21.5	23.5	21.9	22.3	23.0	21.9	24.3	22.5	23.4	22.9
150	23.5	22.9	23.0	23.2	22.8	23.4	23.1	23.8	24.0	22.7	23.8	23.5	24.9	23.8
Mean	21.8a	21.2a	21.3a	21.5a	21.5a	22.3a	21.6	22.1ab	22.7ab	21.7b	23.0a	22.1ab	22.8ab	22.4
	S foliar concentration, g kg^{-1}													
0	1.4	1.4	1.4	1.5	1.4	1.5	1.4	1.9	2.1	1.9	2.0	1.9	1.9	1.9
50	1.4	1.4	1.4	1.6	1.4	1.5	1.5	1.8	2.0	1.8	2.1	2.1	2.1	2.0
100	1.6	1.4	1.5	1.8	1.4	1.8	1.6	2.0	1.8	2.1	2.3	1.9	2.2	2.1
150	1.5	1.4	1.5	2.1	1.4	1.9	1.6	2.1	2.2	1.8	2.6	1.9	2.2	2.1
Mean	1.5bc	1.4c	1.5bc	1.7a	1.4c	1.7ab	1.5	2.0b	2.0ab	1.9b	2.3a	2.0b	2.1ab	2.0

ANOVA *p* values	Foliar N	Foliar S	Foliar N	Foliar S
N rate (R)	≤.001[a]	≤.001[a]	≤.001[a]	ns
N source (S)	≤.05	≤.001	≤.05	≤.01
R × S	ns	ns	ns	ns
CV, %	4.74	12.90	5.39	12.30

Note. Means followed by the same lower-case letter within rows are not different according Tukey's HSD test ($P \geq .05$). ns, nonsignificant.

[a]Linear model adjustment for N rates compared by regression analysis.

amounts may be required to reduce NH_3 losses. In Brazil, Oliveira, Trivelin, and Bendassolli (1999) showed that there were NH_3 losses after 38 mm of rainfall. Even though the high straw amount on Site 2, the rainfall of 17 and 18 mm which occurred over the first week after fertilization may have been more effective in reducing volatilization losses, overcoming the physical barrier and incorporating urea into the straw-covered soil.

Urea with NBPT reduced NH_3 volatilization by 60% in Site 1, and 58% in Site 2. Such reduction in NH_3 losses by NBPT was already reported under field conditions. Cantarella et al. (2008) and Otto et al. (2016) using NBPT-treated urea in the sugarcane trash-blanket system obtained reductions from 15 to 78% of NH_3 loss with a high dependence on rainfall levels following N application. The nominal NH_3 losses observed for ASN is explained by the acidity of both soils, maintaining N as NH_4^+ in the surrounding area of the granules, since ammoniacal sources of N do not undergo hydrolysis by urease.

The DCD can even enhance NH_3 volatilization when compared to untreated urea, since DCD maintain NH_4^+ forms for a longer time in soil, allowing more NH_4^+ to be converted into NH_3 (Soares et al., 2012). However, in our study, this effect was not verified. The NH_3 loss from DCD-treated urea did not overcome the volatilization from untreated urea. We attributed this result to the presence of the sugarcane plants in the system that can absorb the NH_4^+ formed, and to the higher dynamics of nitrification occurring under undisturbed and aerated soil under field conditions.

Sugarcane showed a positive response to N fertilizer addition with yield gains ranging from 14 to 16 Mg ha^{-1}. This large effect on yield can be a possible result of better N nutrition following the application of fertilizers. The study of Vitti et al. (2007) was also developed in a sandy soil with low soil organic matter concentration and showed linear responses to N addition, indicating that under such condition sugarcane ratoon shows high response to N fertilization. This is particularly interesting if considered that recent studies have demonstrated the limited response of sugarcane ratoon to N fertilization (Otto, Mulvaney, Khan, & Trivelin, 2013). Otto et al. (2016) enumerated conditions that limit the responsiveness of sugarcane to N, such as the cultivation of legume break crops and utilization of by-products such as vinasse and filter cake. The result of this study indicates that in sandy soils with low soil organic matter concentration, without previous cultivation of legumes or utilization of organic amendments, sugarcane is highly responsive to N fertilization.

Despite the reduction in NH_3 loss promoted by treating urea with NBPT, the N saved by the urease inhibitor was not translated into yield gains. More interestingly, there was

TABLE 4 Sugarcane stalk yield, pol concentration, and sugar yield as effect of N rates applied over sugarcane straw blanket in two sites in São Paulo, Brazil

N rates	Pol concentration	Stalk yield	Sugar yield	Stalk yield increase due N fertilization	Sugar yield increase due N fertilization
kg ha^{-1}	%	Mg ha^{-1}			
Site 1					
0	16.5	54.1	8.9	–	–
50	16.5	62.9	10.4	8.8b[a]	1.4b
100	16.5	65.7	10.9	11.6ab	1.9ab
150	16.6	70.2	11.7	16.0a	2.7a
Mean	16.5	63.2	10.5	12.1	2.0
ANOVA *p* values					
N rate (R)	ns[b]	≤.001[b]	≤.001[b]	≤.05	≤.05
N source (S)	ns	ns	ns	ns	ns
R × S	ns	ns	ns	ns	ns
CV, %	2.77	15.09	2.77	81.73	84.10
Site 2					
0	15.9	52.7	8.4		–
50	15.9	57.2	9.1	4.5b	0.7b
100	15.7	62.0	9.8	9.3ab	1.4ab
150	15.7	66.9	10.5	14.2a	2.1a
Mean	15.8	59.7	9.4	9.3	1.4
ANOVA *p* values					
N rate (R)	ns	≤.001[b]	≤.001[b]	≤.001	≤.01
N source (S)	ns	ns	ns	ns	ns
R × S	≤.05	ns	ns	ns	ns
CV, %	3.87	12.81	13.99	77.88	88.97

Note. ns, non-significant.

[a]Means followed by the same lower-case letter within columns are not different according Tukey's HSD test ($P \geq .05$). Mean of stalk and sugar yield increase in each N rate was subtracted from mean of control plot.

[b]Linear model adjustment for N rates compared by regression analysis.

also no differentiation in yield between urea, AS, or ASN. The study of Vitti et al. (2007) showed that AS and AN presented the highest sugarcane yield as compared to urea, probably as a consequence of high rates of volatilization of urea. DCD-treated urea also promoted stalk yields similar to other treatments. Possible NO_3^- leaching was limited in the conditions of the study, not resulting in yield gains by treating urea with a nitrification inhibitor. There is a wide variation in leaching losses under sugarcane cultivation, varying from 0 to 22% (Ghiberto et al., 2015; Ghiberto, Libardi, Brito, & Trivelin, 2009), and possibly the leaching losses in both sites were in the lower limit of that range. There was a lack of yield gain using EEF when compared to urea, despite the 60% reduction in NH_3 loss promoted by NBPT, for example, is an indicator that fertilizer contribution to N nutrition of sugarcane is limited. Several studies demonstrate that the soil, not the fertilizer, is the main source of N to sugarcane (Franco et al., 2011; Otto et al., 2013; Vieira-Megda et al., 2015) and this can be the reason to the lack of yield gains despite the reduction in volatilization losses of 60% promoted by urease inhibitor.

Considering the relationship between volatilization losses and stalk yield, apparently, the level of NH_3 losses was not high enough to decrease the sugarcane yield in our study. Different from our results, some studies have shown yield reduction in response to NH_3 loss (Gould, Hagedorn, & McCready, 1986). This disparity is in part attributed to the uptake of N from other sources than fertilizers, such as mineralization of soil organic matter, sustaining sugarcane yield regardless of NH_3 loss occurred in some selected treatments.

There was no effect of N fertilizer management on sugarcane pol concentration (Table 4). There are inconsistent results in the literature about the effect of N on sugarcane pol (Franco et al., 2011) and it has been shown to be more related to specific soil and climate features rather than N fertilization. The limited effect of N fertilization in modifying sugar concentration in plants is possibly related to the fact that N is not directly related to the process of sugar accumulation and transportation in plants. Moreover, in our study, other than an interaction of N rate and source on Pol at Site 2; it seems that the increase in sugar yield with N rates was a consequence of increasing sugarcane biomass and not an effect of sucrose concentration.

The lack of significant effect of N rates and sources on sucrose concentration is less important if considered that nowadays not only sugar is an important product of sugarcane, but also fiber to second-generation ethanol and energy production. Bagasse can be used as a fiber source for second-generation ethanol (through enzymatic hydrolysis) and to produce energy by burning it in boilers. High-yielding sugarcane will promote not only an increase in sugar production, but also in fiber or bagasse. That is particularly important if considered that sugarcane industries aim to increase the production of commercial-valuable products other than sugar (Sordi & Manechini, 2013).

5 | CONCLUSIONS

Urease inhibitor NBPT reduces NH_3 volatilization from urea by 60%, while nitrification inhibitor DCD does not change the volatilization losses. Ammonium sulfate nitrate presents only nominal NH_3 losses when applied over sugarcane straw. Sugarcane yield increases linearly with N rates using all N sources, indicating that green harvesting sugarcane is responsive to N fertilization in sandy soils with low organic matter concentration. Enhanced efficiency N fertilizers show potential in reducing NH_3 loss in the sugarcane field but yield gain compared to urea is not assured due to the small contribution of N from fertilizer for sugarcane nutrition.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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