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Sugarcane Productivity as a Function of Zinc Dose and Application Method

Marcelo de Almeida Silva [1,*], Gabriel Henrique Germino [1], Lucas Almeida de Holanda [2], Laura Costa Oliveira [1], Hariane Luiz Santos [1] and Maria Márcia Pereira Sartori [1]

[1] Laboratory of Ecophysiology Applied to Agriculture (LECA), School of Agricultural Sciences, UNESP-Sao Paulo State University, Botucatu 18610-034, SP, Brazil
[2] Federal Institute of Education, Science, and Technology of Mato Grosso (IFMT), Campo Novo do Parecis 78360-000, MT, Brazil
* Correspondence: marcelo.a.silva@unesp.br

Abstract: Sugarcane is one of the main crops in Brazilian agriculture. It has high economic and productive potential, but its current productivity is still lacking due to poor nutritional management in both the soil and the plant. Zinc (Zn) directly affects tillering and plant growth, which are critical factors to sugarcane productivity and ratoon longevity. Thus, this research aimed to evaluate the effects of Zn chelate doses (185, 260, and 330 g ha^{-1}) and two application methods (furrow and foliar applications) on the tillering, yield, and quality of sugarcane. The Zn chelate fertilization via furrow at a dose of 330 kg ha^{-1} provided increases of 13.59%, 17.6%, and 17.0% in stalk height (SH), stalk (TSH) productivity, and sugar (TPH) productivity, respectively. In contrast, Zn foliar application at a dose of 260 g ha^{-1} provided increases of 3.71%, 20.7%, and 17.0% in SH, TSH, and TPH, respectively. The optimal Zn chelate fertilization in sugarcane cultivation can be performed at a dose of 330 g ha^{-1} via furrow application at planting or at a dose of 260 g ha^{-1} via foliar application 145 days after planting.

Keywords: *Saccharum* spp.; micronutrient; liquid fertilizer; chelate; yield

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1. Introduction

Brazil is the world's largest producer of sugarcane, which is one of the main crops of Brazil's agricultural economy [1,2]. To achieve high agricultural yields, sugarcane production requires advanced techniques and improved efficiency in production factors, such as varieties, plant health treatments, crop practices, and the application of correctives and fertilizers [3].

Despite all of the knowledge applied to sugarcane production, the average yield is approximately 80 t ha^{-1}, which can be considered low due to the genetic potential of the varieties available for cultivation [4]. Under tropical conditions, soil fertility is one of the main limitations to the growth of most crops [5]. The intense implementation of mechanized harvesting and the expansion of the crop to low-fertility soils, especially in degraded pasture areas, has negatively impacted sugarcane productivity [6,7].

In that sense, micronutrient deficiency can cause serious problems in crop development, leading to reduced yields and even plant death, as micronutrients play vital roles in plant metabolism [8,9]. Among the essential micronutrients for sugarcane production, zinc (Zn) can be considered one of the most important, as its deficiency is frequently observed in the crop. It directly affects tillering and plant growth, which are the two critical factors in sugarcane productivity and ratoon longevity [4,10–12].

Zn acts as an activator of several enzymes and participates in the structural composition of others, playing an essential role in the cellular structures [13,14]. In addition, this nutrient is vital to the activation of the pyruvic carboxylase enzyme, which is critical to the photosynthesis of C_4 plants [15]. Regarding plant metabolism, Zn activates tryptophan synthetase, the enzyme responsible for synthesizing tryptophan in the indoleacetic acid

(IAA) biochemical pattern [16]. IAA is responsible for the synthesis of growth-promoting enzymes and cell elongation, and its deficiency directly affects the number of tillers, providing shorter internodes and thinner stalks, which are considered fundamental factors for the formation of sugarcane productivity [3,17–20].

The intensive use of fertilizers without micronutrients and the insufficient application of organic residues result in an expansion of micronutrient-deficient areas [21]. Historically, little attention has been paid to the response of sugarcane to micronutrient application, which has become a practice that is little used by producers [22]. However, the management has changed, and the application of micronutrients has become more frequent [4,20,23]. According to Quaggio et al. [24], the Zn requirement for sugarcane is, on average, 0.59 kg 100 ton^{-1} of stalks, with a relative exportation of 0.35 kg 100 ton^{-1} for the stalks and 0.24 kg 100 ton^{-1} for the leaves. In Brazil, it is recommended to apply 2 to 10 kg ha^{-1} of Zn in sugarcane planting furrows, preferably in the form of sulfate or oxisulfate, with higher doses for low-Zn soils [4,24].

In the case of Zn fertilization studies in sugarcane, there is a heterogeneity of results in which positive, negative, or neutral responses to the application and use of this micronutrient have been observed. However, increases in the brix and pol content in plant cane [25], increases in the yield in ratoon cane [20], and average increases in the sugar yield [26] have already been reported as positive effects of Zn fertilization on this crop.

To our knowledge, research on the liquid foliar application of Zn in sugarcane is scarce. Of the few published studies, Panhwar et al. [27] concluded that foliar Zn application had a more beneficial effect than soil application. These studies are helpful in refining the recommendations for sugarcane micronutrient application, bearing in mind the economic and environmental impact that unnecessary soil applications can cause [25,28].

Planting furrow fertilization problems, such as leaching, oxidation, precipitation, and other losses, are avoided because foliar fertilization provides nutrients directly to the leaf [29,30], which enables the use of smaller amounts of fertilizers, thus, making it more efficient than soil applications. This effectiveness is increased when the elements are applied as chelates because, compared with inorganic foliar fertilizers, chelated foliar fertilizers may improve the migration ability and utilization efficiency of inorganic mineral salts [31]. Chelated micronutrients could provide higher uptake and efficiency rates [32,33], less deteriorating effects on soil salinity or unbalanced soil nutrients [34], better adaptation to plant growth and metabolism [35], minimum precipitation and leaching (mainly using foliar feeding) [36], and increased soil fertility [37].

Due to the importance of supplying Zn to sugarcane, it is necessary to determine the best methods and application rates of liquid fertilizers. In this context, the objective of this work was to evaluate the effects of liquid chelated Zn fertilization, applied in three doses and via two methods, on sugarcane tillering and yield.

2. Materials and Methods

2.1. Cultivation Conditions

The experiment was conducted during the 2016–2017 season in an area located in Lençóis Paulista, Sao Paulo, Brazil (22°35′55″ S, 48°48′01″ W, and 550 m asl).

The region's climate is considered tropical in altitude (CWa) according to the Köppen climate classification, characterized by temperatures ranging from 4 °C (from June to August) to 38 °C (from November to February) [38]. The soil of the experimental area is classified as eutrophic Red Latosol [39]. Granulometric analyses of the soil, proposed by Donagemma et al. [40], showed 61.5% of sand, 23.3% of clay, and 15.2% of silt at a depth of 0–25 cm, and 57.2% of sand, 27.9% of clay, and 14.9% of silt at a depth of 25–50 cm, characterized by a medium-textured soil, according to the texture class grouping triangle [39], with the production environment classified as C2 [41,42].

A soil chemical analysis was performed at 0–25 cm and 25–50 cm depths before the experiment was set up (Table 1), according to the methodology proposed by Raij et al. [43], and it showed Zn contents lower than those recommended (0.5 mg dm^{-3}) by Raij et al. [44]

for sugarcane cultivation. The fertilization was performed with 40 kg ha^{-1} of N, 180 kg ha^{-1} of P_2O_5, and 140 kg ha^{-1} K_2O, corresponding to 88.8 kg ha^{-1} of urea, 346.2 kg ha^{-1} of mono-ammonium phosphate (MAP), and 134 kg ha^{-1} of potassium chloride (KCl), respectively. A supplemental fertilization was performed at 180 DAP with 30 kg ha^{-1} of N and 60 kg ha^{-1} of K_2O, corresponding to 66.6 kg ha^{-1} of urea and 100 kg ha^{-1} of KCl, respectively, according to Vitti et al. [45].

Table 1. Initial soil chemical analysis from the soil of the experimental area.

Sample Depth (cm)	pH	OM	P Resin	H + Al	K	Ca	Mg	SB	CEC	V%	S	B	Cu	Fe	Mn	Zn
	$CaCl_2$	g dm^{-3}	mg dm^{-3}	mmol dm^{-3}							mg dm^{-3}					
0–25	5.3	21	10	29	2.0	41	12	55	84	65	34	0.29	3.1	31	38.6	0.8
25–50	5.0	19	13	34	1.6	36	14	52	86	60	30	0.37	3.4	30	31.0	0.4

pH (hydrogen potential); OM (organic matter); P resin (phosphorus by resin method); SB (sum of bases); CEC (cation-exchange capacity); V% (base saturation).

2.2. Experimental Design, Plant Material, and Treatments

The RB966928 cultivar was used because it is the most cultivated one in Brazil [46]. This cultivar has a high speed of development, a high tillering index, good interrow closing, and high resistance to diseases and pests. In addition, it is considered early and productive and suitable for "Production Environments for Sugarcane" B, C, and D, i.e., the crop productivity potential in each soil mapping unit associated with the climatic and varietal management characteristics of a specific region [42].

The planting was performed on 16 May 2016. Each plot was composed of four double lines of 10 m and a spacing of 0.40 × 1.60 m^2, totaling an area of 3360 m^2. The experimental design used was a randomized block 2 × 3 + 1 factorial scheme consisting of two application methods (furrow and foliar), three Zn doses (185, 260, and 330 g ha^{-1}), and an additional factor (a control without Zn application) with five replicates.

The zinc application was performed in the following two ways: with a micronutrient application in the planting furrow (16 May 2016) and with a foliar application, which was performed on 8 October 2016 (145 days after planting or DAP) because this was the tillering phase. Thus, the plant would be prepared for the grand growth phase when there is the greatest absorption of nutrients by the sugarcane (Table 2).

Table 2. Zinc dose treatments and application methods.

Zinc Dose (g ha^{-1})	Application Method	DAP
0.00	-	-
185	Furrow	0
260	Furrow	0
330	Furrow	0
185	Foliar	145
260	Foliar	145
330	Foliar	145

DAP (days after planting).

The product used consisted of a liquid fertilizer, i.e., a water-soluble Zn (oxide) suspension with a concentration of 7% (90 g Zn L^{-1}), chelated by ethylenediaminetetraacetic acid (EDTA) (3.9–50.2% g Zn L^{-1}), diethylenetriaminepentaacetic acid (DTPA) (1.3–16.7% g Zn L^{-1}), and hydroxy-2-ethylenediamine-tri acetic acid (HEEDTA) (1.8–23.1% g Zn L^{-1}).

For the application of Zn, pressurized equipment (CO_2) was used to spray the fertilizer in the rows of the cane plants using an application bar with flat stream spray nozzles (XR 10 015 VP, TeeJet, Cotia, SP, Brazil) with a flow rate of 40 L ha^{-1} and a working pressure of 40 lb pol^{-2}. The micronutrient concentration in the tank solution was calculated according to the flow rate and was verified to obtain the doses applied in the experiment.

2.3. Crop Management

During the experimental period, meteorological data were collected from the Automated Weather Station of the National Institute of Meteorology (INMET) of Lençóis Paulista, SP, Brazil (Figure 1).

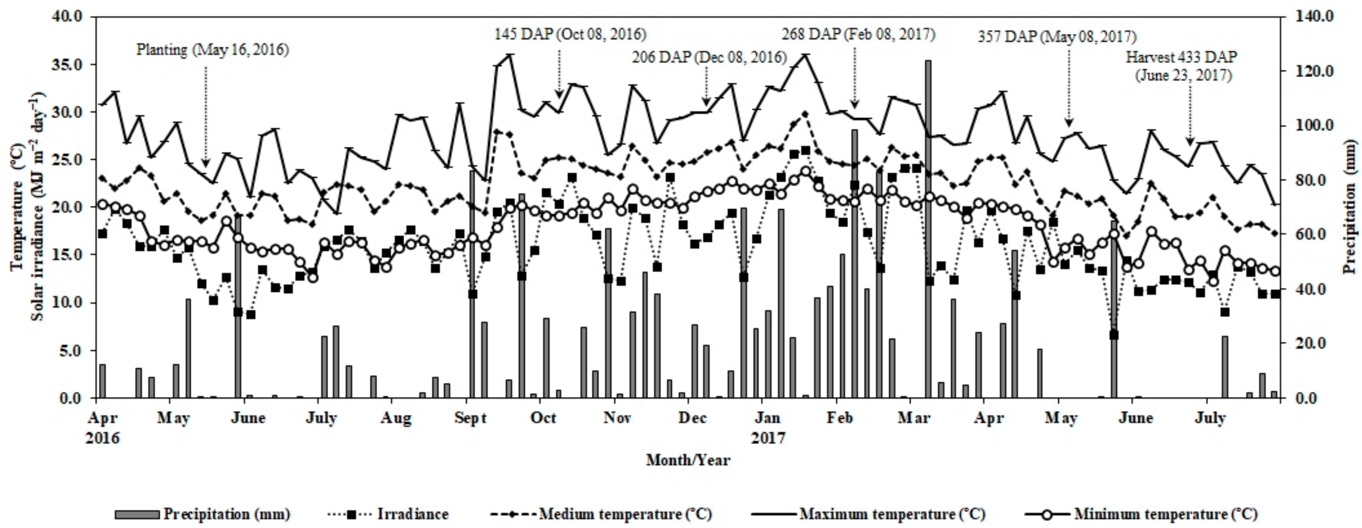

Figure 1. Rainfall (mm), medium, maximum, and minimum temperatures, and solar irradiance, recorded at the Meteorological Station of the National Institute of Meteorology (INMET) in Lençóis Paulista, SP, Brazil, from April 2016 to July 2017.

Other agricultural management techniques, such as the control of weeds and pests, were performed according to the needs of the area and the management adopted by the sugar mill.

2.4. Biometric and Harvest Assessments

Tiller counting was performed during the crop development at 145, 206, 268, 357, and 433 DAP. Thus, the number of tillers per linear meter was obtained.

The harvest was performed on 23 July 2017. For the technological analysis, ten stalks in a row were collected by cutting at the height of the apical bud (breakdown point) continuously in each plot and forwarded to the laboratory for processing based on the methodology defined in the Sucrose Content-Based Sugarcane Payment System by the Consecana's semiannual updates on technological evaluations, described by Fernandes [47].

The following traits were obtained: pol (% of cane, pol percent cane or PCC), fiber (% of cane), and total recoverable sugar (TRS, kg t^{-1}). The pol represents the apparent percentage of sucrose contained in the sugar solution. The pol% of sugarcane juice is evaluated using saccharimetric methods based on the property that sugars deflect polarized light [47].

To obtain the total weight of stalks per plot, a 200 g load-cell scale was used. Soon after, the stalk productivity was obtained (TSH, t ha^{-1}) through the relationship with the plot area. Finally, the pol productivity (TPH, t ha^{-1}), i.e., sucrose productivity, was obtained by multiplying the TSH by the PCC and dividing the product by 100.

2.5. Statistical Analysis

The data were subjected to an analysis of variance (ANOVA) with an F test, with a subsequent comparison of the means using a Tukey's test ($p \leq 0.05$).

3. Results

3.1. Number of Tillers

Applying Zn in the planting furrow had no significant effect on the number of tillers at 145 DAP (Table 3). For the number of tillers at 206 DAP, there was a significant response to Zn fertilization in the interaction between the application method and the applied dose (Table 4). Relatively high values of number of tillers m^{-1} were observed for the dose of 185 g ha^{-1} applied in the planting furrow and the 330 g ha^{-1} foliar application. The number of tillers observed with a foliar dose of 260 g ha^{-1} did not differ statistically from that observed with a 330 g ha^{-1} foliar dose.

Table 3. Number of tillers per meter at 145 days after planting as a function of Zn application in the planting furrow (df = 16).

Doses (g ha^{-1})	Number of Tillers m^{-1}
0 (Control)	22.7 ± 1.25
185	22.0 ± 0.49
260	22.3 ± 0.97
330	21.3 ± 0.47
p value	0.637
CV (%)	8.50

Average ± standard error.

Table 4. Number of tillers per meter as a function of Zn dose and application method (df = 24).

Date	Doses (g ha^{-1})	Furrow (Tillers m^{-1})	Foliar (Tillers m^{-1})	Means	P
206 DAP (December/2016)	0	19.0 ± 0.85		-	P (Application method) = 0.950
	185	20.2 ± 0.42 Aa	18.3 ± 0.41 Bb	19.3	P (Doses) = 0.658
	260	18.9 ± 0.95 Aa	19.4 ± 0.71 ABa	19.2	P (Interaction) = 0.044
	330	18.9 ± 0.72 Aa	20.5 ± 0.49 Aa	19.7	P (C × I) = 0.309
	Means	19.4	19.4		-
268 DAP (February/2017)	0	13.9 ± 0.52		-	P (Application method) = 0.402
	185	14.9 ± 0.41	15.0 ± 0.27	15.0 B	P (Doses) = 0.026
	260	15.5 ± 0.39 *	16.1 ± 0.27 *	15.8 AB	P (Interaction) = 0.602
	330	16.0 ± 0.39 *	15.9 ± 0.47 *	16.0 A	P (C × I) = 0.005
	Means	15.5 a	15.7 a		-
357 DAP (May/2017)	0	12.2 ± 0.28		-	P (Application method) < 0.0001
	185	12.8 ± 0.29 Ba	14.2 ± 0.39 * Ba	13.5 B	P (Doses) < 0.0001
	260	13.4 ± 0.49 Bb	16.0 ± 0.27 * Aa	14.7 A	P ((Interaction) = 0.021
	330	15.1 ± 0.43 * Aa	15.5 ± 0.24 * ABa	15.3 A	P (C × I) < 0.0001
	Means	13.8 b	15.2 a		-
433 DAP (July/2017)	0	10.7 ± 0.18		-	P (Application method) = 0.045
	185	11.1 ± 0.18	11.6 ± 0.15 *	11.4 B	P (Doses) = 0.001
	260	11.7 ± 0.13 *	12.6 ± 0.25 *	12.1 A	P ((Interaction) = 0.091
	330	12.3 ± 0.19 *	12.1 ± 0.36 *	12.2 A	P (C × I) < 0.0001
	Means	11.7 b	12.1 a		-

Df, degrees of freedom; average ± standard error; averages followed by different capital letters indicate significant differences between the application methods and averages followed by different lowercase letters indicate significant differences between the doses by Tukey's test ($p \leq 0.05$). * Averages followed with an asterisk differ from the control ($p \leq 0.05$); (C × I): Control × Interaction.

The doses of 260 and 330 g ha^{-1}, both via planting furrow and foliar application, provided a higher number of tillers compared to the control at 268 DAP (Table 4). On average, among the application methods, the 330 g ha^{-1} dose provided a higher number of tillers per meter than the 185 g ha^{-1} dose and, consequently, higher than the one observed in the control.

Regarding the evaluation of the number of tillers at 357 DAP, there was a significant response to Zn fertilization for both the application method and the applied dose, as well as for the interaction between the two factors. It was found that the doses of 330 g ha^{-1} in the planting furrow and 185, 260, and 330 g ha^{-1} via foliar application provided the highest number of tillers m^{-1} during this period (Table 4). On average, the number of tillers per meter was higher when Zn was applied to the leaves than when it was used in the furrows and at doses of 260 and 330 g ha^{-1}.

Regarding the tillering at 433 DAP, i.e., during the sugarcane harvest, there were significant differences in the method and the application dose. In terms of overall average, the foliar application of Zn provided a higher number of tillers per meter (12.1) than that observed with the planting furrow application (11.7), while in the control, the number of tillers per meter was 10.7. The dose of 185 g ha^{-1} applied in the planting furrow did not promote a significant increase in the number of tillers, while this dose applied to the leaves increased the number of tillers by 0.9. However, the doses of 260 and 330 g ha^{-1} applied both in the planting furrow and via foliar application provided a higher number of tillers than that observed in the control, as well as, in terms of the average, they significantly increased the number of tillers compared to those observed at the dose of 185 g ha^{-1} (Table 4).

3.2. Stalk Height, Stalk Diameter, and Quality of Sugarcane

The Zn applied at the doses of 260 (foliar) and 330 g ha^{-1} (furrow and foliar) provided higher stalk heights compared to the control; however, the stalk diameter was not influenced by the application method or the Zn dose (Table 5).

No characteristics regarding the quality of sugarcane as a raw material were affected by the Zn dose or the application method (Table 5).

Table 5. Stalk height, stalk diameter, fiber% sugarcane, Brix% juice, purity, pol% cane (PCC), and total recoverable sugar (TRS) as a function of the dose and application method (df = 24).

Doses (g ha^{-1})	Stalk Height (cm)	Diameter (cm)	Fiber (%)	BRIX (%)	Purity (%)	PCC (%)	TRS (kg t^{-1})
0 (Control)	276.6 ± 6.93	2.7 ± 0.13	12.7 ± 0.25	22.0 ± 0.54	91.0 ± 0.45	16.8 ± 0.45	164.0 ± 4.13
185 Furrow	287.0 ± 8.11	2.6 ± 0.19	13.1 ± 0.17	21.9 ± 0.48	90.8 ± 0.32	16.5 ± 0.36	163.3 ± 1.83
260 Furrow	296.2 ± 13.15	2.9 ± 0.14	13.0 ± 0.43	21.7 ± 0.58	90.0 ± 0.80	16.3 ± 0.63	163.4 ± 3.14
330 Furrow	314.2 ± 7.75 *	2.9 ± 0.16	12.3 ± 0.38	21.8 ± 0.51	90.8 ± 0.91	16.7 ± 0.29	163.2 ± 2.71
Means	299.1	2.8	12.8	21.8	90.5	16.5	163.3
185 Foliar	302.4 ± 2.32	2.7 ± 0.07	12.7 ± 0.24	21.8 ± 0.33	90.8 ± 0.31	16.5 ± 0.32	161.5 ± 3.01
260 Foliar	310.2 ± 4.87 *	2.7 ± 0.05	12.4 ± 0.19	21.6 ± 0.36	90.2 ± 0.60	16.4 ± 0.34	162.0 ± 1.94
330 Foliar	312.4 ± 8.49 *	2.8 ± 0.13	13.1 ± 0.40	21.1 ± 0.42	89.9 ± 0.57	15.8 ± 0.41	160.7 ± 1.12
Means	308.3	2.8	12.7	21.5	90.3	16.2	161.4
P (Application method)	0.180	0.661	0.811	0.377	0.665	0.418	0.345
P (Doses)	0.095	0.362	0.811	0.779	0.485	0.790	0.948
P (Interaction)	0.514	0.631	0.080	0.770	0.647	0.414	0.972
P (C × I)	0.018	0.710	0.389	0.882	0.725	0.697	0.976

Df, degrees of freedom; average ± standard error; averages followed by different capital letters indicate significant differences between the application methods and averages followed by different lowercase letters indicate significant differences between the doses by Tukey's test ($p \leq 0.05$). * Averages followed with an asterisk differ from the control ($p \leq 0.05$); (C × I): Control × Interaction.

3.3. Tons of Stalks Per Hectare (TSH) and Tons of Pol Per Hectare (TPH)

The stalk yield (tons of stalk per hectare or TSH) was affected by the Zn rates. The application of 330 g Zn ha^{-1} in the planting furrow (123.3 t ha^{-1}) and of 260 and 330 g Zn ha^{-1} via foliar application (126.3 and 125.0 t ha^{-1}, respectively) provided higher yields compared to the control (Table 6). Regarding the general average, the stalk yields obtained at the doses of 260 and 330 g ha^{-1} were higher than the productivity of 113.7 t ha^{-1} observed at 185 g Zn ha^{-1}.

As the productivity of sugar (tons of pol per hectare or TPH) results from the product between the TSH and pol% cane, a significant response to the Zn application was also verified. In the control, a sugar productivity of 17.6 t ha^{-1} was observed. The highest TPH were observed at doses of 330 g ha^{-1} applied in the planting furrow and 260 g ha^{-1} applied via foliar application (Table 6). Regarding the general average, there was no difference between the application methods, but the TPH observed under the dose of 330 g ha^{-1} was higher than that observed at 185 g ha^{-1}.

The components of the sugarcane yield potential formation are the number of tillers and the height and diameter of the stalks [17]. The Zn doses of 260 (foliar) and 330 g ha^{-1} (furrow and foliar) provided a higher number of tillers at 433 DAP (harvest) (Table 4) and a higher stalk height (Table 5), which led to the highest TPH (Table 6). However, the pol% cane was not affected (Table 5).

Table 6. Average values for tons of stalks per hectare (TSH) and tons of pol per hectare (TPH) as a function of the doses and application methods of Zn (df = 24).

	Doses (g ha^{-1})	Furrow (t ha^{-1})	Foliar (t ha^{-1})	Means	P
TSH	0	104.8 ± 5.58		-	P (Application method) = 0.079
	185	112.3 ± 3.28	115.2 ± 3.44	113.7 B	P (Doses) = 0.006
	260	117.1 ± 4.31	126.3 ± 2.35 *	121.7 A	P (Interaction) = 0.426
	330	123.3 ± 2.72 *	125.0 ± 1.55 *	124.2 A	P (C × I) = 0.002
	Means	117.6 a	122.2 a		-
TPH	0	17.6 ± 1.09		-	P (Application method) = 0.329
	185	18.5 ± 0.73	19.0 ± 0.64	18.8 B	P (Doses) = 0.040
	260	19.0 ± 0.64	20.6 ± 0.26 *	19.8 AB	P (Interaction) = 0.080
	330	20.6 ± 0.21 *	19.7 ± 0.43	20.2 A	P (C × I) = 0.023
	Means	19.4 a	19.8 a		-

Df, degrees of freedom; average ± standard error; averages followed by different capital letters indicate significant differences between the application methods and averages followed by different lowercase letters indicate significant differences between the doses by Tukey's test ($p \leq 0.05$). * Averages followed with an asterisk differ from the control ($p \leq 0.05$); (C × I): Control × Interaction.

4. Discussion

Zinc exhibits intense participation in the enzymatic systems that regulate the initial stages of tillering and plant growth, and it is vital for root system development [13]. Thus, in the initial phase of plant development, Zn tends to accumulate in the roots, absorbed as Zn^{2+}, but translocation to the shoots is small [48]. In addition, the root absorption of Zn may be impaired due to the adsorptive action exerted by soil particles [49]. It may explain the lack of response to Zn fertilization in the furrow concerning the number of tillers at 145 DAT since the sugarcane plants were in their youthful stage.

Regarding the tillering phase, initially, there is an increase in the number of tillers until approximately 180 DAP, and some varieties can produce more than 25 tillers per clump. However, this number tends to decrease until it stabilizes. Thus, there is an intermediate phase, marked by severe tiller death, until reaching the final phase when the number of tillers is stabilized [50]. However, foliar fertilization at doses of 260 and 330 g ha^{-1} contributed to the maintenance of the number of tillers beyond 180 DAP since these doses resulted in an increased number of tillers at 206 DAP, confirming the efficiency of foliar fertilization compared to furrow fertilization [31] and the proper positioning of foliar application, preparing the plant for its grand growth phase of development.

At 206 DAP, the crop was at the beginning of its intense growth phase of development [11], and Zn contributed to maintaining tillering, as well as the stalk growth, in terms of length, reflecting the intense division, differentiation, cell elongation, and an exponential increase in the shoot dry matter mass.

In the grand growth phase, Zn is essential for tryptophan synthesis [16], which is responsible for the production of enzymes that promote cell elongation and growth, causing node formation, elongation of internodes, and leaf development [13,20,51]. In other crops, plants with Zn deficiency in the initial development stage have their development affected and hardly reach their maximum genetic potential due to impairments in both the maintenance of enzymatic activity and tryptophan synthesis [52].

Foliar fertilization with Zn, as well as the higher dose of Zn in the furrow, improved plant performance compared to the control, contributing to the maintenance of the number of tillers. The foliar application increased the availability of Zn to the plant, enhancing its absorption and facilitating its action in metabolic processes [31,49]. In addition to being an essential component in several enzymatic systems for energy production, Zn is also required for protein synthesis and growth regulation [19,51], which influences the tillering of the crop.

Jamro et al. [53] observed that the foliar application of Zn at low doses was sufficient for maximizing plant height, stalk length and weight, internode number, and internode length. It evidences that foliar fertilization may be more effective than solid fertilization because it reduces solid fertilizer losses, allowing for the use of lower doses of Zn [30,31,36].

The presence of an adequate amount of Zn in the plant contributes to the growth and cellular elongation of sugarcane stalks. Studies show that a reduced hormone production due to a Zn deficiency shortens internodes and atrophies leaf growth [54,55]. Thus, proper nutrition with Zn will positively influence the height of the sugarcane plant, contributing to the increase in the length of the stalk internodes, representing the compartment where sucrose will be accumulated during the ripening process [25,56,57].

The lack of effect of the Zn doses or application methods on the quality of sugarcane agrees with some results found in the literature [58–60]. However, Zn plays an essential role in regulating carbohydrate metabolism [15,61,62], contributing to the increasing sucrose content in the stalks. This is explained by the fact that the sugarcane quality depends on various factors, mainly the sugarcane variety [63,64] and weather parameters, i.e., rainfall, temperature, sunshine, and humidity [65–67]. Thus, Zn fertilization did not alter these parameters as other conditions controlled the sugarcane quality. However, Marangoni et al. [20] reported that Zn application in the sugarcane furrow improved the sugarcane quality (pol and fiber) in the second crop cycle.

Although Zn fertilization affects crop growth, growth is not directly related to sugarcane quality, which is mainly controlled by factors other than fertilization. The increment of 18.5 TSH (17.6%) with a dose of 330 g Zn ha^{-1} in the planting furrow agrees with Mellis et al. [4], who observed an average increase of 29% in the TSH due to the application of Zn in the planting furrow. Wang et al. [68] also observed that the application of 8.9 kg ha^{-1} of Zn increased the TSH by 23% and 24.8% compared to the control without Zn, respectively, in Dundee and Jeanerette soils. In addition, Cunha et al. [26] reported that compared with the control (without Zn fertigation), the sugarcane productivity (plant and ratoon crops) increased by 30.8% when treated with the maximum dose of zinc (10 kg ha^{-1}).

Increases in internode elongation, stalk diameter and weight [69–71], longer stalk length, and a more significant number of tillers [72] were reported as positive effects of Zn fertilization on sugarcane yield. In other grasses, such as rice, the foliar Zn application resulted in increased plant growth and number of tillers [73]. In wheat, increases in the number of fertile tillers and productivity have already been reported [74].

Zinc improves the development and quality of industrial sugarcane stalks, which is also essential in determining the management of sugarcane fertilization strategies [25]. Currently, in Brazil, adding higher doses of Zn at planting (up to 10 kg ha^{-1}) is recommended to have a residual effect for the entire sugarcane cycle. However, applying higher doses of Zn at once in the planting furrow may not be feasible due to the possibility of phytotoxicity [24].

Plants easily take up Zn from polluted soils, and its excess in the plant interferes with many metabolic and physiological processes and, consequently, limits yield [75,76]. A very high Zn content inhibits seed germination, plant growth, and root development and causes leaf chlorosis. Studies have already shown an adverse effect of Zn stress on plants' photosynthesis, chlorophyll content, and chloroplast ultrastructure [77,78].

However, Brazilian soils are generally poor in Zn [79], and these effects are rare, mainly when lower doses are applied. Additionally, when Zn deficiencies are observed in ratoon cane, foliar applications with phytosanitary treatment may be more efficient than soil applications [24]. Our results showed that the efficiency of foliar Zn fertilization might be more feasible than soil application already in the plant cane.

To obtain higher sugarcane development and productivity in the plant cane cycle, Zn application may be implemented in the planting furrow and via foliar application. This decision is based on the dose to be applied. Thus, it is necessary to use a higher dose of Zn in the planting furrow than in the foliar application, but it requires an additional agricultural process.

5. Conclusions

Zinc fertilization improves the number of tillers, stalk height, and stalk and sugar productivity. These improvements can be obtained by applying Zn chelate at a dose of 330 g ha^{-1} via planting furrow or by foliar application performed 145 days after planting at a dose of 260 g ha^{-1}. Although foliar application requires an additional operation, this can be an exciting strategy in areas with low zinc content, favoring crop productivity, avoiding the losses caused by fertilization in the planting furrow, and causing less deteriorating effects on the soil salinity and on unbalancing soil nutrients.

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