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RESEARCH ARTICLE

Establishment of DRIS Standards and Indices for Ratoon Cane Production in the Southern Region of Goiás, Brazil

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Abstract This study aimed to determine DRIS standards and indices in commercial sugarcane plantations through soil, leaf, and stem samples collected in the southern region of the state of Goiás, Brazil. The experiment was arranged in a 2 × 2 factorial design with two cultivation systems (with or without vinasse application) and two sugarcane varieties (CTC 4 and RB 867515), both with 50 sampling points. The database was created using the total amount of soil samples collected at a depth of 0–0.20 m for chemical analysis, leaves collected in the period of greatest vegetative development of the crop (240 days after ratoon sprouting) for chemical analysis and the yield of stems for the industry. It was found that fertigation with vinasse can promote increases in the yield of cane stalks for the industry in the order of 35 t ha^{-1} for the variety CTC 4. The DRIS indices for the soil enabled to diagnose limitations caused by nutritional deficiencies regarding the available contents of P and Zn for areas cultivated with CTC 4 and the available contents of K, Cu, Fe, and Mg for areas cultivated with RB 867515. The nutritional diagnosis carried out using the DRIS method for the chemical analysis of leaves showed greater sensitivity for detecting nutritional limitations of Ca, Cu, and Mn compared to traditional methods of interpretation by critical levels. The nutritional balance index (NBI) is an efficient tool for the proper diagnosis of nutritional balance, since the lowest NBI indices were the ones that provided the highest stalk yields of ratoon cane for the industry.

Keyword Nutrient balance · Critical levels · Nutritional relationships · *Saccharum spp*

Introduction

Brazil is considered the largest agricultural producer of sugarcane, which has great socioeconomic importance in the country (Unica 2020). For the 2021/22 season, an average production of 592.03 million tons (t) is expected, with 8.24 million hectares (ha) in planted area and stem yield in the order of 71.82 t ha^{-1} (Conab 2021). The state of Goiás, which is part of the Cerrado biome, is the second largest sugarcane producer in the country; for the 2021/22 season, it is estimated that approximately 4.7 billion liters of biofuel and 2.5 million tons of sugar will be generated in the state (Conab 2021).

The soils of the Cerrado region, which are inserted in the southern region of the state of Goiás, have low natural fertility, high acidity, low organic matter content, low cation retention capacity, and high phosphorus fixation capacity (PFC) (Lopes et al. 2012; Gomes et al. 2017). However, the implementation of soil management practices such as correction and the adequate supply of phosphate fertilizers allowed the overcoming of these chemical limitations, favoring the development of agriculture in the region (Lopes et al. 2012), as well as the introduction of sugarcane production under different environmental conditions in Brazil (Casaroli et al. 2019).

However, soil correction and P supply alone are not capable of providing conditions for high yields in the production of stems in sugarcane cultivation. Thus, the

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proper diagnosis of the current conditions of soil fertility and of the nutritional status of sugarcane plants becomes essential to provide adequate nutritional management aiming at high yields.

Traditional methods of interpreting chemical analyses of soils and leaves such as the methods using critical levels (CL) and/or sufficiency ranges (SR) only consider nutrients in isolation (univariate analysis), not considering possible interactions that exist between nutrients both in the soil and in the plant (Calheiros et al. 2018; Morais et al. 2019; Silva et al. 2021a). These methods also have disadvantages for ignoring uncontrolled factors, such as the rate of biomass accumulation of leaf tissue, light, temperature, and water regime (Wadt 2011; Ribeiro et al. 2020; Silva and Chiaia 2021). On the other hand, methods that use bivariate and multivariate analysis, such as DRIS and CND, respectively, consider the interactions between nutrients, indicating nutritional disorders according to the excess or deficiency of one or more nutrients (Calheiros et al. 2018; Ribeiro et al. 2020; Silva and Chiaia 2021).

The use of DRIS has the advantages of quickly obtaining updated nutritional standards and ordering the nutrients responsible for the nutritional imbalance by excess or limitation (Silva and Chiaia 2021). As a bivariate method, the DRIS incorporates the concept of nutritional balance, besides minimizing non-nutritional effects during the interpretation of the plant nutritional status (Beaufils 1973). Furthermore, it is known that nutrient balance is closely related to plant yield (Fageria et al. 2009). Therefore, proper nutritional diagnosis through the use of DRIS can be efficient to the point of reflecting on the management and characteristics of sugarcane plants (Ribeiro et al. 2020; Silva and Chiaia 2021).

On the other hand, factors such as edaphoclimatic conditions, crop management, and sampling time are crucial to improve the accuracy level of DRIS (Beaufils 1973; Reis Junior and Monnerat 2003; Partelli et al. 2006, 2014). Thus, the determination of DRIS indices and norms for nutritional values of regional reference becomes important for the greater accuracy of the nutritional diagnosis of crops (Rocha et al. 2007; Partelli et al. 2014; Guimarães et al. 2015; Leandro 2016; Calheiros et al. 2018; Silva et al. 2021b).

The studies carried out to generate nutritional diagnoses through the DRIS have been limited to chemical analyses of leaves compared to traditional methods such as CL and SR (Reis Junior and Monnerat 2003; Santos et al. 2013; Guimarães et al. 2015; Calheiros et al. 2018; Silva and Chiaia 2021; Silva et al. 2021b). However, the existence of interactions of nutrients in the soil that are capable of influencing leaf chemical composition is known. Thus, the establishment of DRIS standards and indices in the soil and for plants (foliar) may provide more accurate results compared to traditional methods of nutritional diagnosis.

Therefore, the present study aimed to determine DRIS standards and indices in the soil and plants of commercial sugarcane plantations cultivated in the southern region of the state of Goiás, Brazil.

Material and Methods

Location and Characterization of Study Areas

The study was carried out in the 2018/19 crop season in commercial sugarcane plantations belonging to the São Martinho group in the municipality of Quirinópolis, located in the southern region of the state of Goiás, Brazil (18°33′27“ S and 50°25′38″ W, 485 m altitude). According to the Köppen classification, the climate type of the region is Aw, characterized by a warm and humid climate with two well-defined seasons (rainy summers and dry winters), with average annual rainfall of 1,520 mm (Clima-date 2021).

The experiment was arranged in a 2 $\times$ 2 factorial design with two cultivation systems (with or without vinasse application) and two sugarcane varieties (CTC 4 and RB 867515), both with 50 sampling points, totaling 200 experimental units. In addition, for areas fertigated with vinasse, there was a total application of 10 m^3 during the ratoon cycle. In order to detail each experimental area, the history and management adopted by the plant are shown in Table 1. Similarly, the chemical characterization of the vinasse applied in fertigation is shown in Table 2.

Sampling and Creation of the Database from Soil Chemical Analysis

Soil sampling took place 60 days after sprouting of the sugarcane ratoon and soil application of chemical fertilization. Soil samples were collected in a zig-zag form, considering a depth of 0–0.20 m, using a dutch auger. For each composite sample, 10 simple samples were collected.

For the treatment with fertigation with vinasse, soil samples were collected in November 2018, while the other treatments were collected in January 2019, totaling 200 composite samples, which were identified and sent to the Laboratory. Then, the samples were air-dried, crushed, and passed through a 2-mm mesh opening sieve, obtaining the ADFE (air-dried fine earth). Subsequently, the following chemical attributes were determined: pH ($CaCl_2$), Al^{3+}, P, K^+, Ca^{2+}, Mg^{2+}, organic matter (OM), Cu, Fe, Mn, and Zn, according to the methodology described by Teixeira et al. (2017).

Table 1 History, nutritional and phytosanitary management of commercial areas containing the treatments evaluated by Usina Boa Vista in the production of sugarcane ratoon

CTC 4—With vinasse
Soil class: RED LATOSOL
Textural class: Clay
Predominant fertilization: 10 m^3 ha^{-1} flex vinasse[a]
Complementary fertilization: 17.4% boric acid (4.40 kg ha^{-1}); 46–00-00 urea (230 kg ha^{-1});
Herbicides: 62% glyphosate potassium; 50% atrazine; and 2,4-D Dimethylamine Salt
Insecticide: 60% fipronil
RB867515—WITH VINASSE
Soil class: QUARTZAREANIC NEOSOL
Textural class: Loamy sand
Predominant fertilization: 10 m^3 ha^{-1} flex vinasse[a]
Complementary fertilization: 17.4% boric acid (3.60 kg ha^{-1}); urea 46–00-00 (230 kg ha^{-1}); granulated fertilizer 20–04-18 (550 kg ha^{-1})
Herbicides: 62% glyphosate potassium; 50% tebuthiron; 5% sulfentrazone; 50% flumioxazin; and 2,4- D Dimethylamine Salt
Insecticide: chlorantranilip; 20% etipol and teflubenzuron
CTC 4—Without vinasse
Soil class: RED LATOSOL
Textural class: Very clayey
Predominant fertilization: Boric acid (3.6 kg ha^{-1}); urea 46–00-00 (230 kg ha^{-1}); potassium chloride 00–00-60 (128 kg ha^{-1}), granulated fertilizer 20–04-18 (550 kg ha^{-1})
Herbicides: 62% glyphosate potassium; 50% tebuthiron; 36% clomazone; and diuron 46.8 + HEX
Insecticide: clorantranilip; 75% tiametoxam; 60%; fipronil
RB867515—WITHOUT VINASSE
Soil class: RED LATOSOL
Textural class: Clay
Predominant fertilization: Boric acid (3.60 kg ha^{-1}); urea 46–00-00 (230 kg ha^{-1}); potassium chloride 00–00-60 (128 kg ha^{-1}); granulated fertilizer 20–04-18 (550 kg ha^{-1})
Herbicides: 62% glyphosate potassium; 15% hexazinone; carfentrazone E; 50% atrazine; 50% tebuthiron; 36% clomazone; and diuron 46.8 + HEX
Insecticide: chlorantranilip; teflubenzuron; 60% fipronil and 20% etipol

[a]Concentrated vinasse + in natura vinasse

Table 2 Chemical characterization of the vinasse used in the experiment carried out at Usina Boa Vista, Quirinópolis-Goiás region

Vinasse characterization[1]				
N	P	K	pH	Na
11.96	1.57	10.40	4.27	0.12

[1] kg m^{-3}

Sampling and Creation of the Database from Chemical Analysis of Leaves

Leaf sampling was performed following the procedures proposed by Raij et al. (1996) between the eighth and ninth months after sprouting of the sugarcane ratoon (period of greatest vegetative development of the crop). Thus, leaves were collected in a zig-zag form (leaf + 1, collecting leaves from the apex with the first sheath visible), considering 10 simple samples to form a composite sample. Only the central 20 cm of the leaves were considered, discarding the central vein. After collection, the samples were identified and sent to the laboratory to determine the levels of macronutrients (N, P, K, Ca, Mg, and S) and micronutrients (B, Cu, Fe, Mn, and Zn) of the ratoon cane, following the methodology proposed by Silva (2009).

Leaf sampling of plants fertigated with vinasse took place in March 2019 and the leaf sampling of plants fertilized using conventional fertilization was carried out in May 2019. To interpret the results of the chemical analysis of leaves using the critical levels method, the criteria proposed by Malavolta et al. (1997) were used.

Sampling and Construction of the Database from Sugarcane Stem Yield

The sampling of the stalk yield of each stand was carried out approximately 30 days before the harvest planned by the Plant. This procedure was necessary due to the delay in determining yield data and due to possible changes in the harvest schedule of the plant caused by environmental variations. Thus, the harvest of areas with vinasse application was carried out in July 2019 and the harvest of areas without vinasse was carried out in September 2019. At each sampling point, 5 linear meters was collected, totaling 250 linear meters per treatment.

The harvest was carried out manually from the base of the stems, removing all the straw and pointers (upper cutting point of sugarcane) and separating the stems for the industry. This material was weighed using a portable digital scale, whose nominal accuracy was 10 g.

Previous Analysis of Chemical Data from Soil and Leaves

To characterize soil chemical attributes and the chemical contents of sugarcane leaves, the data obtained were initially transformed into the square root of x + 1 root, with the Shapiro–Wilk test for normality (Hardison et al. 1983) being subsequently performed to verify data adequacy. Then, multivariate analysis was performed to compare the homogeneity or heterogeneity between the chemical attributes in different areas in different environments using the SAS® software, version 3.3.

$$\text{Index } A = \frac{Z(A/B) \ + \ Z(A/C) + \cdots + Z(A/N) - Z\ (B/A) \ - Z(C/A) - \cdots - Z(N/A)}{2(n-1)} \tag{1}$$

Establishment of DRIS Standards

Division into Groups

The data received a treatment consisting of obtaining the standards and calculating and interpreting the DRIS indices. The analyses of leaves comprising the database were divided into two subgroups, according to the yield criterion (Beaufils and Sumner 1977). One subgroup presented yields equal to or above 80 t ha^{-1} (reference population), and the other subgroups presented yields below 80 t ha^{-1} of stems for the industry. This yield value for the division of groups was based on the average yield of stems in the state of Goiás in the 2020/21 crop season, which was approximately 72 t ha^{-1} (Conab 2021), while 80 t ha^{-1} was the targeted yield.

The standards are mean values of concentrations and ratios of nutrient concentrations with their respective variances representing crops with good nutritional conditions (Beaufils 1973; Walworth and Sumner 1987; Malavolta et al. 1989). The DRIS standards were obtained based on the group with the highest yield, called the reference population.

Calculation of the Mean Coefficient of Variation and Variance

For each group, the mean, coefficient of variation, and variance of all possible ratios (direct and indirect) of nutrients from the database created from foliar analysis were calculated. The variance ratios of the low and high yield subgroups were also calculated. The ratios used were those that presented the highest ratios between variances (Sumner 1977).

Calculation of primary indices

The indices were calculated through criteria used in mineral nutrition to calculate the DRIS. The procedure by Alvarez and Leite (1992) was used. The indices were calculated by the average of the direct and inverse ratio of nutrients, according to Eq. 1.

where *Z(A/B)* to *Z(N/A)* are the direct and inverse normal ratios between the contents of all nutrients in relation to nutrient *A*, determined by foliar analysis; (*n*-1) is the number of possible ratios.

Before comparing the variable ratios (sample vs. standard), it was necessary to transform the data of the ratios through reduced functions. The reduced functions were calculated by the procedure demonstrated by Beaufils and Sumner (1977), as described by Eqs. 2 and 3, which takes into account whether the nutrient ratio of the sample is higher or lower than the nutrient ratio of the reference population.

$$Z(A/B) = \left(\frac{A/B}{a/b} - 1\right)\frac{\mathrm{Kt}}{\mathrm{CV}a/b} \quad \mathrm{Se}\,A/B \ > a/b \tag{2}$$

$$Z(A/B) = \left(1 - \frac{a/b}{A/B}\right)\frac{\text{Kt}}{\text{CV}a/b} \quad \text{Se } a/b > A/B \qquad (3)$$

where (*A*/*B*) is the quotient of the contents of nutrients *A* and *B* of the sample under analysis and interpretation; (*a*/*b*) is the mean of the ratio of nutrients *A* and *B* of the reference population; (CVa/b)—is the coefficient of variation in the ratio of nutrients *A* and *B* of the reference population, which satisfies a defined minimum yield level; *Kt* is the sensitivity coefficient, which has an arbitrary value, usually 100, 500 or 1000.

Interpretation of DRIS Indices

DRIS indices were interpreted using the standard procedure proposed by Beaufils (1971). Negative values mean a deficiency of the element in relation to the others; positive values indicate excess, and the closer to zero these indices are, the closer the plant will be to nutritional balance.

In order to establish a standard scale between the indices using the methodology described by Leandro (1998), it was determined that nutrients are considered limiting when their calculated indices are greater than |10| (values of -10 or lower mean limiting for deficiency and values of 10 or more mean limiting for excess). Plants were considered in nutritional balance when the indices were within the range between 0 and 9.

The percentage of occurrence of first order and second order was also obtained, which corresponds to the first and second most negative and most positive indices, respectively, at each sampling point.

Calculation of the Nutritional Balance Index

The NBI was calculated by the sum in module of the DRIS indices for each variable of the foliar analysis at each sampling point. According to Beaufils (1973) and Walworth and Sumner (1987), the lower the NBI, the closer the sample will be to nutritional balance.

DRIS Application

The nutritional status of sugarcane was evaluated in order to compare the results of foliar analysis obtained from commercial sugarcane plantations in the state of Goiás with the DRIS indices established from the database with the reference values described in the literature by Malavolta et al. (1997), using the method of interpretation of critical levels. In addition, based on the reference population (group of samples with yields higher than 80 t ha^{-1}), the sufficiency ranges of the nutrients evaluated in the soil and leaf samples were determined.

Statistical Analysis

Tests of descriptive statistics (mean, standard deviation, and coefficient of variation), analysis of variance (F test), Shapiro–Wilk test ($p \leq 0.05$), and the percentage of occurrence (first and second order) proposed by Leandro (1998) in addition to Tukey test to compare the yield of the stands were performed. Bivariate tests applied to DRIS standards and indices were also applied. To determine the analyses, the statistical software Statistical Analysis System—SAS—was used (Freund and Littel 1981).

Results

DRIS Soil Indices

Tables 1 and 2 show the fertilization management adopted in each of the evaluated areas, and it is possible to observe that the area cultivated with the CTC 4 variety with vinasse fertigation received the application of: 0.75 kg ha^{-1} of B; 225.40 kg ha^{-1} of N (105.8 kg ha^{-1} of N in the form of urea and 119.6 kg ha^{-1} of N in the form of vinasse), in addition to 36 kg ha^{-1} of P_2O_5 and 125.3 kg ha^{-1} of K_2O in the form of vinasse. In the area cultivated with the variety RB867515 fertigated with vinasse, the following were applied: 0.61 kg ha^{-1} of B, 335.4 kg ha^{-1} of N (215.8 kg ha^{-1} of N in the form of urea and 119.6 kg ha^{-1} of N in the form of vinasse), 58 kg ha^{-1} of P_2O_5 (22 kg ha^{-1} of P_2O_5 in the form of granulated fertilizer and 36 kg ha^{-1} of P_2O_5 in the form of vinasse), and 224.4 kg ha^{-1} of K_2O (99.0 kg ha^{-1} of K in the form of granulated fertilizer and 125.4 kg ha^{-1} of K_2O in the form of vinasse). For the areas cultivated with the CTC 4 and RB867515 varieties, but without the application of vinasse, 0.61 kg ha^{-1} of B, 215.8 kg ha^{-1} of N, 22 kg ha^{-1} of P_2O_5, and 175.8 kg ha^{-1} of K_2O were applied in each of the evaluated areas. It was noted that in all areas evaluated, soil improvement practices were not carried out, with the application of limestone, as well as secondary macronutrients (sulfur) and micronutrients, with the exception of B, as shown in Table 1.

The mean contents, the standard deviation, and coefficients of variations for the chemical and granulometric attributes of the soil after the analyses in the four evaluated treatments are shown in Table 3. The contents of P, K, and B, cation exchange capacity (CTC), and aluminum saturation (m, %) stand out, which showed the highest average variations between the values observed in the soil. Furthermore, it is possible to observe that the sampled areas presented granulometry ranging between 135 and 704 g kg^{-1} of clay.

Table 3 Chemical and physical attributes (granulometry) of the soil in commercial sugarcane areas. Varieties CTC 4 and RB867515, with and without vinasse at a depth of 0–0.20 m, municipality of Quirinópolis, GO, Brazil

Soil parameters	CTC 4 with vinasse			RB 867515 with vinasse			CTC 4 without vinasse			RB 867515 without vinasse		
	M	SD	CV%	M	SD	CV%	M	SD	CV%	M	SD	CV%
P (mg dm^{-3})	2.42	3.31	137.01	5.52	3.90	71.40	5.91	4.63	78.24	10.03	1.19	11.85
K^+ (mg dm^{-3})	131.90	70.56	53.49	32.56	15.60	48.41	134.70	45.41	33.71	86.72	32.77	37.78
Ca^{2+} ($cmol_c$ dm^{-3})	1.73	0.32	18.81	1.22	0.29	24.26	2.48	0.75	30.32	1.82	0.54	29.63
Mg^{2+} ($cmol_c$ dm^{-3})	1.00	0.29	28.66	0.41	0.16	38.88	1.10	0.31	27.79	0.71	0.23	33.04
B (mg dm^{-3})	0.67	1.09	164.01	0.87	0.37	42.75	0.20	0.07	34.28	0.03	0.03	115.38
Cu (mg dm^{-3})	1.14	0.35	30.38	0.31	0.19	60.36	8.56	2.64	30.91	1.30	1.22	93.69
Fe (mg dm^{-3})	51.74	40.41	78.10	92.54	17.95	19.60	40.58	8.44	20.81	44.72	10.90	24.37
Mn (mg dm^{-3})	33.48	10.99	32.83	19.84	4.57	23.27	60.42	11.61	19.21	39.14	13.24	33.83
Zn (mg dm^{-3})	0.73	0.54	72.89	0.89	0.62	70.25	1.22	0.79	64.99	1.65	0.71	43.30
OM (%)	1.68	0.40	24.08	0.98	0.24	25.17	2.91	0.52	17.79	2.34	0.50	21.49
pH ($CaCl_2$)	5.07	0.20	3.94	5.29	0.58	11.12	4.87	0.16	3.37	5.16	0.51	9.88
H + Al ($cmol_c$ dm^{-3})	3.09	0.62	20.14	1.80	0.43	24.18	3.82	0.89	23.25	2.66	0.74	27.83
Al ($cmol_c$ dm^{-3})	0.03	0.07	133.33	0.08	0.14	192.72	0.11	0.10	92.17	0.11	0.17	159.44
CEC ($cmol_c$ dm^{-3})	6.16	0.87	14.15	3.52	0.43	12.34	7.74	1.67	21.61	5.41	0.65	11.93
m (%)	1.09	2.57	234.65	4.69	8.97	193.07	3.20	3.30	103.14	4.81	8.25	171.57
V (%)	49.86	6.43	12.89	48.84	9.99	20.66	50.26	6.45	12.84	50.94	12.25	24.06
Clay (%)	44.48	8.42	18.93	13.50	5.84	43.28	70.40	3.39	4.82	50.64	12.91	25.50
Silt (%)	3.12	6.71	215.07	6.72	2.69	40.00	13.28	2.63	19.81	12.88	3.46	26.88
Sand (%)	52.40	5.78	11.04	79.78	4.30	5.39	16.32	2.66	16.28	36.48	13.55	37.15

M Mean of treatments, *SD* Standard deviation, *CV* (%) Coefficient of variation, *OM* Organic matter of soil, *CEC* Cation exchange capacity, *m* (%) Aluminum saturation e *V* (%) Base saturation. Means followed by the same letter on the same line do not differ by Tukey's test at 5% probability

Table 4 Summary of the analysis of variance for the yield of industrializable stalks of sugarcane ratoon as a function of cultivated variety and fertigation with vinasse

Variety	Fertilization treatment	Yield	CV (%)
CTC 4	Fertirrigates with vinasse	109.90 a	32.00
RB 867515	Fertirrigates with vinasse	97.70 ab	36.00
RB 867515	Without Fertigation with Vinasse	88.80 bc	35.00
CTC 4	Without Fertigation with Vinasse	74.80 c	27.00
Variety		**Yield**	**CV (%)**
CTC 4		92.37^{ns}	38.42
RB 867515		93.20^{ns}	32.62
Irrigation management			
With vinasse		103.8 a	34.16
Without vinasse		81.74 b	31.89

Equal lowercase letters in the same column do not differ from each other at the 5% probability level by the Tukey test

The average yields of the treatments evaluated as a function the interaction between fertigation with vinasse and the two varieties are shown in Table 4. It is noted that the treatments that received fertigation presented the highest yields of stems for the industry, with the highest yield being observed for variety CTC 4, approximately 110 t ha^{-1}. On the other hand, when there was no fertigation with vinasse, the same variety presented the lowest yield in relation to the other treatments, approximately 75 t ha^{-1}, that is, a difference of 35 t ha^{-1} between the treatments. When evaluating the stem yield for treatments with the variety RB 867515, the treatments with or without fertigation with vinasse did not differ from each other.

Table 4 also shows the results of the analysis of sugar cane stalk yield, analyzed as a function of the variety cultivated and the irrigation system. It is possible to observe that there were no significant differences between the yield obtained by the varieties, RB 867515 (93.20 t ha^{-1}) and CTC 4 (92.37 t ha^{-1}), regardless of the irrigation system applied. At the same time, when the productivity of canes is evaluated as a function of irrigation management, regardless of the variety cultivated, it was observed that the areas that received fertigation with vinasse, in the amount of 10 m^3 ha^{-1}, showed higher productivity of canes, about 21% higher compared to rain fed areas.

The percentages of occurrence of nutritional limitations due to deficiency or excess observed through chemical analysis of the soil in areas cultivated with the variety CTC 4 for the reference population (total of 122 sampling points with stem yield higher than 80 t ha^{-1}) are shown in Table 5. For the classification of nutritional limitation of first order, DRIS indices equal to or greater than 10 were considered, regardless of whether being positive (limiting by excess) or negative (limiting by deficiency), while for the classification of nutritional limitation of second order, DRIS indices lower than 10 were considered.

When evaluating the limitation of first order due to deficiency for the variety CTC 4 fertigated with vinasse, the following order was observed: P > Fe > Mn = Zn > K = Ca > Mg = Cu, while the limitation of first order due to excess for the same treatment was: Mg > Cu > K > Ca = Mn = Zn > Fe > P. When evaluating the percentage of occurrence of nutritional limitation due to deficiency for the CTC 4 variety without fertigation by vinasse, the following order is observed: P > Zn > K > Ca > Mg, while for the nutrients Cu, Mn, and Fe there were no occurrences of limitations due to nutritional limitations of first order (Table 5). In addition, when the occurrence of nutritional limitations due to excess was evaluated, the following order was observed: K > Mn > Mg > Ca > P > Zn, while limitations of first order due to excess were not observed for Cu and Fe.

Table 6 shows the percentages of occurrence of nutritional limitations observed through chemical analysis of the soil due to deficiency or excess in areas cultivated with the RB 867515 variety for the reference population (total of 122 sampling points with stem yield higher than 80 t ha^{-1}).

For the classification of nutritional limitations of first order, DRIS indices equal to or greater than 10 were

Table 5 Percentage of occurrence of limiting nutrients due to deficiency and excess determined by DRIS indices, obtained by chemical analysis of the soil, population of the variety CTC 4 with vinasse and without vinasse (productivity > 80 t ha^{-1}) of sugarcane

Nutrients	Deficiency limiting nutrients			Excessive limiting nutrients		
	1st order	2nd order	$\sum$*	1st order	2nd order	$\sum$*
With vinasse						
P (mg dm^{-3})	51.75	10.00	61.75	5.11	2.74	7.85
K (mg dm^{-3})	7.89	4.00	11.89	29.48	15.07	44.55
Ca ($cmol_c$ dm^{-3})	7.89	18.00	25.89	13.62	1.37	14.99
Mg ($cmol_c$ dm^{-3})	4.71	2.00	6.71	34.89	5.48	40.36
Cu (mg dm^{-3})	4.71	4.00	8.71	32.76	15.07	47.83
Mn (mg dm^{-3})	31.91	11.00	42.91	13.62	2.74	16.36
Fe (mg dm^{-3})	49.23	14.00	63.23	8.39	0.00	8.39
Zn (mg dm^{-3})	31.91	11.00	42.91	13.62	2.74	16.36
Without vinasse						
P (mg dm^{-3})	70.53	8.00	78.53	15.50	0.00	15.50
K (mg dm^{-3})	15.46	16.00	31.46	47.84	2.50	50.34
Ca ($cmol_c$ dm^{-3})	13.04	8.00	21.04	24.88	2.50	27.38
Mg ($cmol_c$ dm^{-3})	8.70	8.00	16.70	32.57	2.50	35.07
Cu (mg dm^{-3})	0.00	0.00	0.00	0.00	45.00	45.00
Mn (mg dm^{-3})	0.00	8.00	8.00	35.70	0.00	35.70
Fe (mg dm^{-3})	0.00	0.00	0.00	0.00	45.00	45.00
Zn (mg dm^{-3})	28.00	12.00	40.00	7.69	0.00	7.69

*$\sum$ the sum of the limitations of each nutrient is on the line. 1st order (index $\geq|10|$) is more limiting, deficiency or excess, and the 2nd order (index $<|10|$) is less limiting, deficiency or excess, according to the DRIS indices

Table 6 Percentage of occurrence of limiting nutrients due to deficiency and excess determined by DRIS indices, obtained by chemical analysis of the soil, population of the variety RB 867515 with vinasse and without vinasse (productivity > 80 t ha^{-1}) of sugarcane

Nutrients	Deficiency limiting nutrients			Excessive limiting nutrients		
	1st order	2nd order	∑*	1st order	2nd order	∑*
With vinasse						
P (mg dm^{-3})	15.36	15.38	30.74	8.33	13.89	22.22
K (mg dm^{-3})	56.79	10.26	67.04	1.04	0.00	1.04
Ca ($cmol_c$ dm^{-3})	5.36	10.26	15.61	20.67	0.00	20.67
Mg ($cmol_c$ dm^{-3})	34.64	15.38	50.03	5.04	2.78	7.82
Cu (mg dm^{-3})	50.00	11.54	61.54	5.21	0.00	5.21
Mn (mg dm^{-3})	7.14	3.85	10.99	26.42	19.44	45.86
Fe (mg dm^{-3})	1.79	3.85	5.63	22.25	38.89	61.14
Zn (mg dm^{-3})	7.14	3.85	10.99	26.42	19.44	45.86
Without vinasse						
P (mg dm^{-3})	0.00	0.00	0.00	26.23	71.43	97.66
K (mg dm^{-3})	23.33	24.56	47.89	10.34	4.76	15.11
Ca ($cmol_c$ dm^{-3})	18.74	12.28	31.02	20.39	0.00	20.39
Mg ($cmol_c$ dm^{-3})	15.41	12.28	27.69	20.10	0.00	20.10
Cu (mg dm^{-3})	53.24	3.51	56.75	14.60	0.00	14.60
Mn (mg dm^{-3})	19.37	15.79	35.16	18.26	0.00	18.26
Fe (mg dm^{-3})	53.24	3.51	56.75	14.60	0.00	14.60
Zn (mg dm^{-3})	0.00	5.26	5.26	32.86	14.29	47.15

*∑—the sum of the limitations of each nutrient is on the line. 1st order (index ≥|10|) is more limiting, deficiency or excess, and the 2nd order (index <|10|) is less limiting, deficiency or excess, according to the DRIS index

considered, regardless of whether they were positive (limiting by excess) or negative (limiting by deficiency), while for the classification of nutritional limitations of second order, DRIS indices lower than 10 were considered (Table 6).

When evaluating the limitation of first order due to deficiency for the variety RB 867515 fertigated with vinasse, the following order was observed: K > Cu > Mg > P > Mn = Zn > Ca > Fe, while the limitation of first order due to excess for the same treatment was: Mn = Zn > Fe > Ca > P > Cu > Mg > K. When evaluating the percentage of occurrence of nutritional limitation due to deficiency for the variety RB 867515 without fertigation by vinasse, the following order is observed: Cu = Fe > K > Mn > Ca > Mg, whereas for the nutrients P and Zn there were no occurrences of deficiencies due to limitation of first order (Table 6). In addition, when evaluating the occurrence of nutritional limitations due to excess, the following order is observed: Zn > P > Ca > Mg > Mn > Cu = Fe > K.

Table 7 shows the range of sufficiency for the soil nutrient contents to obtain the yield of stems for the industry above 80 t ha^{-1} of cane ratoons cultivated in the southern region of the state of Goiás. It should be noted that the sufficiency ranges for the exchangeable contents of Ca and Mg were the ones that normally presented the closest relationships due to the smallest variation between the contents obtained for the evaluated treatments. On the other hand, it is observed that the contents of K, Fe, and Mn were those that presented the greatest variations for the values obtained in the soil, thus presenting the largest interval in the sufficiency ranges.

In Fig. 1, the DRIS soil indices obtained from the database of soil analyses and the yield of stems for the industry of the varieties CTC 4 and RB 867515 fertigated or not with vinasse are shown. It is noted that for the treatment with the variety CTC 4 fertigated with vinasse (Fig. 1A), DRIS indices greater than 10 were not observed, regardless of whether being positive or negative, suggesting that the chemical analyses of the soil did not present limitations of first order. When performing the DRIS indices for treatments with the variety CTC 4 without fertigation with vinasse (Fig. 1C), it was possible to observe that Cu (55) and Fe (-27) were the two nutrients that presented limitations of first order (≥ 10) for excess and deficiency, respectively. When evaluating the Dris indices in the soil for treatments with the variety RB 867515 fertigated with vinasse (Fig. 1B), it was observed that Fe (25), Cu (–20), P (15), and K (–13) were the nutrients that presented limitations of first order, with

Table 7 Sufficiency range for the soil nutrient contents considered adequate to obtain stalk productivity above 80 t ha^{-1} for the South region of the State of Goiás

Range of sufficiency	
P (mg dm^{-3})	3.01–8.93
K (mg dm^{-3})	55.01–137.93
Ca ($cmol_c$ dm^{-3})	1.36–2.27
Mg ($cmol_c$ dm^{-3})	0.56–1.05
B (mg dm^{-3})	0.43–0.89
Cu (mg dm^{-3})	0.39–5.27
Fe (mg dm^{-3})	36.55–78.24
Mn (mg dm^{-3})	26.10–50.34
Zn (mg dm^{-3})	0.61–1.63

positive indices referring to limitation by excess and negative indices referring to limitation by deficiency. However, for the treatment with variety RB 867515 without fertigation with vinasse (Fig. 1D), only the P (13) and Fe (–11) contents presented nutritional limitations of first order due to excess and deficiency, respectively.

After establishing the DRIS soil indices, the NBI of the evaluated treatments was determined, as shown in Fig. 2. The lowest NBI was obtained in treatments with the variety CTC 4 fertigated with vinasse (NBI = 33) and with the variety RB 867515 fertigated with vinasse (NBI = 51), reflecting in higher stem yields, 109.9 and 97.7 t ha^{-1}, respectively. On the other hand, for treatments with variety CTC 4 without fertigation, higher NBIs were observed (NBI = 116), followed by the treatment without the variety RB 867515 (NBI = 97), suggesting greater nutritional imbalance in the soil, which is reflected in the yield of stems for the industry in these treatments, 74.8 and 88.8 t ha^{-1}, respectively.

DRIS Foliar Indices

Table 8 presents the distribution of frequency for the nutritional diagnosis obtained through the chemical analysis of the leaves of sugarcane ratoon in commercial plantations as a function of the applied treatments. For treatments with the variety CTC 4, the order of frequency of diagnoses with limitations caused by nutritional deficiency was Ca = S > Cu > Fe > Mn > Zn > P > B > K > N > Mg and Ca = Cu > S > Fe > Mn > Zn > K > P > N > Mg for treatments fertigated or not with vinasse, respectively. Regarding the treatments with variety RB 867515, the order of frequency of diagnoses with limitations caused by nutritional deficiency was: Ca = S > Cu > Fe > Zn > Mn > P > B > K > N = Mg and Ca = S = Cu > Fe > P > Mn > B > K > Zn > Mg > N for treatments fertigated or not with vinasse, respectively.

Regarding the frequency of diagnoses considered high, only N presented high percentages, 44% and 52% for treatments with the variety CTC 4 fertigated or not with vinasse, respectively (Table 8). Similarly, the frequency of high percentages of diagnosis for N contents also occurred for treatments with the variety RB 867515, presenting 56 and 66% for treatments fertigated or not with vinasse, respectively.

Mg and B were the nutrients that presented the highest frequencies of diagnoses considered adequate for treatments with the variety CTC 4, which presented values of 92% for Mg, regardless of the application or not of vinasse, while for B the percentages observed were 48 and 66% for the treatments fertigated and not fertigated with vinasse, respectively (Table 8). For treatments with variety RB 867515, the highest percentages of frequency of adequate diagnoses were observed for Mg (86% fertigated or not with vinasse), K (42% fertigated with vinasse and 40% without fertigation), and B (36% fertigated with vinasse and 40% without fertigation).

The range of sufficiency of the foliar chemical analyses of sugarcane is also shown in Table 8. These are represented by the nutritional range obtained from the samples with the highest stem yields, above 80 t ha^{-1}. When comparing the nutrient concentration ranges in leaves, only N showed greater amplitude in relation to the critical levels proposed by the traditional method for sugarcane cultivation. However, it is also possible to observe that the sufficiency range presented lower intervals than traditional methods for some nutrients, such as for Ca (CL–8–10 g kg^{-1}; SR–2.2–4.0 g kg^{-1}), B (CL–10–30 mg kg^{-1}; SR–7.8–13.4 mg kg^{-1}), Cu (CL–8–10 mg kg^{-1}; SR–3.3–5.2 mg kg^{-1}), Fe (CL–26.7–500 mg kg^{-1}; SR–26.7–108.7 mg kg^{-1}), and Mn (CL–100–250 mg kg^{-1}; SR–35–87.7 mg kg^{-1}).

Figure 3 shows the DRIS leaf indices from the database of analysis of leaves and yield of stems for the industry of varieties CTC 4 and RB 867515 fertigated or not with vinasse. In general, it is observed that for all evaluated treatments, the DRIS indices for B and Mn were the closest to zero, being considered a strong indicator of nutritional balance for the analyzed samples. When analyzing the DRIS indices for each treatment, it is observed that for the variety CTC 4 fertigated with vinasse (Fig. 3A), there were no indices greater than 10 (nutritional limitations of first order), regardless of whether they were negative or positive, indicating a trend toward nutritional balance of sugarcane plants. However, for the same variety without fertigation with vinasse (Fig. 3C), the DRIS indices for Zn (–13), N (–11), and Fe (10) presented the greatest nutritional limitations of first order, respectively. For the

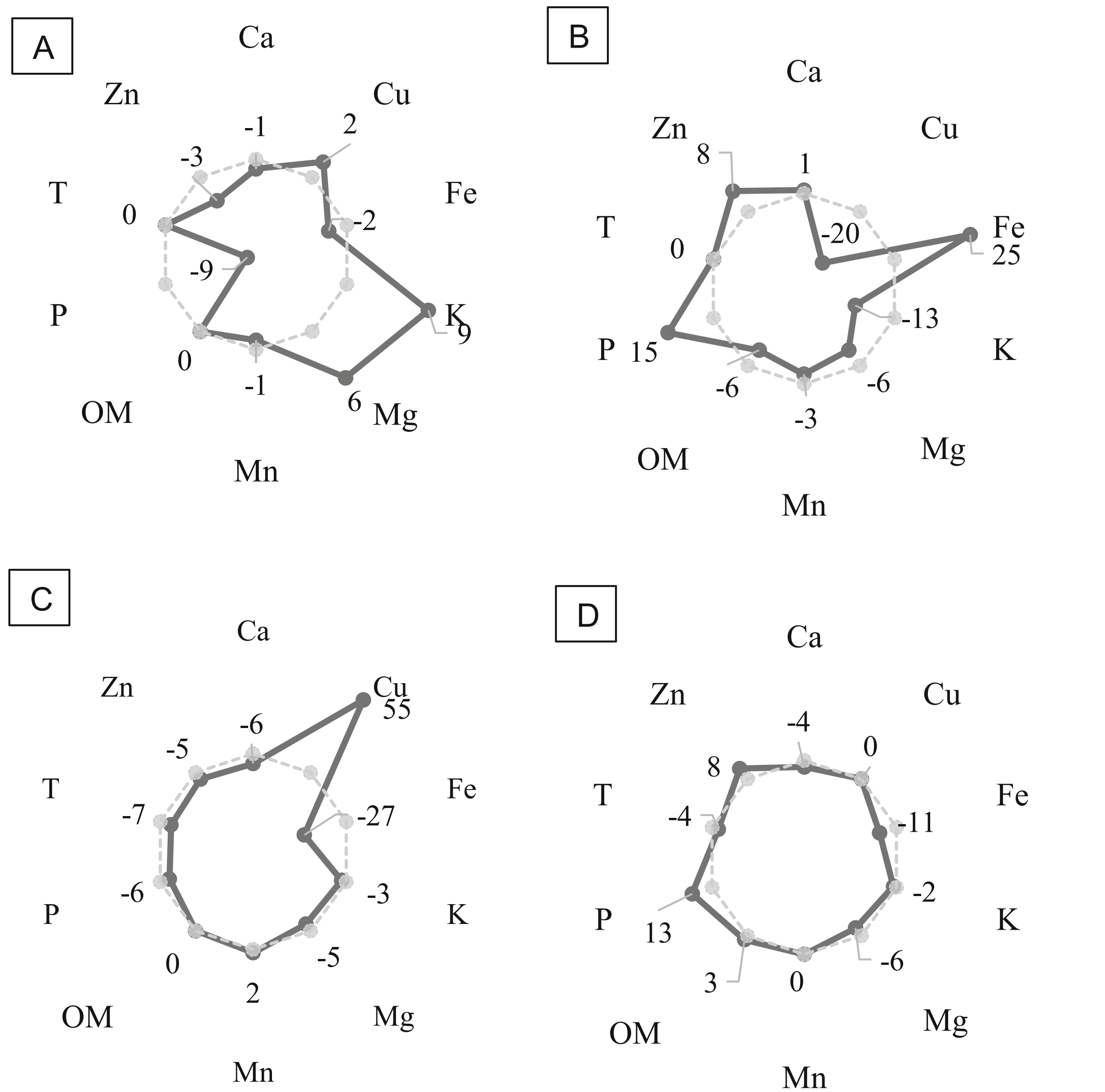

Fig. 1 DRIS soil indices for sugarcane cultivation: **A** DRIS indices for variety CTC 4 fertigated with vinasse; **B** DRIS indices for variety RB 867515 fertigated with vinasse; **C** DRIS indices for variety CTC 4 with conventional fertilization; **D** DRIS indices for variety RB 867515 with conventional fertilization

treatments with the variety RB 867515 fertigated with vinasse (Fig. 3B), only Mn (–11) presented nutritional limitation of first order due to deficiency, while DRIS indices were below 10 for the other nutrients. Similarly, for the treatments with the variety RB 867515 without fertigation with vinasse (Fig. 3D), only Zn (17) showed nutritional limitation due to excess.

After calculating the DRIS indices for the foliar analyses, the NBI of the evaluated treatments was established, as shown in Fig. 4. The lowest NBI was obtained for the treatments with the variety CTC 4 fertigated with vinasse (NBI = 43) and with the variety RB 867515 fertigated with vinasse (NBI = 47), reflecting in higher stem yields, 109.9 and 97.7 t ha^{-1}, respectively. On the other hand, higher NBIs were observed for treatments with the variety CTC 4 without fertigation (NBI = 64), followed by the treatment with variety RB 867515 (NBI = 61), suggesting greater nutritional imbalance in the soil, which is reflected in stem yield of these treatments, 88.8 and 74.8 t ha^{-1}, respectively.

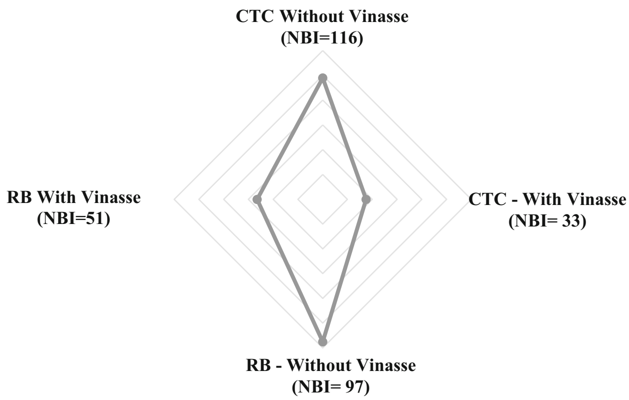

Fig. 2 Nutritional Balance Indices–NBI values obtained from the DRIS indices, chemical analysis of soil, for sugarcane cultivation. Varieties RB 867515 and CTC 4, under fertilization with vinasse and fertilization without vinasse

Discussion

Yield

The average yield of the commercial sugarcane plantations under study presented stands with high stem yields, obtaining higher values than the average for the state of Goiás (72 t ha^{-1}) (Conab 2021). Furthermore, it is possible to observe that in the treatments in which there was fertigation with vinasse, the average stalk yields were higher when compared to treatments without fertigation with vinasse, especially when cultivating the variety CTC 4 (Table 4). When comparing the average yield between the treatments with fertigation and without fertigation with vinasse for the variety CTC 4, stem yield was 35 t ha^{-1} higher in relation to the treatments without fertigation with vinasse.

The same behavior of gains in stem yield after the application of vinasse was also reported by Barbosa et al. (2012) for the variety RB 855536, which presented 16.6 t ha^{-1} higher yields when compared to dry farming (fertilization without vinasse). In another study, Silva et al. (2014) also observed increases in the production of stalks of cane ratoons in the order of 15 t ha^{-1}. Oliveira et al. (2014) claimed that the supply of vinasse alone as a mineral supplement is able to meet the nutritional demand of the sugarcane crop when applied in sufficient quantities, ensuring adequate yield.

If we observe the amount of vinasse applied to the treatments that received fertigation, it is possible to see that there was a supply of 120 kg ha^{-1} N, 36 kg ha^{-1} P_2O_5, and 125 kg ha^{-1} K_2O, which may have favored the greater supplementation of these nutrients for greater absorption and conversion into biomass. Silva et al. (2014) reported that the application of vinasse promotes effects both on the soil and on the yield of sugarcane stalks, with increases in the order of 15 t ha^{-1} in the stem yield in the third ratoon (RB 855536) with the application of up to 800 m^{-3} ha^{-1} vinasse.

DRIS index for Soil Analysis

According to Leandro (1998), DRIS indices can be interpreted considering the order of total nutrient limitation (evaluating all variables with negative and positive indices). Thus, the present study divided the order of nutritional limitation established by the DRIS indices in the two following classes: the first class is characterized by indices that were equal to or greater than 10 (regardless of being positive or negative), being classified as presenting limitations of first order; the second class is characterized by DRIS indices below 10, being classified as presenting limitations of second order (or less limiting). After this definition, it was possible to diagnose which would be the most limiting nutrients for the yield of cane ratoons as a function of the evaluated treatments.

In all treatments evaluated except for the treatment with variety RB 867515, the greatest nutritional limitations due to deficiency were observed for P contents in the soil. This result corroborates the natural soil fertility conditions in the region, where there are low natural contents of P due to its high fixation rate in the soils (Raij et al. 1997; Sousa and Lobato 2004). When evaluating the levels of available P in the soil, it is observed that for the areas that received vinasse, CTC 4 and RB 867515, before its application, the levels in the soil were below the critical level (CL) according to Sousa and Lobato (2004), that is, less than 8.1 mg dm^{-3} when the clay content is between 360 and 600 g kg^{-1} and 18.1 mg dm^{-3} when the clay content is less than 150 g kg^{-1}, respectively. For the areas that did not receive fertigation with vinasse, CTC 4 and RB 867515, the levels of P in the soil were above the CL established as a function of the clay content present in each of the areas, according to Sousa and Lobato (2004), i.e., greater than 4.1 mg dm^{-3} when the clay content is greater than 600 g kg^{-1} and greater than 8.1 mg dm^{-3} when the clay content is between 360 and 600 g kg^{-1}. In addition, an average of 40 kg ha^{-1} P_2O_5 is normally recommended for the production of cane ratoons in the region, as stated by Rein et al. (2016). As shown in Table 1, in the commercial areas evaluated, the following were applied: 36 kg ha^{-1} P_2O_5 in areas cultivated with the variety CTC fertirrigated with vinasse, 58 kg ha^{-1} P_2O_5 in areas cultivated with the variety RB 867515 fertirrigated with vinasse, and 22 kg ha^{-1} P_2O_5 in areas cultivated with the CTC 4 and RB 867515, but without vinasse fertigation.

For micronutrient contents, it was observed that both areas presented diagnoses of limitations due to deficiency.

Table 8 Frequency distribution of nutritional diagnoses obtained by foliar chemical analysis of sugarcane ratoon in commercial crops compared to critical levels and range of sufficiency available for the Cerrado region

Nutrients	Low (%)		Adequate (%)		High (%)		Critical Levels	Sufficiency Range [c]
	With vinasse	Without vinasse	With vinasse	Without vinasse	With vinasse	Without VINASSE		
Variety CTC 4								
N (g kg^{-1})	22.00	20.00	34.00	28.00	44.00	52.00	19.00–21.00[a]	19.5–28.1
P (g kg^{-1})	68.00	58.00	30.00	42.00	2.00	0.00	2.00–2.40[a]	1.3–2.3
K (g kg^{-1})	46.00	78.00	42.00	20.00	12.00	2.00	11.00–13.00[a]	9.3–11.9
Ca (g kg^{-1})	100.00	100.00	0.00	0.00	0.00	0.00	8.00–10.00[a]	2.2–4.0
Mg (g kg^{-1})	8.00	8.00	92.00	92.00	0.00	0.00	2.00–3.00[a]	1.7–2.2
S (g kg^{-1})	100.00	98.00	0.00	0.00	0.00	2.00	2.50–3.00[a]	0.7–1.3
B (mg kg^{-1})	52.00	34.00	48.00	66.00	0.00	0.00	10.00–30.00[b]	7.8–13.4
Cu (mg kg^{-1})	98.00	100.00	0.00	0.00	2.00	0.00	8.00–10.00[a]	3.3–5.2
Fe (mg kg^{-1})	94.00	92.00	4.00	8.00	2.00	2.00	200.00–500.0[a]	26.7–108.7
Mn (mg kg^{-1})	92.00	86.00	8.00	14.00	0.00	0.00	100.00–250.00[a]	35.0–87.7
Zn (mg kg^{-1})	86.00	82.00	8.00	4.00	6.00	12.00	25.00–50.00[a]	10.8–32.6
Variety RB 867515								
N (g kg^{-1})	14.00	12.00	30.00	22.00	56.00	66.00	19.00–21.00[a]	19.5–28.1
P (g kg^{-1})	76.00	90.00	14.00	10.00	10.00	0.00	2.00–2.40[a]	1.3–2.3
K (g kg^{-1})	46.00	56.00	42.00	40.00	12.00	4.00	11.00–13.00[a]	9.3–11.9
Ca (g kg^{-1})	100.00	100.00	0.00	0.00	0.00	0.00	8.00–10.00[a]	2.2–4.0
Mg (g kg^{-1})	14.00	14.00	86.00	86.00	0.00	0.00	2.00–3.00[a]	1.7–2.2
S (g kg^{-1})	100.00	100.00	0.00	0.00	0.00	0.00	2.50–3.00[a]	0.7–1.3
B (mg kg^{-1})	64.00	60.00	36.00	40.00	0.00	0.00	10.00–30.00[b]	7.8–13.4
Cu (mg kg^{-1})	94.00	100.00	2.00	0.00	4.00	0.00	8.00–10.00[a]	3.3–5.2
Fe (mg kg^{-1})	94.00	96.00	6.00	4.00	0.00	0.00	200.00–500.0[a]	26.7–108.7
Mn (mg kg^{-1})	82.00	88.00	18.00	12.00	0.00	0.00	100.00–250.00[a]	35.0–87.7
Zn (mg kg^{-1})	88.00	42.00	8.00	26.00	14.00	32.00	25.00–50.00[a]	10.8–32.6

[a]Based on the appropriate levels described by Malavolta et al. (1997). [b]Recommendation of critical levels for B (Raij e Cantarella, 1997). [c]Nutrient concentration ranges in the leaves of nutritionally balanced plants, which presented productivity higher than 80 t ha^{-1}

When compared to the critical level (CL) of these nutrients in the soil, it is observed that in the areas that did not receive vinasse fertigation, the B contents were below the CL, that is, less than 0.2 mg dm^{-3} (Sousa and Lobato 2004). However, for the areas that received fertigation, the Zn contents in the soil were below the CL, that is, less than 1.0 mg dm^{-3}, as shown in Table 3. Naturally, the soils present in regions of the Cerrado biome are quite weathered and have a low natural reserve of micronutrients (Raij et al. 1997; Sousa and Lobato 2004), such as the types of soils present in the region of this study. Furthermore, fertilizer recommendations containing micronutrients were established approximately 20 years ago (Raij et al. 1997; Sousa and Lobato 2004) and their practice in field conditions is limited. These factors contribute to the reduction in the natural reserve of these nutrients in the soil, causing a greater frequency of nutritional limitations promoted by micronutrients over time. This behavior can be observed by the management adopted in all areas evaluated, regardless of the variety and management of fertigation with vinasse, which did not receive sources of micronutrients, with the exception of B, as shown in Table 1.

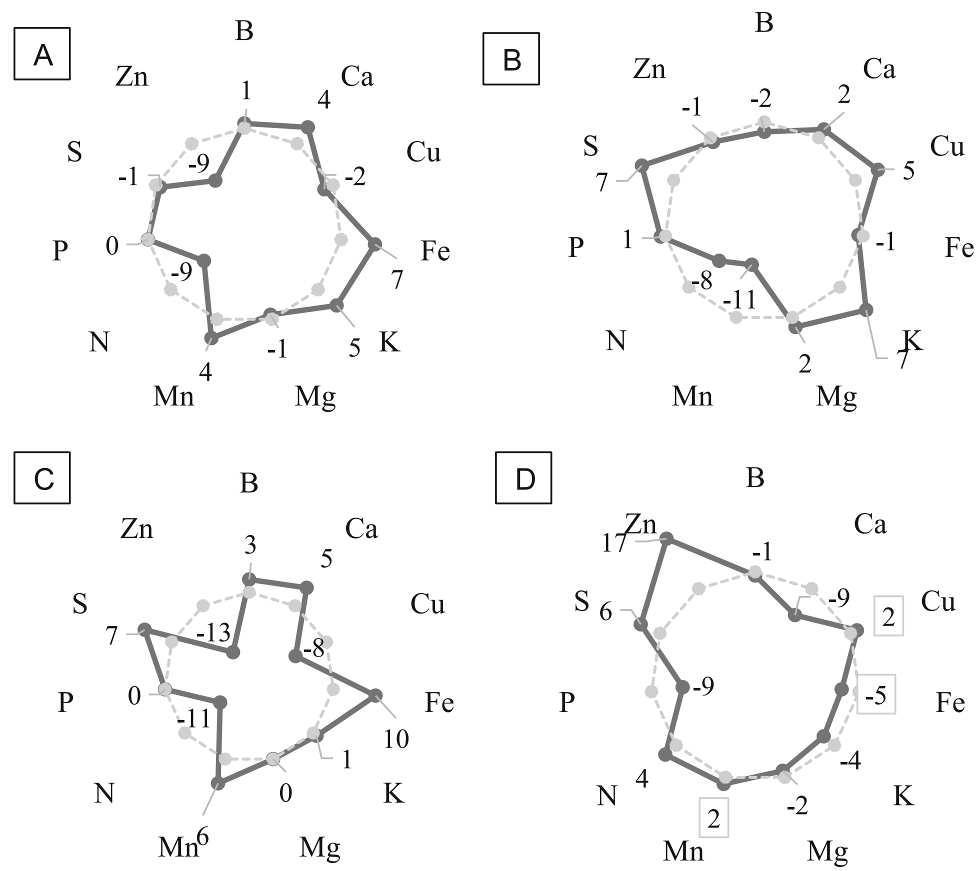

Fig. 3 Leaf DRIS indices for sugarcane crop: **A** DRIS indices for variety CTC 4 fertigated with vinasse; **B** DRIS indices for variety RB 867515 fertigated with vinasse **C** DRIS indices for variety CTC 4 with conventional fertilization; **D** DRIS indices for variety RB 867515 with conventional fertilization

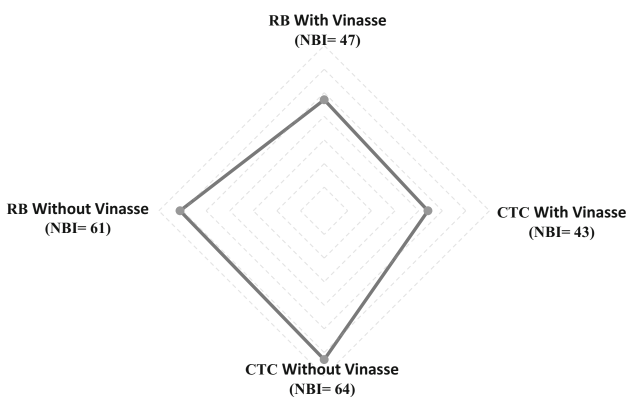

Fig. 4 Nutritional Balance Indices–NBI values obtained from the DRIS indices, leaf chemical analysis, for sugarcane cultivation. Varieties RB 867515 and CTC 4, under fertilization with vinasse and fertilization without vinasse

When comparing the sufficiency range (SR) established for the nutrient contents in the soil, it is not possible to make a comparison with the traditional methods of recommendation and interpretation, since they consider the clay contents of the soil, the expected yield, and the soil cation exchange capacity (Sousa and Lobato 2004). However, the established SR appears as an important tool for the evaluation and diagnosis of intervals of nutrient contents in the soil when seeking to reach yields above 80 t ha^{-1} in cane ratoons cultivated under similar conditions similar to those found in the present study. It is worth mentioning that exchangeable K contents in the soil with intervals ranging between 32.56 and 134.70 mg dm^{-3} were observed probably due to the difference between treatments that were fertigated with vinasse and those without fertigation (Table 3). It is also worth noting that in all cultivated areas, the levels of K in the soil were above the CL established by Sousa and Lobato (2004) and, even so, they received at least 125.3 kg ha^{-1} of K_2O in the form of chloride of potassium or combined with vinasse fertigation (Table 1).

According to Oliveira et al. (2005), the continued application of vinasse in fertigation in sugarcane crops, besides being a rich source of N, P, and K, can change the concentration of other elements, including Fe, Cu, and Zn, increasing its contents in the soil profile and possibly in the structures of sugarcane plants. Silva et al. (2014) studied the application of vinasse for the cultivation of sugarcane and reported changes in the contents of N, P, K, Ca, Mg, S, Cu, Zn, Mn, and Fe. In addition, they observed that the chemical characterization of vinasse should be performed annually, since its composition can be changed depending on the industrialization processes and mineral composition of the sugarcane crop used during the vinasse production process. Silva et al. (2007) claimed that although vinasse can improve soil fertility, the amounts applied should not consider its nutrient concentration so that it does not negatively alter the cation exchange capacity in the soil, as it affects plant development and growth. Fernandes and Soratto (2016) also reported that the application of large amounts of vinasse affects the availability of nutrients in the soil, consequently affecting the balance between the nutrients in the soil that are available to the plants. An important aspect of the application of stillage is the concentration of heavy metals in its composition. Even though the initial levels in the soil and in the stillage applied have not been determined, it is known that stillage is a residue that is known not to contain heavy metals (Camilotti et al. 2009). However, Gatto (2003) found in some samples the concentration of 0.06 mg kg^{-1} of Cd, 0.05 mg kg^{-1} of Cr, 0.20 mg kg^{-1} of Ni, and 0.03 mg kg^{-1} of Pb (dry basis). In view of this, (Camilotti et al. 2009) evaluated the application of approximately 125 m^3 ha^{-1} of stillage in each year of cultivation, during a total of four consecutive harvests, totaling 532 m^3 ha^{-1} of stillage applied at the end of the study, concluding that the application of stillage did not offer any risk of soil contamination regarding the presence of these heavy metals. It is noteworthy that the amount of stillage applied in this study is at least 12 times greater than the present research carried out in commercial plantations located at Usina Boa Vista in the municipality of Quirinópolis in Goiás, Brazil.

The NBI expresses how much the variables soil or leaf are nutritionally balanced, with effects on crop yield. Calheiros et al. (2018) detailed that the determination of the NBI reflects the combined effect of production factors on crop production. This effect was observed for the NBI calculated for the DRIS indices in the soil, since the lowest NBIs were observed for treatments with the variety CTC 4 fertigated with vinasse (NBI = 33 and stem yield = 109.9 t ha^{-1}) and the lowest stem yields were observed for treatments with variety CTC 4 without fertigation (NBI = 116 and stem yield = 74.8 t ha^{-1}). These results corroborate Serra et al. (2013) and Queiroz et al. (2014), who also observed correlations between the lowest NBI indices with the highest crop yields.

DRIS index for Foliar Analysis

The use of foliar nutritional patterns represents an alternative for the evaluation and diagnosis of crop nutritional status and is presented as a tool for adjustments in recommendation programs under specific conditions of the production system (Oliveira et al. 2019). On the other hand, most of these diagnoses are performed using traditional methods, such as CL and/or SR, such as in Malavolta et al. (1997), Raij et al. (1997) and Sousa and Lobato (2004). The main advantages of these methods are the existence of pre-established nutritional standards in the literature, as well as the ease of interpretation of the analytical results (Creste and Echer 2010; Oliveira et al. 2019). However, most of these standards are defined under cultivation conditions that do not reflect the current cultivation system for sugarcane cultivation, especially in ratoons. This is due to the fact, for example, of the adoption of the mechanized harvesting system without prior removal of straws using fire for manual cutting.

In this way, the DRIS contemplates all the variables inherent to the production process of a particular culture and can be applied in specific agricultural or regionalized production systems, through the evaluation of the interaction between nutrients (Reis Junior and Monnerat 2003), and not only relating the fixed intervals (sufficiency range, FS) in the nutritional bulletin tables which consider specific growing conditions (Calheiros et al. 2018). Furthermore, DRIS allows the consideration of varieties, production systems, as well as soil and climate conditions in the database referring to the population of interest (high productivity), promoting the existing variability in the evaluated commercial cultivation areas (Gopalasundaram et al. 2012).

In the current cultivation system with mechanized cutting, there is the deposition of residues (straw) on the soil surface, which can reach 20 t ha^{-1}, promoting nutrient cycling and consequently greater efficiency in the use of nutrients by cane ratoons (Flores et al. 2014a, 2014b, 2020; Almeida et al. 2015; Pancelli et al. 2015; Cavalcante et al. 2016; Cherubin et al. 2019; Andrade et al. 2021a, 2021b). Furthermore, there are increases in the soil contents of nutrients, especially N, P, and K, resulting from the use of vinasse and filter cake (Silva et al. 2007, 2014; Moda et al. 2015; Fernandes and Soratto 2016).

The use of DRIS allows contemplating all production factors that are involved in the system, since it considers the crop yield to determine its standards and indices. Thus, comparing the CLs proposed in the literature in Table 8 with the SR proposed for the data obtained from the stands evaluated in this study, it is observed that for Ca, S, B, Cu, Fe, Mn, and Zn the intervals are narrower for SR in relation to CLs. This result demonstrates that the nutritional diagnoses for expected stem yields above 80 t ha^{-1} promoted by DRIS were more sensitive compared to traditional methods. These results corroborate the reports by Oliveira et al. (2019), who attributed this behavior to the better relationship between the nutritional status of plants with the stem yield, enabling greater efficiency in the nutritional diagnosis.

When analyzing the results of the frequency of distribution of diagnoses considered high, it is observed that for both treatments, N was the element one with the highest frequency, ranging between 44 and 66% (Table 8). N is the second most required nutrient for sugar cane production, second only to K, being important for the production of proteins, enzymes, and nucleic acids (Malavolta et al. 1997; Rossetto et al. 2008). The SR obtained for N in the present study, from 19.5 to 28.1 g kg^{-1}, obtained by DRIS, is considered high, as it is considered high by the traditional interpretation methods proposed by Malavolta et al. (1997) when above 21 g kg^{-1}. On the other hand, Píperas et al. (2009) evaluated sugarcane varieties and observed N contents ranging between 13.5 and 16.5 g kg^{-1} for stem yields corresponding to 82.9 t ha^{-1} and 125.9 t ha^{-1}, respectively. The explanation for the high foliar N contents was the fertilization containing nitrogen fertilizers with concentrations higher than 200 kg ha^{-1} N carried out in the evaluated areas, which are values well above those recommended for the production of sugarcane ratoons for the region, 100 kg ha^{-1} N for yields above 80 t ha^{-1} (Spironello et al. 1997).

When evaluating the distribution of frequency of nutritional diagnoses in Table 8, it is possible to observe that there was 100% frequency of diagnoses considered low for Ca contents in both treatments. These results may have occurred due to the absence of soil correction for the supply of Ca and Mg through liming before cultivation or even by the greater supply of K in the soil, either by mineral fertilization and/or associated with fertigation by vinasse. Prado (2021) reported that there is a negative interaction between K, Mg, and Ca in the soil, which must present a ratio of 1:3:9 for reaching balance in the process of absorption of these nutrients by plants. Furthermore, the author attributed greatest efficiency in the uptake of K by the plant as this element has a specific carrier, while Mg and Ca compete for the same non-specific absorption site. The average contents of K in the leaves in the evaluated areas ranged between 9.3 and 11.9 g kg^{-1}, which are considered adequate by Malavolta et al. (1997). Nonetheless, Píperas et al. (2009) obtained high stem yields (140 t ha^{-1}) when the K contents were higher than 14 g kg^{-1}, that is, higher than those found in the present study.

K is the most demanded nutrient by sugarcane, performing several metabolic functions such as the translocation of solutes, activating more than 60 enzymes in plants, which are responsible for several reactions, including protein synthesis and photosynthesis (Rossetto et al. 2008). Treatments that were fertigated with vinasse presented higher frequencies of positive diagnoses when compared to those without fertigation (Table 8) and, in general, DRIS indices were lower than 10, suggesting greater nutritional balance for this nutrient (Fig. 3). For Silva et al. (2014), the application of vinasse can be advantageous as an important source of K, reducing the need for mineral supplementation with chemical fertilizers, consequently reducing the costs of production of ratoons.

When evaluating the nutritional diagnoses promoted by the DRIS indices in Fig. 3, it is observed that for treatments with the variety RB 867515, the greatest limitations occurred for the contents of Zn in the plants, both by excess when fertigated with vinasse (17) and by deficiency when not fertigated (-13). The explanation for this behavior lies in the composition of the vinasse that was used for fertigation, as shown in Table 1. It is noted that the applied vinasse was enriched with zinc sulfate, which may have improved the efficiency of utilization of the applied Zn applied on the soil.

Similar to what was observed for DRIS in the soil (Fig. 2), the NBI obtained from DRIS in leaves also presented correlations with the best yield of cane ratoons (Fig. 4). Both treatments fertigated with vinasse presented lower NBIs, 43 for the treatment with CTC 4 and 47 for the treatment with RB 867515 (Fig. 4). Partelli et al. (2005) and Serra et al. (2013) also reported a negative correlation between NBI and stem yield, that is, the lower the observed NBI, the higher the stem yield obtained, suggesting that the plants are nutritionally balanced when compared to plants with higher NBI.

The correct use of the interpretation of the results of foliar analyzes made possible by the DRIS method has greater sensitivity in diagnosing the nutritional balance, as well as in indicating the order of limitation of nutrients that can affect the achievement of high yields. Thus, it enables to increase the efficiency regarding the use of chemical fertilizers, avoiding waste and promoting productive sustainability in the sugar alcohol sector.

Conclusions

Fertigation with vinasse can increase stem yield in the order of 35 t ha^{-1} for the variety CTC 4. The DRIS indices for the soil diagnosed limitations was due to nutritional deficiencies for the available contents of P and Zn in areas cultivated with CTC 4 and for the contents of K, Cu, Fe, and Mg in areas cultivated with RB 867515. Nutritional diagnosis performed using the DRIS method for leaf chemical analysis showed greater sensitivity in detecting the nutritional limitations of Ca, Cu, and Mn compared to traditional methods of interpretation by critical levels. The NBI is an efficient tool for the proper diagnosis of nutritional balance, since the lowest NBI indices were the ones that provided the highest yields of ratoon crops of sugarcane.

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Declarations

Conflict of interest The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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