

Article

Foliar Fertilization Improves the Nitrogen Nutrition of Sugarcane

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Abstract: Increasing the recovery of N fertilizer (RNf) is the main challenge in managing nitrogen fertilization in sugarcane. This study aimed to evaluate the efficiency of complementary foliar fertilization in managing nitrogen nutrition in sugarcane. Four fertilization managements, combining soil (5.0 and 4.5 g plot⁻¹ of N) and foliar (1.0 and 1.5 g plot⁻¹ of N) fertilization in up to two application events (0.5 + 0.5 and 0.75 + 0.75 g plot⁻¹ of N), were compared with conventional fertilization (6.0 g plot⁻¹ of N in soil). The change from 6.0 g plot⁻¹ to 4.5 g plot⁻¹ of N reduced the RNf by 46% before the first foliar fertilization. The RNf (26%) was similar between managements after the first foliar fertilization. After the second foliar fertilization, the RNf was 38% higher than that for conventional management. The accumulation of N in the aerial part of sugarcane was similar between managements until the first foliar fertilization. After the second foliar fertilization, the accumulation of N increased by 3.5% with foliar fertilization. The biomass accumulated by the managements was similar before and after the first and second foliar fertilization. The splitting of foliar fertilization increased the accumulation of N and RNf by 22% and 24%, respectively. The fertilization management with 4.5 g plot⁻¹ of N applied to the soil, with two applications of 0.75 g plot⁻¹ of N on the leaf, obtained greater accumulations of N and RNf. Foliar fertilization increases the efficiency of fertilization and improves the N nutrition of sugarcane.

Keywords: fertilization management; plant nutrition; foliar urea-N; recovery of N fertilizer; *Saccharum* spp.



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1. Introduction

Nitrogen (N) is one of the most limiting nutrients in tropical climates and the second most required element of sugarcane [1,2]. To produce 100 t ha⁻¹ of stalk, sugarcane consumes on average 192 kg ha⁻¹ of N [3,4]. Therefore, N fertilization is used to meet the nutritional demands of sugarcane [5].

The low efficiency of nitrogen fertilization is the main challenge in fertilization management in sugarcane fields. On average, the recovery of N fertilizer (RNf) by sugarcane at the end of the cycle is limited to 20% and 50% of the N applied to plant cane and ratoon cane, respectively [6,7]. Soil N transformations and loss are the main causes of low RNf in crops [8]. On average, immobilization, volatilization, denitrification, and leaching can reduce the nitrogen availability of fertilizer by 58% [8,9].

Strategies to increase the efficiency of nitrogen fertilization in sugarcane, such as modifying sources, method, and time of application; increasing the N dose; using volatilization and nitrification inhibitors; and altering the agroecosystem; have already been tested, but the results show that the RNf by sugarcane is limited to less than 50% of the N applied [5,8,10–15]. Thus, adopting fertilization management that is less susceptible to soil N transformations and losses can increase the RNf for sugarcane [16,17].

Foliar fertilization has a higher RNf than soil fertilization because it optimizes plant nutrient absorption, translocation, and assimilation [18–20]. Among the sources of N, Uscola [18] found that the recovery of N-urea is 75% higher than for other N sources such as $(\text{NH}_4^+)_2\text{SO}_4$, KNO_3 , and glycine. In sugarcane, foliar fertilization with N-urea has the potential to recover between 60% and 70% of the N applied in up to 120 h [16,21]. In the combination of soil and foliar nitrogen fertilization, each 1.0 kg ha^{-1} of N applied to the sugarcane leaf can replace up to 5.0 kg ha^{-1} of N applied to the soil [22].

Studies of foliar fertilization evaluate the effects of RNf recovery by sugarcane at up to 20 days after the treatment application or at up to 100 days of plant growth [16,21], [23]. The participation of fertilizer-derived N in sugarcane tends to decrease as the crop cycle progresses due to the increased participation of other N sources [7,24]. Therefore, this evaluation period may overestimate the effect of foliar fertilization on sugarcane nutrition and RNf.

The doses of N applied to the leaves vary between 5 and 30 kg ha^{-1} of N [25]. Increasing the amount of N applied in foliar fertilization can cause leaf injuries and affect the metabolic activity of the damaged tissue, as well as reduce the RNf in sugarcane [16,20], [26]. Fractionating the amount of N applied can mitigate the effects of leaf burn from foliar fertilization [22].

Adopting a nitrogen fertilization management that combines soil and foliar fertilization can be a rational alternative to overcome limitations and increase the efficiency of nitrogen fertilization in sugarcane [22,27]. Therefore, the hypothesis of this study is that complementary foliar fertilization is more efficient in recovering N fertilizer than conventional fertilization via soil, and that N fertilizer recovery from management with foliar fertilization is greater when foliar application is fractionated into smaller doses. This study aims to evaluate the efficiency of complementary foliar fertilization in the management of nitrogen nutrition in sugarcane.

2. Material and Methods

The experiment was conducted at the Federal Rural University of Pernambuco, UFRPE, located in Recife, Pernambuco, Brazil, at $8^\circ 01' 7'' \text{ S}$ and $34^\circ 56' 41'' \text{ W}$.

The plots were assembled in drainage lysimeters with a useful volume of 0.49 m^3 (Figure 1). The soil used in the experiment corresponds to a humiluvic orthic duric spodosol, corresponding to podzol [28]. The soil was collected in the 0–60 cm layer in the geoenvironmental unit of the coastal tablelands of Paraíba, Brazil. After collection, the soil was characterized according to its chemical and physical attributes (Table 1).

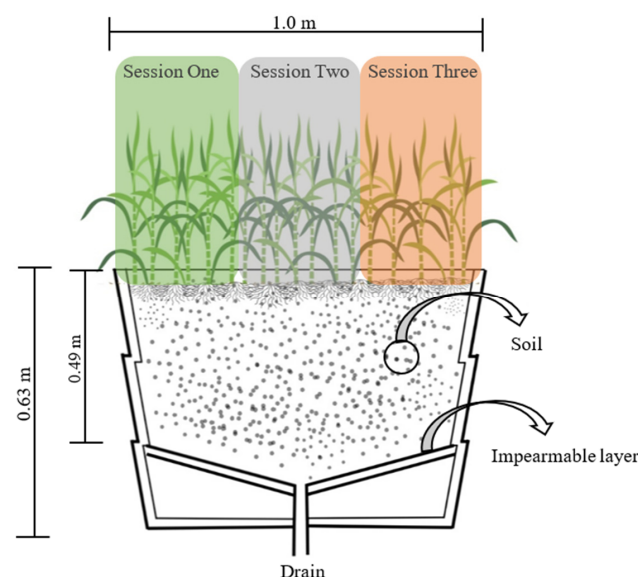


Figure 1. Illustration of the experimental plot.

Table 1. Physical and chemical attributes of the soil.

Chemical Attributes		
pH (CaCl ₂)		4.70
O.M (g.dm ⁻³)		11.16
P (m g.dm ⁻³)		5.38
Ca ⁺² (cmol _c .dm ⁻¹)		1.12
Mg ⁺² (cmol _c .dm ⁻¹)		0.52
K ⁺ (cmol _c .dm ⁻¹)		0.043
Al ⁺³ (cmol _c .dm ⁻¹)		0.04
H + Al (cmol _c .dm ⁻¹)		1.17
S.B (cmol _c .dm ⁻¹)		1.68
CTC _(total) (cmol _c .dm ⁻¹)		3.39
Fe ⁺² (mg.dm ⁻³)		34.00
Co ⁺² (mg.dm ⁻³)		0.51
Zn ⁺² (mg.dm ⁻³)		1.90
Mn (mg.dm ⁻³)		2.10
SB (mg.dm ⁻³)		0.26
V (%)		49.55
m (%)		2.33
Physical attributes		
Sandy (g.kg ⁻¹)		970.60
Silt (g.kg ⁻¹)		22.60
Clay (g.kg ⁻¹)		1.20
Ds (g.cm ⁻³)		1.32
Dp (g.cm ⁻³)		2.92
α _{total} (%)		31.58
α _{macro} (%)		26.51
α _{micro} (%)		5.06
θ _{CC} (m ³ m ⁻³)		0.21
θ _{PWP} (m ³ m ⁻³)		0.01

SB, sum of bases; V (%), base saturation; m (%), aluminum saturation; Ds, soil bulk density; Dp, particle density; α, porosity; θ_{CC}, moisture content at field capacity; θ_{PWP}, permanent wilting point.

Soil base saturation was corrected to 70% with the application of 99 g.plot⁻¹ of limestone 15 days before planting [29]. At planting, fertilization was conducted at the bottom of the planting furrow with 100% of the P dose and 50% of the K, Mn, Zn, Cu, Mo, and B doses. Topdressing fertilization was conducted 90 days after planting (DAP). For this purpose, 0.05 m deep holes were opened 0.10 m from the plant row, and the remaining doses of K, Mn, Zn, Cu, Mo, and B were applied. Fertilization was conducted based on the maximum physical efficiency dose, capable of providing a yield greater than/equal to 100 Mg ha⁻¹. The doses of P (120 kg ha⁻¹ P₂O₅), K (150 kg ha⁻¹), Mn (2.5 kg ha⁻¹), and Mo (0.2 kg ha⁻¹) were based on those recommended in the studies by Simões-Neto [30], Da Rocha [31], Benett [32], and dos Santos [33], respectively. The Zn and B doses were based on those suggested in the study by Marangoni [34]. The sources of P, K, Mo, and B used were triple superphosphate, potassium chloride, sodium molybdate, and boric acid, respectively. The Mn, Zn, and Cu sources used were manganese, zinc, and copper sulfate, respectively. At 120 DAP, an extra application of 50 kg ha⁻¹ K₂O was applied to the soil since the plants showed visual K deficiency symptoms.

The RB92-579 variety was used in the experiment because it presents important characteristics for foliar fertilization, such as a wide leaf blade, high tillering, and a high N demand [35,36].

2.1. Description of Treatments and Experimental Conduct

The treatments consisted of five N application managements that combined soil and foliar fertilization in up to two application events: (i) 6.0 g plot⁻¹ of N applied to the soil, (ii) 5.0 g plot⁻¹ of N applied to the soil with 1.0 g plot⁻¹ of N applied to the leaf, (iii) 5.0 g plot⁻¹ of N applied to the soil with two applications of 0.5 g plot⁻¹ of N to the leaf, (iv) 4.5 g plot⁻¹ of N applied to the soil with 1.5 g plot⁻¹ of N applied to the leaf, and (v) 4.5 g plot⁻¹ of N applied to the soil with two applications of 0.75 g plot⁻¹ of N to the leaf. The five treatments were arranged in three randomized blocks, totaling 15 experimental units (Figure 1).

The dose of 6.0 g plot^{-1} of N, equivalent to 60 kg ha^{-1} of N, was based on the best agronomic efficiency of nitrogen fertilization in sugarcane found by Santana [37]. The dose of 1.5 g plot^{-1} , equivalent to 15 kg ha^{-1} of N, was used, based on the critical limit with risk of leaf injury observed by Philips and Mullins [25].

Soil and foliar N applications were conducted with urea ($\text{CO}[\text{NH}_2]_2$) enriched with 2.08 atom% of ^{15}N produced in the stable isotope laboratory of the Center for Energy in Agriculture (CENA) of the University of São Paulo (USP). During planting, 1/3 of the applied N was applied at the bottom of the planting furrow. The remaining N (2/3) was applied as a topdressing 90 days after planting (DAP) in open holes at a distance of 0.10 m from the tillers and 0.05 m deep.

The first foliar application was performed at 163 DAP on leaves +1, +2, and +3 on all plants in the plot [16]. The second foliar application was performed at 195 DAP when leaf +1 from the first application became leaf +3. Both applications were performed in the late afternoon on the adaxial and abaxial surfaces of the leaves using a manual sprayer. The volume of spray used in the applications was equivalent to 150 L ha^{-1} , and the urea concentrations in the solution were 7.5%, 11.1%, 14.8%, and 22.2% for the doses of 0.5 g plot^{-1} ; 0.75 g plot^{-1} , 1.0 g plot^{-1} , and 1.5 g plot^{-1} of N, respectively. The solution received a drop of a water-based adjuvant (Disperse Ultra®) to uniformize the application and break the surface tension of the drop.

The experiment was maintained under full irrigation to meet the water requirements of sugarcane (Figure 2). The daily applied water depths were estimated from the reference evapotranspiration (ET_o) and the K_c of each development stage, minus the precipitation of the previous day. The ET_o was estimated using the Penman–Monteith method, and the K_cs used were 0.2, 0.4, 0.6, and 1.25 [38]. The meteorological variables (Figure 1) used to estimate ET_o and monitor the meteorological conditions at the study site were obtained from the National Institute of Meteorology (INMET) database.

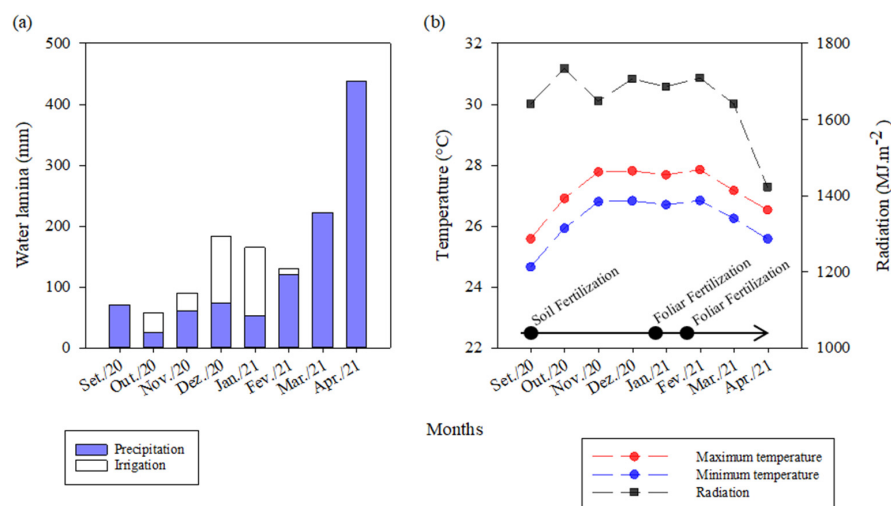


Figure 2. Meteorological characterization of the experimental area. Accumulated precipitation (a); maximum temperature, minimum temperature, and accumulated global solar radiation (b).

2.2. Biomass Accumulation and Nitrogen Recovery in the Aerial Part

The accumulation of biomass and nitrogen in the aerial part of sugarcane was performed at 162 DAP (before the first foliar application), 194 DAP (before the second foliar application), and 224 DAP (leaf +1 of the second fertilization became leaf +3). Each plot was divided into three 0.33 m sessions, and three tillers were randomly collected (Figure 1).

The components of the collected tillers, i.e., the tip, leaf, stem, and leaf +1, were separated, weighed, and crushed in a forage mill. A subsample of each component was collected and dried in an oven with forced air circulation at 65°C until reaching constant mass [39]. With the result of the fresh and dry mass of the components, the moisture content

of the subsample was estimated. The biomass accumulation in the aerial part per plant was estimated by the sum of the dry mass of each component.

The dry components of sugarcane were processed in a Willey-type mill and sieved (1 mm mesh) to determine the total N content using the Kjeldahl method [40]. The amount of N accumulated per tiller was obtained from the product of the sum of the N content and the biomass accumulated by each compartment.

The dry leaves +1 were processed in a laboratory ball mill until a fine powder was obtained. The dried leaves +1 were processed in a ball mill, and 0.1 g of this material was separated and subjected to digestion using the Duma method [41]. The abundance of ^{15}N atoms (% in ^{15}N atoms) was assessed by mass spectrometry using an N analyzer, model ANCA-GSL [41]. With the results of the abundance of ^{15}N atoms, the amount of nitrogen derived from the fertilizer source (NDDF) in the aerial part (Equations (1) and (2)) and the RNf in the sugarcane (Equation (3)) were estimated [7,42].

$$\text{NDDF (\%)} = [(a - c)/(b - c)] \times 100 \quad (1)$$

$$\text{NDDF (g plant}^{-1}\text{)} = (\text{NDDF}/100) \times \text{Ntotal} \quad (2)$$

$$\text{RNf (\%)} = (\text{NDDF}/\text{Np}) \times 100 \quad (3)$$

where NDDF = nitrogen derived from fertilizer; a = abundance of ^{15}N atoms in the plant; b = abundance of ^{15}N atoms in the fertilizer (2.08%); c = natural abundance of ^{15}N atoms (0.3663%); Ntotal (g plant $^{-1}$) = total nitrogen of the aerial part; RNf (%) = recovery of nitrogen from fertilizer; Np (g plant $^{-1}$) = amount of N fertilizer applied in the treatment.

2.3. Data Analysis

The results obtained were subjected to an analysis of normality of the residues using the Shapiro–Wilk test ($p < 0.05$) and an evaluation of the homogeneity of variances using the Levene test ($p < 0.05$). The normal and homoscedastic results were subjected to the analysis of variance (ANOVA) and the F test ($p < 0.05$ and 0.10). The variables that presented significant differences in the F test had their means compared using the Tukey test ($p < 0.05$ and 0.10). The SAS (Analytics Software & Solutions, <https://welcome.oda.sas.com/>, accessed on 3 October 2024) OnDemand for Academics Software was used in the data analysis.

3. Results

3.1. Accumulation and Recovery of N Fertilizer in the Aerial Part of Sugarcane

The reduction of the N dose applied to the soil did not affect the accumulation of N in the plant until the first foliar fertilization (162 DAP) (Figure 3) but reduced the abundance of ^{15}N atoms, NDDF, and RNf (Figure 4a–c). The dose of 4.5 g plot $^{-1}$ of N in the soil reduced ($p < 0.05$) the abundance of ^{15}N atoms (%), NDDF, and RNf by approximately 18%, 34%, and 48%, respectively, concerning the doses of 6.0 g plot $^{-1}$ and 5.0 g plot $^{-1}$ of N (Figure 4a–c).

Thirty-two days after the first foliar fertilization (194 DAP), a difference in N accumulation between the managements was only noted in the leaves (Figure 3). The N accumulated in the leaf of the 4.5 + (1.5) g plot $^{-1}$ management was 31% higher than that in the management using conventional (6.0 g plot $^{-1}$) and 5.0 + (1.0) g plot $^{-1}$ of N (Figure 3). Managements that received the highest doses of foliar N, 5.0 + (1.0) and 4.5 + (1.5) g plot $^{-1}$, increased the ^{15}N (%) and NDDF in the aerial part of the sugarcane by 22% and 34%, respectively, compared to the results for the conventional fertilization management (6.0 g plot $^{-1}$). The RNf was similar between the N managements, with an average of 26% of the N applied (Figure 4c).

The N managements that received the second foliar application of N, 5.0 + (0.5 + 0.5) and 4.5 + (7.5 + 7.5) g plot $^{-1}$, increased N accumulation in the tip and plant at 224 DAP (Figure 3). Foliar fertilization increased ^{15}N (%), NDDF, and RNf compared to the results for conventional fertilization (6.0 g plot $^{-1}$ of N). The management 4.5 + (0.75 + 0.75) g plot $^{-1}$ of N surpassed the others with a greater N accumulation in the whole plant (0.63 g plant $^{-1}$

of N), along with a greater abundance of ^{15}N atoms (1.06% of ^{15}N atoms) and a higher NDDF (41%) and RNf (46%) (Figure 4a–c).

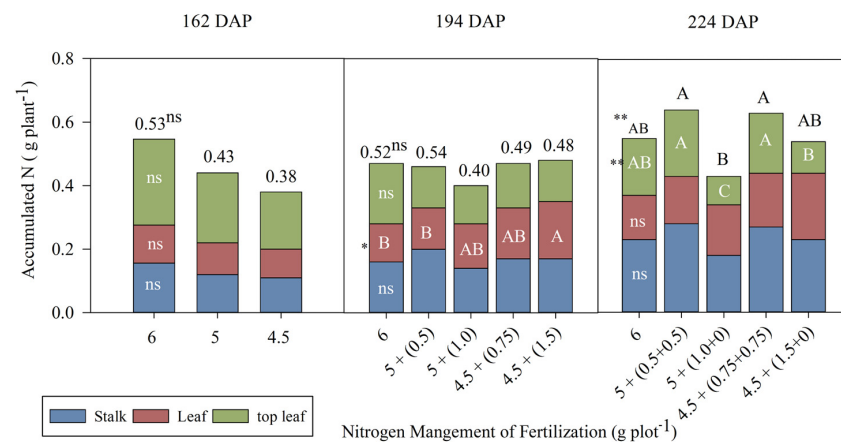


Figure 3. Nitrogen accumulated in the aerial part of sugarcane due to different nitrogen fertilizer managements. ^{ns}, ^{**} and ^{*} followed by different letters (A, B, C) between plants and compartments indicate not significant, significant difference at $p < 0.05$ and $p < 0.10$, respectively, according to the Tukey test. The values in parentheses represent the nitrogen dose applied to the sugarcane leaf. DAP, days after planting.

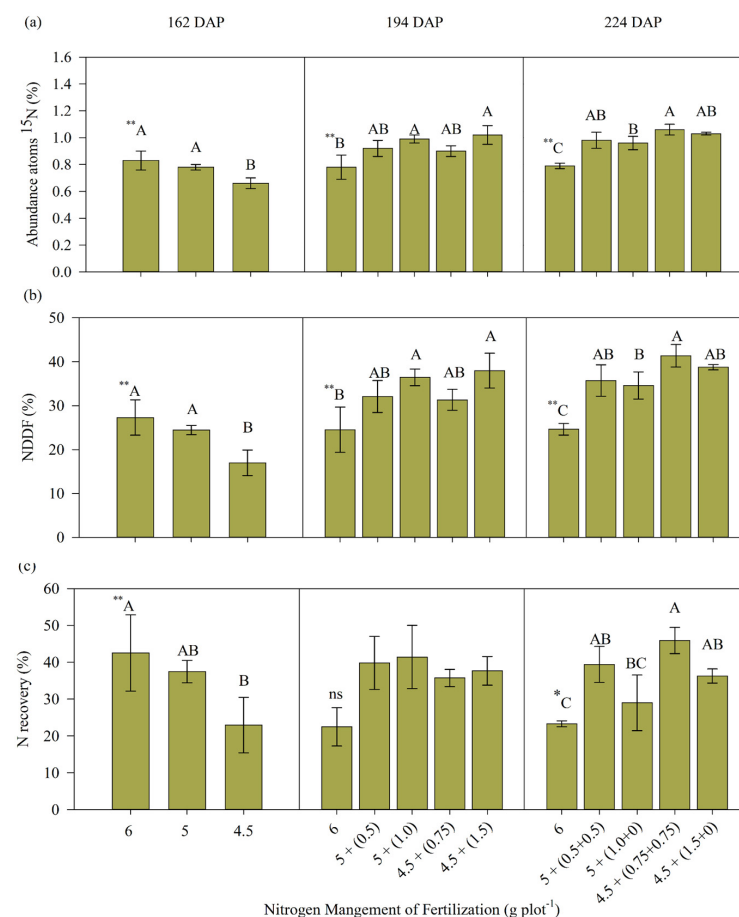


Figure 4. Abundance of ^{15}N atoms in leaf +1 of sugarcane (a), Nitrogen derived from fertilizer in the aerial part (b) and Nitrogen recovery in the aerial part (c). ^{ns}, ^{*} and ^{**} followed by different letters (A, B, C) between plants and compartments indicate not significant, significant difference at $p < 0.05$ and $p < 0.10$, respectively, by the Tukey test. The values in parentheses represent the nitrogen dose applied to the sugarcane leaf. DAP; days after planting.

3.2. Biomass Accumulation in the Aerial Part of Sugarcane

The reduction of the N dose in the soil before foliar fertilization and the supplementation of N with foliar fertilization (194 and 224 DAP) did not affect biomass accumulation in the components or the plant (Figure 5). On average, the biomass accumulated by the plant before and after the first and second foliar fertilization corresponded to 162 g plant⁻¹, 226 g plant⁻¹, and 301 g plant⁻¹, respectively.

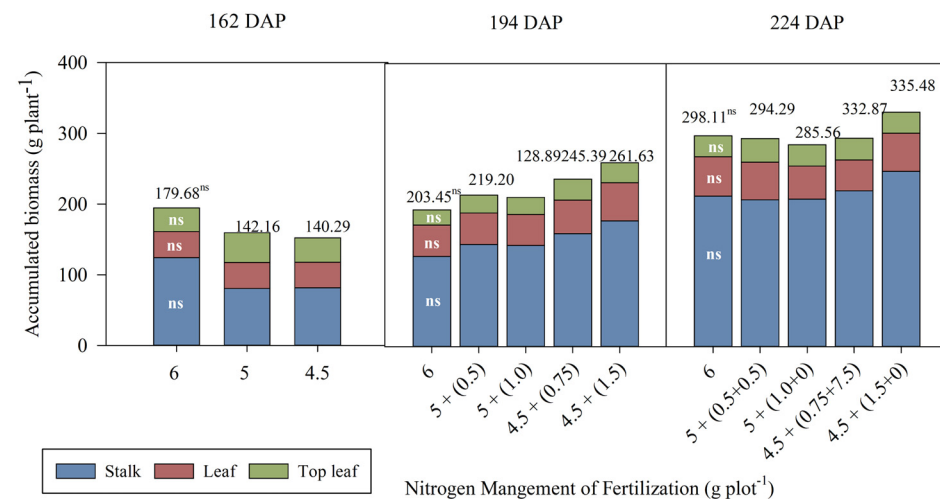


Figure 5. Accumulated biomass in the aerial part. ^{ns} in plants and compartments indicate not significant according to the Tukey test. The values in parentheses represent the nitrogen dose applied to the sugarcane leaf. DAP, days after planting.

4. Discussion

In Brazil, the nutritional requirements of the sugarcane (cane plant) are met with 60 kg ha⁻¹ of N, but on average, 26% of the applied N is recovered by the plant in the sugarcane field [9]. In this study, the RNf in the management with conventional fertilization (6.0 g plot⁻¹ of N via soil) was low and reduced from 42% to 23% of the N applied between 162 and 224 DAP (Figure 4c). The difference between the fertilization time and the phase of maximum absorption of the crop, associated with the immobilization and losses of N fertilizer in the system, are the main causes of the low RNf in conventional fertilization management [5,8].

The amount of N applied to the soil affects fertilization efficiency and sugarcane nutrition [43,44]. In this study, the reduction from 6.0 g plot⁻¹ to 4.5 g plot⁻¹ of soil N reduced ¹⁵N (%), NDDE, and RNf by 13%, 24%, and 28%, respectively, before the first foliar fertilization (162 DAP) (Figure 4a–c). However, it did not affect the accumulation of N in the sugarcane aerial part (Figure 3). This indicates that the plant compensated the uptake and assimilation of ¹⁵N fertilizer with other natural sources of N in the environment resulting from atmospheric N deposition, biological N fixation (BNF), or soil organic matter (SOM) [45–47]. N from MOS is the main natural source of N for sugarcane in the sugarcane field [47–49], capable of contributing up to 90% of the N absorbed by the plant [24].

When the amount of N applied by the management systems was equal to 6.0 g plot⁻¹ (224 DAP), the assimilation and RNf were higher in the management systems with foliar fertilization (Figures 3 and 4a–c). These management systems increased the NDDE and RNf by 30% and 40% on average, respectively, compared to the results for the management system using conventional fertilization (6.0 g plot⁻¹ of N via soil). The main reason for this result is the greater availability of N applied to the leaves than N applied to the soil [5,16].

In conventional fertilization management (via soil), only 42% of the applied N is available for sugarcane due to the processes of loss and immobilization of N [9]. In conventional fertilization management, sugarcane absorbs N through the roots in nitric (NO₃⁻) and ammoniacal (NH₄⁺) forms. Before being assimilated, the absorbed NO₃⁻ is

reduced to NO_2^- by nitrate reductase (NR) and then to NH_4^+ by nitrite reductase (NiR) in the root plastids or the chloroplasts of the leaves [26]. The NH_4^+ reduced or absorbed by the roots is assimilated, preferentially, by the enzymes glutamine synthase (GS) and glutamate synthase (GOGAT) in the plastids/chloroplasts [17,50].

In sugarcane, the activity of the enzymes NR and GS/GOGAT is greater in the leaf [43,51] because the NR-NADH/NiR and GS/GOGAT-Fed complexes of the leaf chloroplasts are more efficient in transferring energy to the reduction and assimilation reactions than are the NR-NADPH/NiR and GS/GOGAT-NADH complexes of the root plastids [52]. Therefore, the abundance of ^{15}N atoms (Figure 4a), the NDDF (Figure 4b), and the RNf (Figure 4c) in the management with foliar fertilization (244 DAP) are higher compared to those in conventional fertilization management.

On average, 37% of the applied N was recovered by sugarcane in the management with foliar fertilization (244 DAP) (Figure 4c). This represents an average increase of 38% in RNf under conventional fertilization management. These results are lower than those of Leite [23], Castro [16], and Trivelin [21], who obtained an RNf of 58%, 60%, and 70%, respectively, with foliar fertilization in sugarcane.

The lower RNf found in this study may have occurred due to any of the following: (i) The presence of more than one N source in the environment, which can dilute to ^{15}N (%). In this study, sugarcane was grown in soil and was susceptible to natural N sources, mainly from SOM (Table 1). In the studies of Leite [23], Castro [16], and Trivelin [21], sugarcane was grown on a sandy substrate in which ^{15}N fertilizer was the only source of N for the plant; this may have resulted in an overestimation of the efficiency of foliar fertilization. (ii) There was no leaf rehydration after foliar fertilization. The rehydration of the leaf after foliar fertilization increases the mobility and diffusivity of urea through the cuticle [53]. Leite [23] found that leaf rehydration increases RNf by 70%. In this study, the absence of rehydration promoted the formation of salts on the leaf surface at the most concentrated doses of N-urea (14.80% urea, 1.0 g plot^{-1} , and 22.20% urea, 1.50 g plot^{-1}). (iii) The occurrence of rain after the first (8 h) and second (24 h) foliar application. Trivelin [21] found that precipitation after foliar fertilization reduces RNf by 10%. (iv) The time of RNf evaluation. RNf in the studies of Leite [23], Castro [16], and Trivelin [21] coincided with the early stages of sugarcane growth, when N fertilizer is the main source of N for the crop [7,47].

The splitting of foliar fertilization (7.50% , $0.5 + 0.5 \text{ g plot}^{-1}$, and 11.10% , $0.75 + 0.75 \text{ g plot}^{-1}$) implied better assimilation and RNf by sugarcane (Figures 3 and 4c) compared to the results for single-dose fertilization (14.80% , 1.0 g plot^{-1} , and 22.20% , 1.5 g plot^{-1}) due to the lower concentration of urea-N in the applied solution. Similarly, Castro [16] found the highest RNf in foliar fertilization with 8% N-urea, while a solution with more than 16% N-urea reduced RNf and promoted injuries in the sugarcane leaves (RB92 579).

In foliar fertilization, N-urea $[(\text{NH}_2)_2\text{CO}]$ crosses the amorphous domain of the cuticle by dissolution–diffusion [53–55]. It passes through the cell membrane through aquaporins [56]. In the cytoplasm, urea is hydrolyzed to NH_4^+ by the enzyme urease, which is preferentially assimilated by the GS-GOGAT complex [26,57]. At high concentrations, NH_4^+ saturates via GS-GOGAT, and glutamate dehydrogenase (GDH) is used to reduce the concentration of NH_4^+ in the plant [16,26,58,59]. High concentrations of NH_4^+ in the cell dissipate the electrochemical gradient of protons and compromise the flow of elements across the plasma membrane [60–62]. In this condition, the biosynthesis of metabolites and the exclusion/metabolization of toxic metabolites are compromised. Cell apoptosis, tissue senescence, and leaf blight occur in this situation [16,26,59,63].

The N application close to metabolic sites; greater absorption, assimilation, remobilization; and the conversion of N into biomass are the main advantages of foliar fertilization in the management of nitrogen nutrition [19,20]. In this study, foliar fertilization improved the absorption and assimilation of nitrogen from fertilizer compared to the results for conventional fertilization (Figures 3 and 4a–c). However, the conversion of N into biomass was similar to that for conventional fertilization (Figure 5). This may have occurred because,

in this study, the amount of N applied to the leaves represented between 20% and 30% of all N accumulated in the aerial part of sugarcane (Figure 3).

Plant age at the time of foliar fertilization may also have affected the N conversion to biomass in the plant [64]. The N requirements of RB92-579 sugarcane are a maximum of between 90–120 DAP, while the maximum capacity for conversion of N into biomass occurs up to 180 DAP [65]. In this study, foliar fertilization was performed at 163 DAP and 195 DAP. The best N conversion capacity into biomass was observed after the first foliar fertilization (Figure 5). After the second application, the management responses for both foliar and conventional fertilization were similar.

Therefore, it is possible that the timing of foliar fertilization and the amount of N assimilated by the plant directed N to the regulatory pathways of secondary metabolism to the detriment of the carbon assimilation and biomass production pathways associated with the plant's primary metabolism [16,66,67].

5. Conclusions

Reducing the N rate applied at planting did not affect N accumulation in the aerial part of sugarcane during the initial growth phase (162 days after planting). Sugarcane compensated for the absorption and assimilation of ^{15}N fertilizer by other N sources in the environment when the N dose applied to the soil was reduced from 6.0 g plot $^{-1}$ of N to 5.0 and 4.5 g plot $^{-1}$ of N.

The N fertilizer recovery in the management employing complementary foliar fertilization was 38% higher than that in conventional fertilization management (224 days after planting). Foliar fertilization management in sugarcane was more efficient for absorbing and recovering N fertilizer, especially when using split foliar fertilization (0.5 + 0.5 g plot $^{-1}$, 7.50% of N-urea; 0.75 + 0.75 g plot $^{-1}$, 11.10% of N-urea).

Fertilization management using 4.5 g plot $^{-1}$ of N, applied to the soil in two applications of 0.75 g plot $^{-1}$ of N via foliar application, was the most efficient management method, providing a larger accumulation of N, a greater abundance of ^{15}N atoms, and an increased participation and recovery of the ^{15}N fertilizer in the aerial part of the sugarcane.

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References

1. Do Vale, D.W.; Prado, R.D.M.; Avalhães, C.C.; Hojo, R.H. Omissão de macronutrientes na nutrição e no crescimento da cana-de-açúcar cultivada em solução nutritiva. *Rev. Bras. Ciênc. Agrár.* **2011**, *6*, 189–196. [\[CrossRef\]](#)
2. Cherubin, M.R.; Lisboa, I.P.; Silva, A.G.B.; Varanda, L.L.; Bordonal, R.O.; Carvalho, J.L.N.; Otto, R.; Pavinato, P.S.; Soltangheisi, A.; Cerri, C.E.P. Sugarcane Straw Removal: Implications to Soil Fertility and Fertilizer Demand in Brazil. *Bioenergy Res.* **2019**, *12*, 888–900. [\[CrossRef\]](#)

3. Oliveira, E.C.A.d.; Freire, F.J.; de Oliveira, R.I.; de Oliveira, A.C.; dos Santos Freire, M.B.G. Acúmulo e alocação de nutrientes em cana-de-açúcar. *Rev. Cienc. Agron.* **2011**, *42*, 579–588.
4. Shrivastava, A.K.; Solomon, S.; Rai, R.K.; Singh, P.; Chandra, A.; Jain, R.; Shukla, S.P. Physiological Interventions for Enhancing Sugarcane and Sugar Productivity. *Sugar Tech* **2015**, *17*, 215–226. [\[CrossRef\]](#)
5. Otto, R.; Souza-Netto, G.J.M.d.; Ferraz-Almeida, R.; Altarugio, L.M.; Favarin, J.L. Multisite response of sugarcane to nitrogen rates and split application under Brazilian field conditions. *Agron. J.* **2021**, *113*, 419–435. [\[CrossRef\]](#)
6. Trivelin, P.C.O.; Vitti, G.C.; Oliveira, M.W.; Gava, G.J.C.; Sarriés, G.A. Utilização de nitrogênio e produtividade da cana-de-açúcar (cana-planta) em solo arenoso com incorporação de resíduos da cultura. *Rev. Bras. Cienc. Solo* **2002**, *26*, 637–646. [\[CrossRef\]](#)
7. Franco, H.C.J.; Otto, R.; Faroni, C.E.; Vitti, A.C.; Almeida de Oliveira, E.C.; Trivelin, P.C.O. Nitrogen in sugarcane derived from fertilizer under Brazilian field conditions. *Field Crops Res.* **2011**, *121*, 29–41. [\[CrossRef\]](#)
8. Yang, L.; Zhou, Y.; Meng, B.; Zhan, J.; Xi, M.; Deng, Y.; Wu, W.; Lakshmanan, P.; Chen, X.; Zhang, F. High sugarcane yield and large reduction in reactive nitrogen loss can be achieved by lowering nitrogen input. *Agric. Ecosyst. Environ.* **2024**, *369*, 109032. [\[CrossRef\]](#)
9. Otto, R.; Castro, S.A.Q.; Mariano, E.; Castro, S.G.Q.; Franco, H.C.J.; Trivelin, P.C.O. Nitrogen Use Efficiency for Sugarcane-Biofuel Production: What Is Next? *Bioenergy Res.* **2016**, *9*, 1272–1289. [\[CrossRef\]](#)
10. Boschiero, B.N.; Mariano, E.; Trivelin, P.C.O. “Preferential” ammonium uptake by sugarcane does not increase the ¹⁵N recovery of fertilizer sources. *Plant Soil* **2018**, *429*, 253–269. [\[CrossRef\]](#)
11. Moreira, L.A.; Otto, R.; Cantarella, H.; Junior, J.L.; Azevedo, R.A.; de Mira, A.B. Urea-Versus Ammonium Nitrate-Based Fertilizers for Green Sugarcane Cultivation. *J. Soil Sci. Plant Nutr.* **2021**, *21*, 1329–1338. [\[CrossRef\]](#)
12. Carvalho, J.L.N.; Oliveira, B.G.; Cantarella, H.; Chagas, M.F.; Gonzaga, L.C.; Lourenço, K.S.; Bordonal, R.O.; Bonomi, A. Implications of regional N₂O–N emission factors on sugarcane ethanol emissions and granted decarbonization certificates. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111423. [\[CrossRef\]](#)
13. Vera, J.C.; Portocarrero, R.; Piñeiro, G.; Acreche, M.M. Increases in nitrogen use efficiency decrease nitrous oxide emissions but can penalize yield in sugarcane. *Nutr. Cycl. Agroecosyst.* **2022**, *122*, 41–57. [\[CrossRef\]](#)
14. Gava, G.J.C.; Trivelin, P.C.O.; Vitti, A.C.; Oliveira, M.W. Recovery of nitrogen (N-15) from urea and cane trash by sugar cane ratoon (*Saccharum* spp.). *Rev. Bras. Cienc. Solo* **2003**, *27*, 621–630. [\[CrossRef\]](#)
15. Dos Santos, R.L.; Oliveira, D.M.d.A.; Santos, R.V.d.S.; de Moura, M.J.A.; Guedes, V.H.d.F.; Barbosa, J.d.A.; Lopes, N.R.d.C.; Costa, L.G.d.A.F.; da Silva, J.L.F.; da Costa Santos, M.B.; et al. Nitrate Reductase Activity, Productivity and Technological Quality of Sugarcane Under Molybdenum and Nitrogen Fertilization. *Sugar Tech* **2022**, *24*, 463–472. [\[CrossRef\]](#)
16. Castro, S.A.Q.; Sermarini, R.A.; Rossi, M.L.; Castro, R.R.L.; Trivelin, P.C.O.; Linhares, F.S. Optimizing foliar N-fertilization in sugarcane depends on plant genotype. *Physiol. Plant.* **2023**, *175*, 14085. [\[CrossRef\]](#)
17. Cassim, B.M.A.R.; Lisboa, I.P.; Besen, M.R.; Otto, R.; Cantarella, H.; Inoue, T.T.; Batista, M.A. Nitrogen: From discovery, plant assimilation, sustainable usage to current enhanced efficiency fertilizers technologies—A review. *Rev. Bras. Cienc. Solo* **2024**, *48*, e0230037. [\[CrossRef\]](#)
18. Uscola, M.; Villar-Salvador, P.; Oliet, J.; Warren, C.R. Foliar absorption and root translocation of nitrogen from different chemical forms in seedlings of two Mediterranean trees. *Environ. Exp. Bot.* **2014**, *104*, 34–43. [\[CrossRef\]](#)
19. Checa, R.R.; Pérez-Jordán, H.; García-Gómez, H.; Prieto-Benítez, S.; González-Fernández, I.; Alonso, R. Foliar nitrogen uptake in broadleaf evergreen Mediterranean forests: Fertilisation experiment with labelled nitrogen. *Sci. Total Environ.* **2024**, *926*, 171865. [\[CrossRef\]](#)
20. Kaya, C.; Ashraf, M. Foliar Fertilization: A Potential Strategy for Improving Plant Salt Tolerance. *CRC Crit. Rev. Plant Sci.* **2024**, *43*, 94–115. [\[CrossRef\]](#)
21. Trivelin, P.O.C.; Carvalho, J.G.d.; Silva, A.Q.; Promavesi, A.C.P.A.; Camacho, E.; Elmor, M.R.; Guilherme, M.R. Adubação foliar de Cana-de-açúcar (*Saccharum* spp): Absorção e translocação de Uréia ¹⁵-N. *Energ. Nucl. Agric.* **1988**, *9*, 52–65.
22. Sangplung, N.; Rosário, E.L. Response of sugarcane to foliar application of urea. *Philipp. J. Crop Sci.* **1978**, *3*, 103–109.
23. Leite, J.M.; Pitumpe Arachchige, P.S.; Ciampitti, I.A.; Hettiarachchi, G.M.; Maurmann, L.; Trivelin, P.C.O.; Prasad, P.V.V.; Sunoj, S.V.J. Co-addition of humic substances and humic acids with urea enhances foliar nitrogen use efficiency in sugarcane (*Saccharum officinarum* L.). *Heliyon* **2020**, *6*, e05100. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Joris, H.A.W.; Vitti, A.C.; Ferraz-Almeida, R.; Otto, R.; Cantarella, H. Long-term N fertilization reduces uptake of N from fertilizer and increases the uptake of N from soil. *Sci. Rep.* **2020**, *10*, 18834. [\[CrossRef\]](#)
25. Phillips, S.B.; Mullins, G.L. Foliar burn and wheat grain yield responses following topdress-applied nitrogen and sulfur fertilizers. *J. Plant Nutr.* **2004**, *27*, 921–930. [\[CrossRef\]](#)
26. Shilpha, J.; Song, J.; Jeong, B.R. Ammonium Phytotoxicity and Tolerance: An Insight into Ammonium Nutrition to Improve Crop Productivity. *Agronomy* **2023**, *13*, 1487. [\[CrossRef\]](#)
27. Betiol, R.A.B.; Ferraz-Almeida, R.; Otto, R.; Cesar Vitti, G. Borated Fertilizations via Foliar and Soil for Peanut Production during the Sugarcane Reform. *Agriculture* **2023**, *13*, 347. [\[CrossRef\]](#)
28. FAO. *World Reference Base for Soil Resources 2014 Maps, International Soil Classification System for Naming Soils and Creating Legends for Soil*; FAO: Rome, Italy, 2015. [\[CrossRef\]](#)
29. Crusciol, C.A.C.; Rossato, O.B.; Foltran, R.; Martello, J.M.; do Nascimento, C.A.C. Soil Fertility, Sugarcane Yield Affected by Limestone, Silicate, and Gypsum Application. *Commun. Soil Sci. Plant Anal.* **2017**, *48*, 2314–2323. [\[CrossRef\]](#)

30. Neto, D.E.S.; de Oliveira, A.C.; Freire, F.J.; dos Santos Freire, M.B.G.; de Oliveira, E.C.A.; da Rocha, A.T. Adubação fosfatada para cana-de-açúcar em solos representativos para o cultivo da espécie no Nordeste Brasileiro. *Pesqui. Agropecu. Bras.* **2015**, *50*, 73–81. [\[CrossRef\]](#)
31. Da Rocha, I.T.M.; Freire, F.J.; de Oliveira, E.C.A.; de Souza, E.R.; Freire, M.B.G.d.S.; Neto, D.E.S.; da Silva, A.V. Salt effect of potassium fertilizer on productivity and technological quality of sugarcane. *Aust. J. Crop Sci.* **2019**, *13*, 1552–1560. [\[CrossRef\]](#)
32. Benett, C.G.S.; Buzetti, S.; Silva, K.S.; Teixeira Filho, M.C.M.; Garcia, C.M.d.P.; Maestrello, P.R. Produtividade e desenvolvimento da cana-planta e soca em função de doses e fontes de manganês. *Rev. Bras. Ciênc. Solo* **2011**, *35*, 1661–1667. [\[CrossRef\]](#)
33. Dos Santos, R.L.; Freire, F.J.; de Oliveira, E.C.A.; Neto, D.E.S.; de Medeiros, M.R.F.A.; Bezerra, P.d.C.; de Moura, M.J.A.; Barbosa, J.d.A.; Lopes, N.R.d.C.; Santos, N.d.L. Productivity and technological quality of sugarcane under fertilization of nitrogen and molybdenum. *J. Soil Sci. Plant Nutr.* **2018**, *18*, 1002–1020. [\[CrossRef\]](#)
34. Marangoni, F.F.; Otto, R.; de Almeida, R.F.; Casarin, V.; Vitti, G.C.; Tiritan, C.S. Soluble Sources of Zinc and Boron on Sugarcane Yield in Southeast Brazil. *Sugar Tech* **2019**, *21*, 917–924. [\[CrossRef\]](#)
35. Simões-Neto, D.E. Variedades de Cana-de-açúcar no Estado de Pernambuco Contribuição do Melhoramento Clássico da RIDESA-UFRPE. *An. Acad. Pernamb. Ciênc. Agron.* **2009**, *5*, 125–146.
36. De Oliveira, E.C.A.; Freire, F.J.; de Oliveira, R.I.; Freire, M.B.G.d.S.; Neto, D.E.S.; da Silva, S.A.M. Extração e Exportação de Nutrientes por Variedades de Cana-de-Açúcar Cultivadas Sob Irrigação Plena. *Rev. Bras. Ciênc. Solo* **2010**, *34*, 1343–1352. [\[CrossRef\]](#)
37. Santana, A.C.A.; de Oliveira, E.C.A.; da Silva, V.S.G.; Dos Santos, R.L.; da Silva, M.A.; Freire, F.J. Critical nitrogen dilution curves and productivity assessments for plant cane | Curvas de diluição do nitrogênio crítico e produtividade da cana planta. *Rev. Bras. Eng. Agric. Ambient.* **2020**, *24*, 244–251. [\[CrossRef\]](#)
38. Marin, F.R.; Pellegrino, G.Q.; Pinto, H.S.; Zullo Junior, J. *Agrometeorologia dos Cultivos*, 1st ed.; Monteiro, J.E.B.A., Ed.; Instituto Nacional de Meteorologia—INMET: Brasília, Brazil, 2009; p. 530.
39. Embrapa. *Manual de Análise Químicas de Solo, Plantas e Fertilizantes*, 2nd ed.; Embrapa: Brasília, Brazil, 2009.
40. Trivelin, P.C.O.; Salati, E.; Matsui, E. *Boletim Técnico*; Escola Superior de Agricultura “Luiz de Queiroz”-USP/CNEN: São Paulo, Brazil, 1973; p. 44.
41. Trivelin, P.C.O.; Lara Cabezas, W.A.R.; Victoria, R.L.; Reichardt, K. Evaluation of a 15N plot design for estimating plant recovery of fertilizer nitrogen applied to sugar cane. *Sci. Agric.* **1994**, *51*, 226–234. [\[CrossRef\]](#)
42. Yang, Y.; Gao, S.; Jiang, Y.; Lin, Z.; Luo, J.; Li, M.; Guo, J.; Su, Y.; Xu, L.; Que, Y. The physiological and agronomic responses to nitrogen dosage in different sugarcane varieties. *Front. Plant Sci.* **2019**, *10*, 406. [\[CrossRef\]](#)
43. Zeng, X.; Zhu, K.; Lu, J.; Jiang, Y.; Yang, L.; Xing, Y. Long-Term Effects of Different Nitrogen Levels on Growth, Yield, and Quality in Sugarcane. *Agronomy* **2020**, *10*, 353. [\[CrossRef\]](#)
44. Zhang, Y.; Ding, H.; Zheng, X.; Cai, Z.; Misselbrook, T.; Carswell, A.; Müller, C.; Zhang, J. Soil N transformation mechanisms can effectively conserve N in soil under saturated conditions compared to unsaturated conditions in subtropical China. *Biol. Fertil. Soils* **2018**, *54*, 495–507. [\[CrossRef\]](#)
45. Wang, W.; Xu, W.; Wen, Z.; Wang, D.; Wang, S.; Zhang, Z.; Zhao, Y.; Liu, X. Characteristics of Atmospheric Reactive Nitrogen Deposition in Nyingchi City. *Sci. Rep.* **2019**, *9*, 4645. [\[CrossRef\]](#) [\[PubMed\]](#)
46. Pereira, W.; Oliveira, R.P.; Pereira, A.; Sousa, J.S.; Schultz, N.; Urquiaga, S.; Reis, V.M. Nitrogen acquisition and 15N-fertiliser recovery efficiency of sugarcane cultivar RB92579 inoculated with five diazotrophs. *Nutr. Cycl. Agroecosyst.* **2021**, *119*, 37–50. [\[CrossRef\]](#)
47. Zhu, J.; He, N.; Wang, Q.; Yuan, G.; Wen, D.; Yu, G.; Jia, Y. Science of the Total Environment The composition, spatial patterns, and influencing factors of atmospheric wet nitrogen deposition in Chinese terrestrial ecosystems. *Sci. Total Environ.* **2015**, *511*, 777–785. [\[CrossRef\]](#) [\[PubMed\]](#)
48. Antunes, J.E.L.; De Freitas, A.D.S.; Oliveira, L.M.S.; De Lyra, M.D.C.C.P.; Fonseca, M.A.C.; Santos, C.E.R.S.; De Oliveira, J.P.; De Araújo, A.S.F.; Figueiredo, M.V.B. Sugarcane inoculated with endophytic diazotrophic bacteria: Effects on yield, biological nitrogen fixation and industrial characteristics. *An. Acad. Bras. Ciênc.* **2019**, *91*, e20180990. [\[CrossRef\]](#)
49. Daubresse, C.M.; Daniel-Vedele, F.; Dechorgnat, J.; Chardon, F.; Gaufichon, L.; Suzuki, A. Nitrogen uptake, assimilation and remobilization in plants: Challenges for sustainable and productive agriculture. *Ann. Bot.* **2010**, *105*, 1141–1157. [\[CrossRef\]](#)
50. Dos Santos, R.L.; Freire, F.J.; de Oliveira, E.C.A.; Freire, M.B.G.D.S.; West, J.B.; Barbosa, J.d.A.; de Moura, M.J.A.; Bezerra, P.d.C. Nitrate reductase activity and nitrogen and biomass accumulation in sugarcane under molybdenum and nitrogen fertilization. *Rev. Bras. Ciênc. Solo* **2019**, *43*, e0180171. [\[CrossRef\]](#)
51. Yoneyama, T.; Suzuki, A. Light-independent nitrogen assimilation in plant leaves: Nitrate incorporation into glutamine, glutamate, aspartate, and asparagine traced by 15n. *Plants* **2020**, *9*, 1303. [\[CrossRef\]](#)
52. Fernández, V.; Gil-Pelegrín, E.; Eichert, T. Foliar water and solute absorption: An update. *Plant J.* **2021**, *105*, 870–883. [\[CrossRef\]](#)
53. Schreiber, L. Polar paths of diffusion across plant cuticles: New evidence for an old hypothesis. *Ann. Bot.* **2005**, *95*, 1069–1073. [\[CrossRef\]](#)
54. Tredenick, E.C.; Farrell, T.W.; Forstes, E.A.; Psaltis, S.T.P. Nonlinear Porous Diffusion Modeling of Hydrophilic Ionic Agrochemicals in Astomatous Plant Cuticle Aqueous Pores: A Mechanistic Approach. *Front. Plant Sci.* **2017**, *8*, 746. [\[CrossRef\]](#)
55. Wang, M.; Ding, L.; Gao, L.; Li, Y.; Shen, Q.; Guo, S. The interactions of aquaporins and mineral nutrients in higher plants. *Int. J. Mol. Sci.* **2016**, *17*, 1229. [\[CrossRef\]](#) [\[PubMed\]](#)

56. Witte, C.P. Urea metabolism in plants. *Plant Sci.* **2011**, *180*, 431–438. [[CrossRef](#)] [[PubMed](#)]
57. Ali, A. Nitrate assimilation pathway in higher plants: Critical role in nitrogen signalling and utilization. *Plant Sci. Today* **2020**, *7*, 157–163. [[CrossRef](#)]
58. Xiao, C.; Fang, Y.; Wang, S.; He, K. The alleviation of ammonium toxicity in plants. *J. Integr. Plant Biol.* **2023**, *65*, 1362–1368. [[CrossRef](#)]
59. Viciado, D.O.; Prado, R.d.M.; Toledo, R.L.; Aguilar, D.S.; dos Santos, L.C.N.; Hurtado, A.C.; Calzada, K.P.; Aguilar, C.B. Physiological role of silicon in radish seedlings under ammonium toxicity. *J. Sci. Food Agric.* **2020**, *100*, 5637–5644. [[CrossRef](#)]
60. Hachiya, T.; Inaba, J.; Wakazaki, M.; Sato, M.; Toyooka, K.; Miyagi, A.; Kawai-Yamada, M.; Sugiura, D.; Nakagawa, T.; Kiba, T.; et al. Excessive ammonium assimilation by plastidic glutamine synthetase causes ammonium toxicity in *Arabidopsis thaliana*. *Nat. Commun.* **2021**, *12*, 4944. [[CrossRef](#)]
61. Liu, Y.; Von Wirén, N. Ammonium as a signal for physiological and morphological responses in plants. *J. Exp. Bot.* **2017**, *68*, 2581–2592. [[CrossRef](#)]
62. De Castro, S.A.Q.; Kichey, T.; Persson, D.P.; Schjoerring, J.K. Leaf Scorching following Foliar Fertilization of Wheat with Urea or Urea–Ammonium Nitrate Is Caused by Ammonium Toxicity. *Agronomy* **2022**, *12*, 1405. [[CrossRef](#)]
63. De Castro, S.G.Q.; Neto, J.R.; Kölln, O.T.; Borges, B.M.M.N.; Franco, H.C.J. Decision-making on the optimum timing for nitrogen fertilization on sugarcane ratoon. *Sci. Agric.* **2019**, *76*, 237–242. [[CrossRef](#)]
64. Wanderley, L.R.d.S.; de Oliveira, E.C.A.; Freire, F.J.; Simões Neto, D.E.; dos Santos, R.L. Nutritional Requirement by Irrigated Brazilian Sugarcane Varieties. *Sugar Tech* **2021**, *23*, 762–775. [[CrossRef](#)]
65. Frungillo, L. Mapping the genomic basis of developmental and metabolic responses to nitrogen. *Plant Cell* **2022**, *34*, 4663–4664. [[CrossRef](#)] [[PubMed](#)]
66. Fredes, I.; Moreno, S.; Díaz, F.P.; Gutiérrez, R.A. Nitrate signaling and the control of *Arabidopsis* growth and development. *Curr. Opin. Plant Biol.* **2019**, *47*, 112–118. [[CrossRef](#)] [[PubMed](#)]
67. Salam, U.; Ullah, S.; Tang, Z.H.; Elateeq, A.A.; Khan, Y.; Khan, J.; Khan, A.; Ali, S. Plant Metabolomics: An Overview of the Role of Primary and Secondary Metabolites against Different Environmental Stress Factors. *Life* **2023**, *13*, 706. [[CrossRef](#)] [[PubMed](#)]

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