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**Abstract:** Composted sewage sludge (CSS) contains large amounts of organic matter and nutrients and can be used as an organic fertilizer to improve growth, yield, and quality of sugarcane. However, there is a lack of information regarding the impact of CSS application on sugarcane seedling performance in nursery environments. A field study was conducted using a randomized complete block design to evaluate the development, nutritional status, productivity, and technological quality of sugarcane seedlings after CSS application with or without mineral fertilizer. Morphological variables (stem height, diameter, and number, as well as leaf area), technological attributes (total recoverable sugar: ATR; quantity of sucrose in sugarcane juice: Pol; Brix: percentage (weight/weight) of soluble solids contained in juice; TAH: tons of sugar per hectare), nutritional status, and sugarcane productivity were evaluated. Treatments did not influence morphological and technological variables except for TAH but did positively alter nutritional status and seedling productivity. The application rates of 5.0 and 7.5 Mg ha$^{-1}$ of CSS with or without mineral fertilizers (MF) provided the greatest increase in crop productivity. Our results indicate that CSS can be a sustainable nutritional management option in sugarcane seedling nurseries, resulting in greater crop productivity at lower mineral fertilization rates.

**Keywords:** alternative fertilizer; nutrient balance; *saccharum* spp.; solid waste; sustainable development

## 1. Introduction

Brazil leads the world in sugarcane and biofuel production [1] and contributing 568 million tons of sugarcane over 8.2 million hectares in 2021 [2]. Large amounts of mineral fertilizers are used to meet the high nutritional demand and achieve satisfactory yields of sugarcane. However, the increasing demand for mineral fertilizers produced with imported raw materials has increased production costs in the sugarcane sector over the years in Brazil [3].

Because of its deep rooting system, sugarcane responds positively to high levels of plant-available nutrients in both shallow and deep soil layers [4]. In tropical areas, low soil fertility is a major constraint in limiting sugarcane production [5]. Tropical soils are highly weathered and often have low organic matter content and nutrient availability coupled with high acidity. Therefore, application of mineral fertilizers and corrective materials are essential to provide adequate conditions for sugarcane development [6]. Sugarcane extracts large amounts of nutrients (especially N, P, and K) from soil during its development [7]. Macronutrient extraction by sugarcane to produce 1.0 t ha$^{-1}$ of stem can amount to 237 kg N ha$^{-1}$, 19 kg P ha$^{-1}$, 264 kg K ha$^{-1}$, 238 kg Ca ha$^{-1}$, and 90 kg Mg ha$^{-1}$ [8].

Sugarcane growers are highly dependent on mineral fertilizers to produce high cane yields and remain profitable [9]. Previous studies have pointed to the need to adopt alternative organic and organo-mineral fertilizers, and biostimulants that allow for an integrated nutrient management approach [10]. Balanced use of organic and mineral fertilizers is also essential to maintain optimal soil physical and chemical conditions [11]. The combined application of organic and mineral fertilizers may increase sugarcane yields [12]. Furthermore, Composted sewage sludge (CSS) may reduce production costs because a smaller amount of mineral fertilizers would be required to achieve yield goals [13].

Composted sewage sludge (CSS) is a potential organic fertilizer for use in sugarcane production. It is derived from sewage sludge produced in large quantities in Wastewater Treatment Plants (WTPs). Sewage sludge has considerable amounts of organic matter and plant nutrients, including N, P, Ca, B, Cu, Fe, Mn, and Zn [14]. Several countries use sewage sludge in crop production, including Ireland, Norway, United States, China, Lithuania, Bulgaria, France, and Germany [15]. In addition, Brazil has generated an estimated 372,000 tons (dry matter) of sewage sludge annually, but only a small portion (~3%) is destined for agriculture [16].

Sewage sludge must undergo a process to reduce risk of pathogens and heavy metal contamination before it can be used on agricultural soils [17]. Composting has been adopted by some sewage sludge treatment plants to eliminate pathogens It also avoids contamination of agricultural soils by limiting the mobility and bioavailability of heavy metals [18]. After sewage sludge has been composted, it can be applied on agricultural soils if it meets the criteria (absence of pathogens and inorganic contaminants) established in the Normative Instruction No. 61 of 8 July 2020 under the Ministry of Agriculture, Livestock and Food Supply [19].

The application of CSS may reduce reliance on mineral fertilizers, making it a sustainable option for maintaining soil health, while reducing sugarcane production costs [20]. El-Naggar et al. [21] reported that CSS gradually provides nutrients, which is advantageous for a long-term crop like sugarcane. Some studies have pointed to the benefits of the combined use of mineral and organic fertilizers to enhance sugarcane productivity [22,23]. However, the use of CSS and mineral fertilizer combinations in sugarcane seedling nurseries has not been widely investigated.

In this study, we hypothesized that, even at low application rates of mineral fertilizer (MF), CSS would provide an optimal balance of nutrients in sugarcane, improving technological variables while also increasing productivity. While previous studies have demonstrated efficiencies in CSS application as fertilizer/amendment, our research is novel by accounting for low MF rates and nutrient balance for a commercial/industrial crop under nursery conditions. Our objective in this research was to evaluate sugarcane seedling nutritional status, productivity, and technological quality after application of CSS with or without mineral fertilizer in a field nursery.

## 2. Materials and Methods

The experiment was conducted in a commercial nursery environment in the municipality of Suzanápolis, São Paulo, Brazil (20°28′47.40″ S and 51°4′33.14″ W) from November 2019 to August 2020 using a randomized complete block design with 11 treatments and four replications. Each plot consisted of six rows spaced 1.5 m by 10 m (90 $m^2$ per plot; 3960 $m^2$ whole experimental area).

In total, 11 different treatments, combining CSS (wet basis), NPK (6–30–24), and mineral fertilizer (MF), were evaluated: T1 (control)—without CSS and MF application; T2—100% of the recommended MF (33 kg $ha^{-1}$ of N, 165 kg $ha^{-1}$ of $P_2O_5$, and 132 kg $ha^{-1}$ of $K_2O$); T3—2.5 Mg $ha^{-1}$ of CSS; T4—5.0 Mg $ha^{-1}$ of CSS; T5—7.5 Mg $ha^{-1}$ of CSS; T6—2.5 Mg $ha^{-1}$ of CSS + 50% of MF; T7—5.0 Mg $ha^{-1}$ of CSS + 50% of MF; T8—7.5 Mg $ha^{-1}$ of CSS + 50% of MF; T9—2.5 Mg $ha^{-1}$ of CSS + 100% of MF; T10—5.0 Mg $ha^{-1}$ of CSS + 100% of MF; T11—7.5 Mg $ha^{-1}$ of CSS + 100% of MF. The applied CSS doses were based on recommendations by the CSS supplier [24]. The 100% MF was applied based on technical recommendations of Usina Vale do Paraná, State of São Paulo, Brazil.

The CSS consisted of urban organic and urban/agro-industrial organic wastes (bagasse, fruit, vegetable peels from food processing, poultry litter, and wood chips). During composting, the organic compounds underwent: (i) decomposition; (ii) biological stabilization through thermophilic processes with a temperature above 60 °C for approximately 2 weeks. After this period, CSS was ready for use (40% moisture). The CSS was characterized following Resolution-498/2020 [25] recommendations, thus being considered appropriate for agricultural reuse (Table 1).

**Table 1.** Composted sewage sludge chemical and biological features (mean ± SE, *n* = 3).

| | Unit | Concentration (Wet Basis) | Limits [a] |
|---|---|---|---|
| Chemical Features | | | |
| pH ($CaCl^2$) | - | 7.9 ± 0.15 | - [b] |
| Moisture (60–65 °C) | % | 33.9 ± 1.42 | - |
| Total moisture | % | 35.1 ± 1.51 | - |
| Total OM | g $kg^{-1}$ | 230.4 ± 8.3 | - |
| CEC | $mmol_c$ $dm^{-3}$ | 25.0 ± 4.62 | - |
| C/N | - | 11.0 ± 1.73 | - |
| Total N | g $kg^{-1}$ | 10.5 ± 1.81 | - |
| Total P | g $kg^{-1}$ | 13.2 ± 3.9 | - |
| Total K | g $kg^{-1}$ | 8.0 ± 1 | - |
| Total Ca | g $kg^{-1}$ | 30.6 ± 3.47 | - |
| Total Mg | g $kg^{-1}$ | 9.5 ± 2.29 | - |
| Total S | g $kg^{-1}$ | 6.2 ± 0.44 | - |
| Total Na | mg $kg^{-1}$ | 4342.5 ± 3751.2 | - |
| As | mg $kg^{-1}$ | 6.4 ± 2.34 | 20.0 |
| B | mg $kg^{-1}$ | 17.0 ± 6.0 | - |
| Cd | mg $kg^{-1}$ | 0.9 ± 0.29 | 3.0 |
| Cu | mg $kg^{-1}$ | 178.0 ± 61.99 | - |
| Pb | mg $kg^{-1}$ | 17.8 ± 10.18 | 150.0 |
| Cr | mg $kg^{-1}$ | 65.7 ± 46.22 | - |
| Fe | mg $kg^{-1}$ | 18,207.0 ± 788.01 | - |
| Mn | mg $kg^{-1}$ | 435.0 ± 208.01 | - |
| Hg | mg $kg^{-1}$ | 0.3 ± 0.07 | 1.0 |
| Mo | mg $kg^{-1}$ | 6.0 ± 3.47 | - |
| Ni | mg $kg^{-1}$ | 30.1 ± 3.4 | 70.0 |
| Zn | mg $kg^{-1}$ | 679 ± 73.06 | - |
| Biological analysis | | | |
| *Salmonella* sp. | MPN/10 g | Absent | |
| *Fecal coliform* | MPN/g | 0 | |
| Viable helminth eggs | Eggs $g^{-1}$ on dry weight | 0.12 | |

[a] Limits to organic fertilizers used established by the Ministry of Agriculture, Livestock and Food Supply in Brazil [25]. [b] NR—not ruled; MPN—most probable number.

The sugarcane was harvested in August 2020, and soil surface (0.0–0.25 m) and subsurface (0.25–0.50 m) horizons were collected. Six subsamples were randomly collected per plot and composited. Soil samples were air-dried, crushed, and passed through a sieve with a mesh size of 2.0 mm, packed in identified polyethylene bags, and stored in a dry chamber until the time of analysis. Comprehensive details on the development of the experiment such as experimental area, agrochemicals application, sugarcane variety, soil characterization, and soil fertility evaluation are described by Silva et al. [26].

### 2.1. Nutritional, Morphological, Technological, and Productivity Analysis

Leaf area (LA) was obtained by measuring the length (L) and width (W) of 20 leaves per plot at 150 days after planting and applying the formula for evaluation of leaf area LA ($m^2$) = 0.75 × L × W [27]. During the same period, 10 leaves were collected per plot, removing the central 20 cm of the leaf + 1 (highest leaf with visible collar—"TVD"), excluding leaf midrib [28] to determine N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn concentration as described by Malavolta et al. [29].

Morphological parameters were used to estimate sugarcane productivity. Stem length (m) and plant height (m) were measured from the soil surface to the first visible leaf with the aid of a tape measure. The stalks were counted in 20-meter lines for the number of tillers per meter. Stem diameter (mm) was measured at the fifth internode with the aid of a graduated caliper. The spacing between the furrows was 1.50 m.

We used 9-month-old sugarcane seedlings that were manually harvested in August 2020. Sugarcane productivity (TCH, Mg $ha^{-1}$) was evaluated by weighing total stalks in the three central rows of each plot. A total of 10 stalks/m $plot^{-1}$ were harvested to evaluate technological characteristics by determining °Brix—the percentage (weight/weight) of soluble solids contained in juice (concentration of sucrose in sugarcane juice, total recoverable sugar (ATR, kg $ha^{-1}$) and quantity of sucrose in sugarcane juice (Pol, %)), quantified according to Consecana [30]. Moreover, sugar productivity was calculated in tons of sugar per hectare (TAH, Mg $ha^{-1}$) through the product of ART by TCH and divided by 1000.

### 2.2. Statistical Analysis

The results were submitted to analysis of variance using F-test ($p \leq 0.05$) and the Scott–Knott test to group means of qualitative variables and regression analysis for quantitative variables (CSS doses). Statistical analyses and correlation by heatmaps were performed using AgroEstat program version 1.1 [31] and R software version 4.0.1 [32].

## 3. Results and Discussion

Leaf nitrogen (N) concentration was similar under all treatments (Figure 1a) and in most cases was in the adequate range (18 to 25 g $kg^{-1}$) according to findings by Raij [28]. Only T10 and T11 were slightly lower than the limit of sufficiency. There were no visual symptoms of N deficiency for all treatments.

Previous studies in which sewage sludge was applied to sugarcane have shown that leaf N concentration can range from 8.6 and 9.0 g $kg^{-1}$ during the first 12-month cycle and is approximately 12.1 g $kg^{-1}$ in the second 12-month cycle [33,34]. Although CSS loses large amounts of N during composting, it still provided adequate levels for sugarcane growth in our study as leaf N concentration were higher than in the aforementioned studies.

Leaf P concentrations were also not affected by treatments (Figure 1b), and all P levels were within the interpretation range (1.5 to 3.0 g $kg^{-1}$) according to findings by Raij [28]. Crusciol et al. [3] also found P concentrations ranging from 1.7 to 1.8 g $kg^{-1}$ in sugarcane leaf grown in an Oxisol fertilized with an organo-mineral. The application of organo-mineral fertilizer based on sewage sludge provided similar concentration of N, P and K in sugarcane as compared to mineral fertilizers, where P concentrations ranged from 1.9 to 2.0 g $kg^{-1}$ [35]. In addition, Chiba et al. [36] found that the application of sewage sludge and synthetic N fertilizer doses (0 to 120 kg $ha^{-1}$) to an Ultisol soil cultivated with sugarcane resulted in leaf P concentrations ranging from 1.2 to 2.0 g $kg^{-1}$ of P.

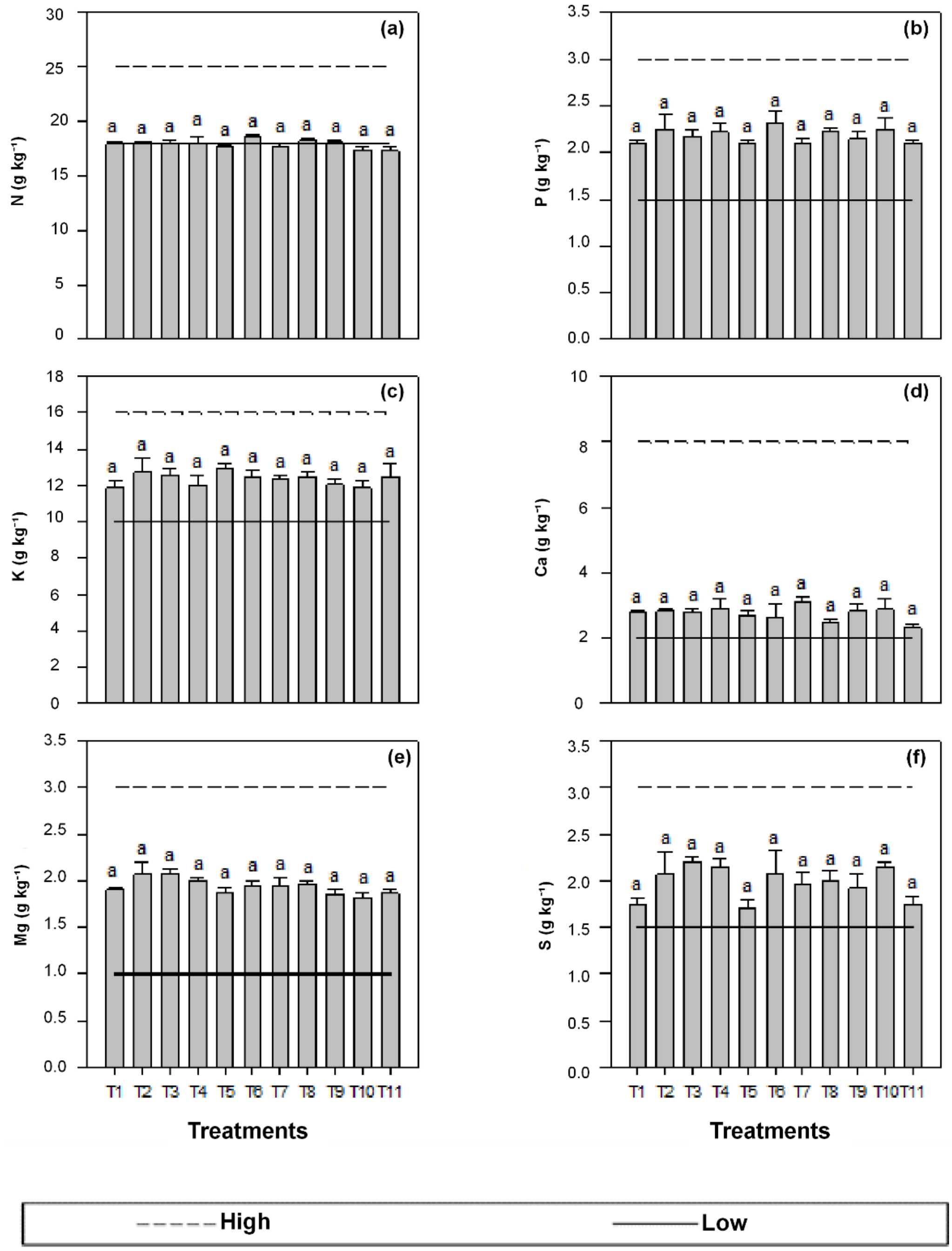



**Figure 1.** Concentration of N (**a**), P (**b**), K (**c**), Ca (**d**), Mg (**e**), and S (**f**) in leaves of sugarcane crop depending on treatments: T1: control—without composted sewage sludge (CSS) and mineral fertilization (MF); T2: 100% of the recommended MF for sugarcane; doses of CSS (Mg ha$^{-1}$, wet basis) = T3: 2.5; T4: 5.0; T5: 7.5; doses (Mg ha$^{-1}$, wet basis) of CSS + MF with NPK (kg ha$^{-1}$) = T6: 2.5 + 50%; T7: 5.0 + 50%; T8: 7.5 + 50%; T9: 2.5 + 100%; T10: 5.0 + 100%; T11: 7.5 + 100%. Means followed by same letter do not differ from each other by Scott–Knott test at 5% probability (mean ± SE, $n$ = 4). The horizontal lines on graph bars represent range of interpretation of macronutrient concentrations for sugarcane crop as described by Raij [28].

Treatments did not affect leaf K concentration in sugarcane (Figure 1c). All treatments results in leaf K concentrations within the limits of interpretation (10.0 to 16.0 g kg$^{-1}$) as described by Raij [28], indicating adequate K nutrition.

Although no difference in response to CSS associated or not with mineral fertilizers was noted, leaf Ca concentrations were within the ranges of interpretation (2.0 to 8.0 g $kg^{-1}$) for cultivation of sugarcane [28]. Similarly, Mg and S concentrations also did not differ as a function of the different treatments (Figure 1e,f), but they were within the ranges (Mg = 1.0 to 3.0 g $kg^{-1}$ and S = 1.5 to 3.0 g $kg^{-1}$) according to Raij [28]. It is worth noting that adequate nutrient supply is essential for sugarcane development since the crop has relatively high macronutrient demand [8].

We observed that B concentration did not differ among treatments (Figure 2a). In addition, B concentrations were below the lower range (10 to 30 mg $kg^{-1}$) as established by Raij [28]. for sugarcane. The low B concentration in sugarcane is related to the low B availability in soil [26]. Therefore, even though B is a component of CSS, it is necessary to supply B with mineral fertilizer. Although the B concentration in leaves was less than 5 mg $kg^{-1}$, there was no visual symptom of deficiency of this nutrient in plants cultivated in all treatments. Boron is absorbed in small amounts but still plays a fundamental role in the survival of plant species, as it takes part in pollen tube formations, fructification processes, N metabolism, and hormonal activities [37]. Boron as a borate ion can participate in the transport of sugar carbohydrates from leaves to other organs, which is a very important function in sugarcane [38].

Leaf Cu concentrations did not vary among treatments (Figure 2b). In most cases, leaf Cu concentrations were within the adequate range (6 to 16 mg $kg^{-1}$) according to Raij [28]. The Fe concentration in sugarcane leaves also did not vary among treatments (Figure 2c) and remained above the lower limits (40 mg $kg^{-1}$) of interpretation [28]. Leaf Mn concentration varied among treatments (Figure 2d). We noted that T5, T6, T8, T9, T10, and T11 resulted in lower Mn concentrations than other treatments. Despite these differences, all Mn concentrations were within the adequate nutritional range (25 to 250 mg $kg^{-1}$) for sugarcane [28]. In addition, leaf Zn concentrations were not influenced by treatments (Figure 2e), and all levels were within the limits of interpretation (10 to 50 mg $kg^{-1}$) proposed by Raij [28].

Despite an increase in the levels of some micronutrients in soils after the application of CSS [26], we noted that micronutrient levels were sufficient. Previous work has shown that CSS is made up of different micronutrients and is able to supply enough Cu, Mn, Fe, and Zn for sugarcane cultivation [39] as well as soybean [20]. Moretti et al. [40] evaluated micronutrients concentrations under residual effect of sewage sludge (dry basis) in sugarcane cultivation and observed that Cu and Zn concentrations in soil were influenced by CSS application.

In the present study, leaf micronutrient concentrations followed the following order: Fe > Mn > Zn > Cu > B. These results were supported by Silva [41] who reported that low leaf micronutrients concentrations in sugarcane may be a reason for low yields (average of 60 Mg $ha^{-1}$) in three different regions of Brazil. Therefore, micronutrient application in sugarcane resulted in an increase of ~17% in production of stalks and demonstrated the importance of micronutrient provisioning for sugarcane [42].

There was no difference among treatments for stem length (Figure 3a). Similar results were reported by Moraes et al. [43] who studied the vegetative and biometric development of sugarcane fertilized with organo-mineral fertilizer based on sewage sludge and biostimulants. Treatments also did not influence stem diameter at 150 days after planting (Figure 3b). There also were no treatment effects on plant height, which peaked at 154.8 cm. Our findings are supported by Noronha [44] who evaluated sugarcane seedlings in a Rhodic Hapludox management system and did not observe differences between stem diameter and plant height. Application of biosolids with or without mineral fertilization did not significantly influence plant height and stalk diameter of sugarcane [35].

The number of tillers was also not influenced by treatments with the range from 8.2 to 9.2 tillers $m^{-1}$ (Figure 3c). Santos et al. [45] evaluated tillering in four sugarcane varieties (CTC2, RB867515, RB92579, and CTC4) and did not observe difference for this variable; however, variety RB867515 produced more tillers (17.0–18.8 $m^{-1}$) than in our study.

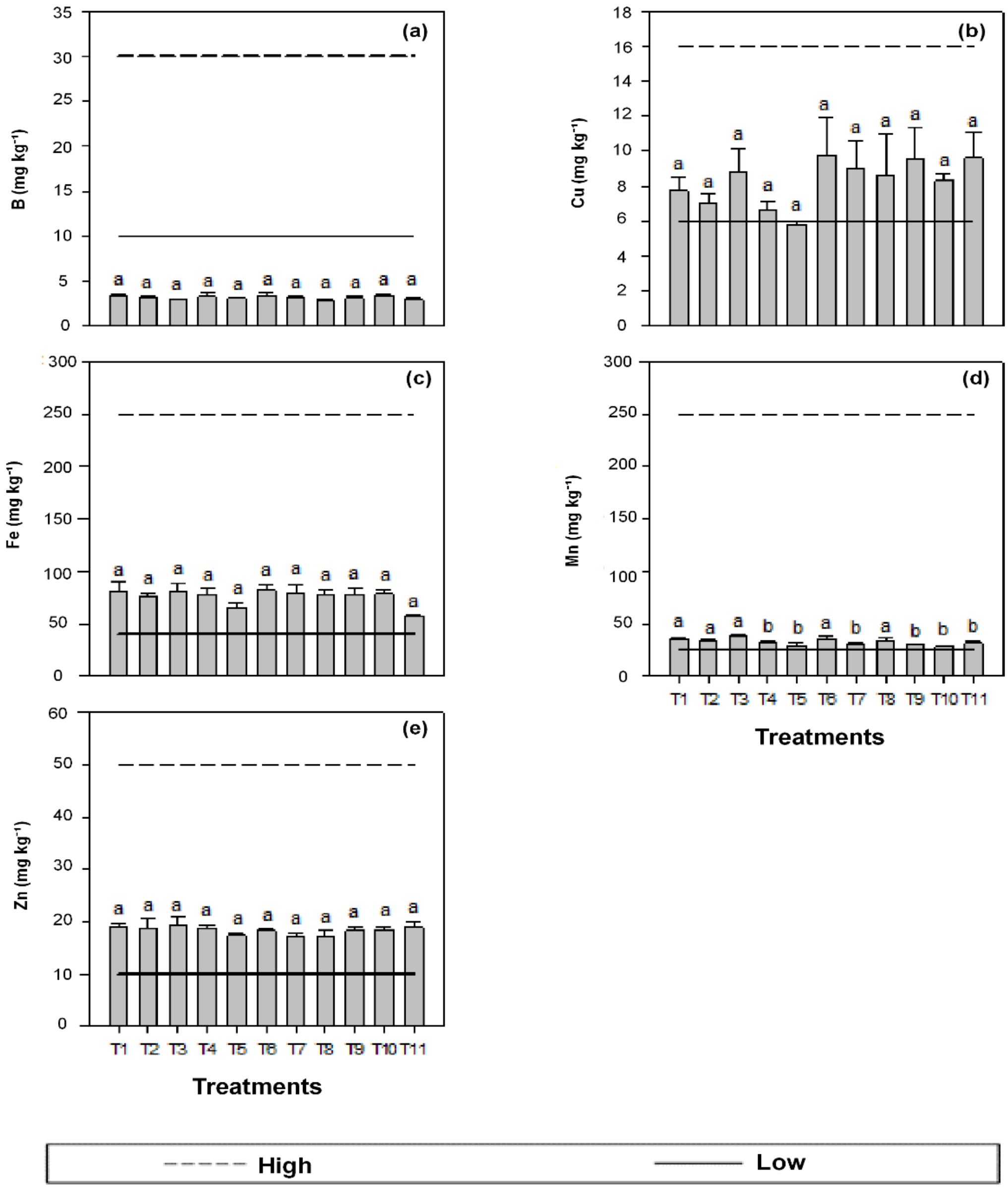



**Figure 2.** Concentrations of B (**a**), Cu (**b**), Fe (**c**), Mn (**d**), and Zn (**e**) in leaves of sugarcane crop depending on the treatments: T1: control—without composted sewage sludge (CSS) and mineral fertilizer (MF); T2: 100% of the recommended MF for sugarcane; doses of CSS (Mg ha$^{-1}$, wet basis) of CSS = T3: 2.5; T4: 5.0; T5: 7.5; doses (Mg ha$^{-1}$, wet basis) of CSS + MF with NPK (kg ha$^{-1}$) = T6: 2.5 + 50%; T7: 5.0 + 50%; T8: 7.5 + 50%; T9: 2.5 + 100%; T10: 5.0 + 100%; T11: 7.5 + 100%. Means followed by same letter do not differ from each other by Scott–Knott test at 5% probability (mean ± SE, $n$ = 4). The horizontal lines on the graph bars represent range of interpretation of micronutrient concentrations for sugarcane crop as described by Raij [28].

Leaf area (LA) of sugarcane was significantly similar within treatments, ranging from 0.049 to 0.052 m$^2$ (Figure 3d). Bozza and Marchiori [46] evaluated sugarcane variety RB867515 under the application of sewage sludge associated with mineral fertilization and found a small difference in relation to leaf area with best results observed in treatments with mineral fertilization.

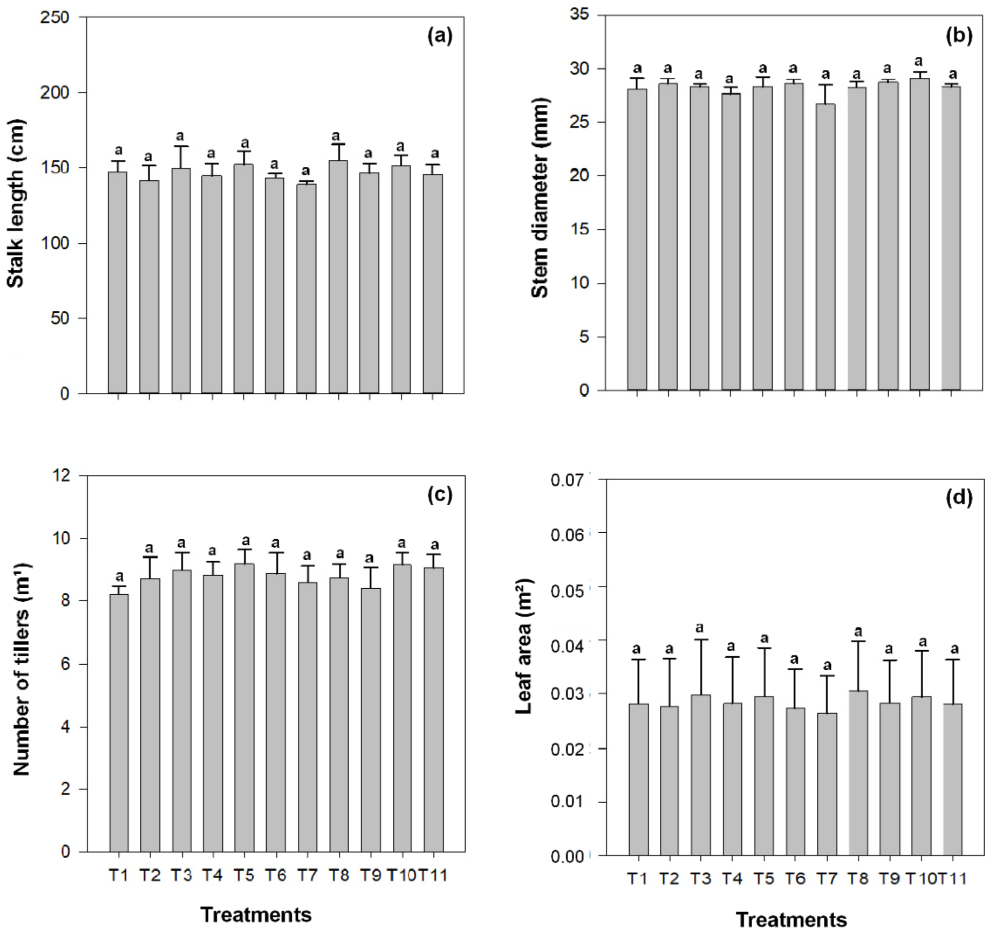



**Figure 3.** Stalk length (**a**), stem diameter (**b**), number of tillers (**c**), and leaf area (**d**) as a function of treatments: T1: control—without application of composted sewage sludge (CSS) and mineral fertilization (MF); T2: 100% of the recommended MF for sugarcane; doses of CSS (Mg ha$^{-1}$, wet basis) = T3: 2.5; T4: 5.0; T5: 7.5; doses of CSS (Mg ha$^{-1}$, wet basis) + MF with NPK (kg ha$^{-1}$) = T6: 2.5 + 50%; T7: 5.0 + 50%; T8: 7.5 + 50%; T9: 2.5 + 100%; T10: 5.0 + 100%; T11: 7.5 + 100%. Means followed by same letters do not differ from each other by Scott–Knott test at 5% probability (mean ± SE, *n* = 4).

There was no effect of treatments on technological quality of sugarcane, the °Brix ranging from 21.9 to 22.4% (Figure 4a), TRS ranging from 158.2 to 161.5 kg ha$^{-1}$ (Figure 4b) and Pol% ranging from 19.1 to 19.5% (Figure 4c). Temperature variation and rainfall [28] may explain higher TRS concentration under all treatments. These quality characteristics were not affected by CSS and mineral fertilizer application. Previous studies indicated that average daily temperature of 30 °C is ideal for sugarcane development, while temperatures above 38 °C will cause reduction in photosynthesis and an increase in respiration. Relatively low temperatures (12 to 14 °C) are desirable for ripening; however, they have notable influence on reducing vegetative growth and increasing sucrose concentration [47,48].

There were significant differences in sugarcane yield among treatments (Figure 4d), ranging from 7.6 to 16.7 Mg ha$^{-1}$. The highest yields were achieved under TY (16.7 Mg ha$^{-1}$), which was statistically similar to yields under T3 and T5, which were 14.7 and 15.7 Mg ha$^{-1}$, respectively. These differences may relate to variation in sugarcane productivity per hectare (Figure 5). However, no differences were verified for TRS (Figure 4b). Menezes and Resende [49] studied technological traits of sugarcane at different planting times of two varieties (RB92579 and RB962962) and found similar yields, ranging from 18.86 to 24.76 Mg ha$^{-1}$ while TRS ranged from 139.25 to 144.14 kg ha$^{-1}$, not being significant.

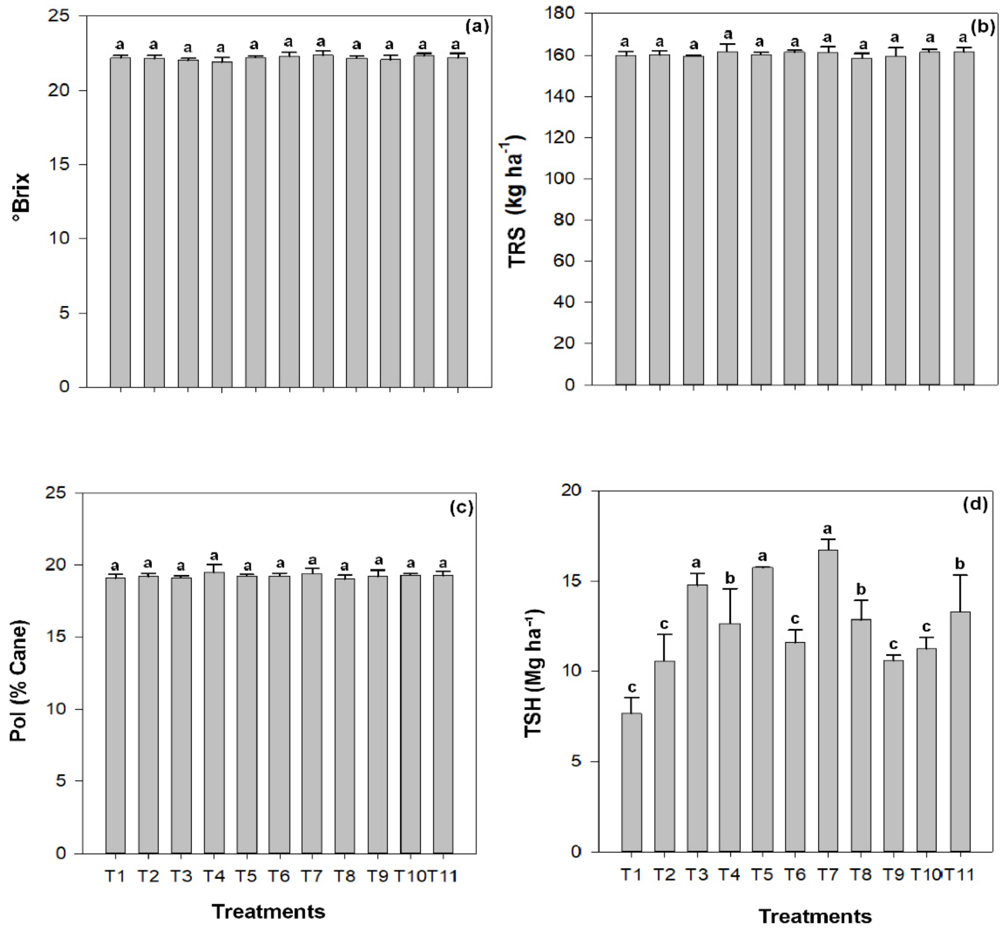



**Figure 4.** °Brix (**a**), total recoverable sugar (TRS) (**b**), percentage of sugar cane sucrose (Pol% cane) (**c**), and sugar productivity in tons of sugar per hectare (TSH) (**d**) as a function of treatments: T1: control—without application of composted sewage sludge (CSS) and mineral fertilization (MF); T2: 100% of the recommended MF for sugarcane; doses of CSS (Mg ha$^{-1}$, wet basis) = T3: 2.5; T4: 5.0; T5: 7.5; doses of CSS (Mg ha$^{-1}$, wet basis) + MF with NPK (kg ha$^{-1}$) = T6: 2.5 + 50%; T7: 5.0 + 50%; T8: 7.5 + 50%; T9: 2.5 + 100%; T10: 5.0 + 100%; T11: 7.5 + 100%. Means followed by same letters do not differ from each other by Scott–Knott test at 5% probability (mean ± SE, $n$ = 4).

The average productivity of stalks per hectare ranged from 47.8 to 103.8 Mg ha$^{-1}$ (Figure 5), with T7 inducing the highest yield with an increase of 20.5%, which was an increase of 53.9% in relation to T1. It was observed that T3 and T5 also showed similar productivity to T7, demonstrating that CSS with or without MF can be a viable alternative strategy to increase sugarcane productivity. Gonçalves et al. [10] reported that sugarcane productivity increased with application of organo-mineral fertilizer based on sewage sludge, showing higher productivity per hectare in first year of application.

It was noted that the contribution of macro and micronutrients to soil through the application of CSS [26] may significantly increase sugarcane productivity (Figure 5). Several authors have already shown that use of sewage sludge (composted or not) in agriculture can enhance crop productivity [20,50].

Taking into account only the effect of CSS doses (0 to 7.5 Mg ha$^{-1}$) on attributes of development, technological quality, and productivity of sugarcane crop, no alterations were observed in leaf area, °Brix, TRS, and Pol% of sugarcane (Table 2).

Possible correlations between soil properties (0.0–0.25 and 0.25–0.50 m) and sugarcane were evaluated (Figure 6a,b).

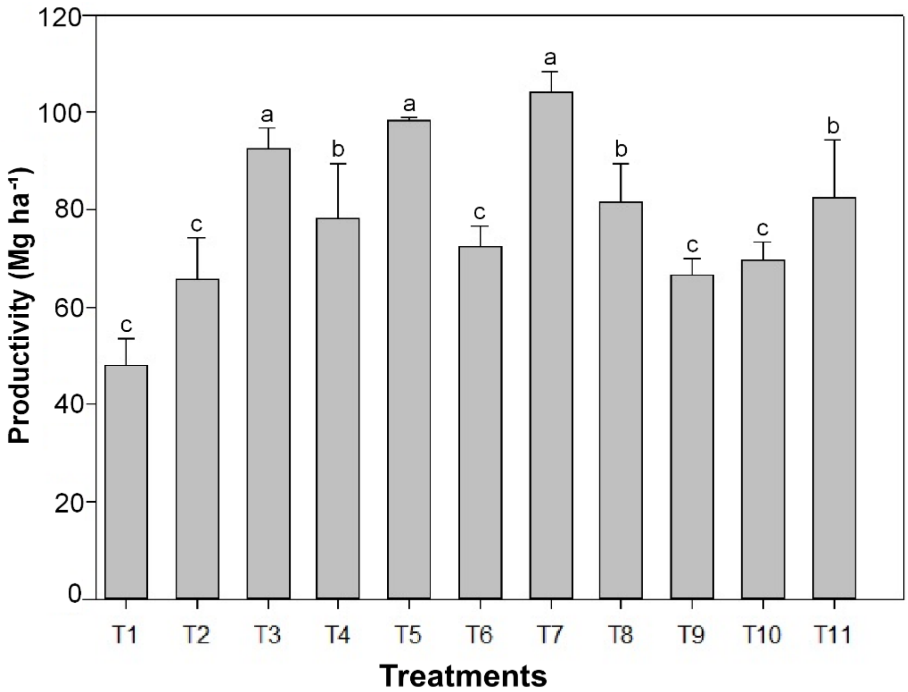


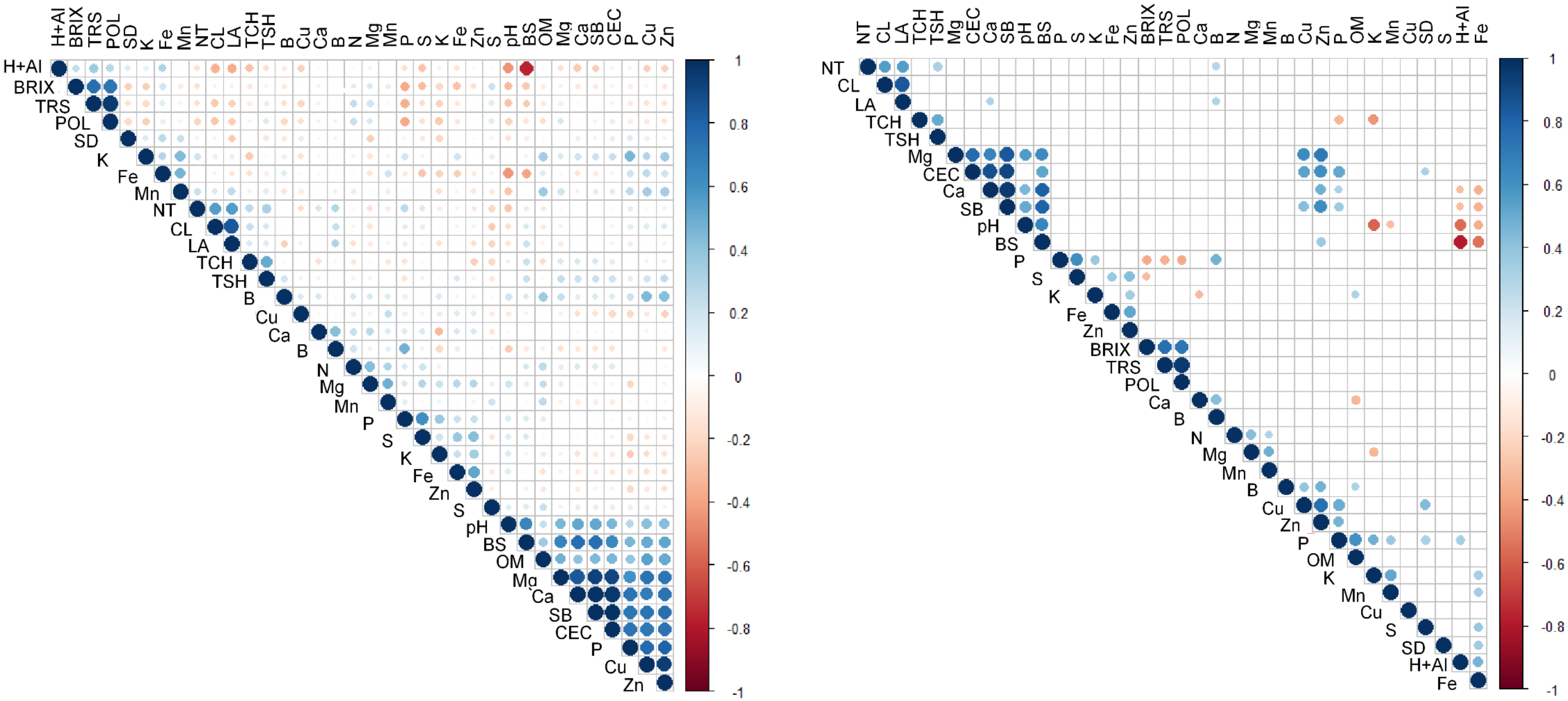

**Figure 5.** Sugarcane productivity in tons of stalks per hectare (TSH) as a function of treatments, T1: control—without application of composted sewage sludge (CSS) and mineral fertilization (MF); T2: 100% of the recommended MF for sugarcane; doses of CSS (Mg ha$^{-1}$, wet basis) = T3: 2.5; T4: 5.0; T5: 7.5; doses of CSS (Mg ha$^{-1}$, on a wet basis) + MF with NPK (kg ha$^{-1}$) = T6: 2.5 + 50%; T7: 5.0 + 50%; T8: 7.5 + 50%; T9: 2.5 + 100%; T10: 5.0 + 100%; T11: 7.5 + 100%. Means followed by same letters do not differ from each other by Scott–Knott test at 5% probability (mean ± SE, *n* = 4).

**Table 2.** Regression analysis of leaf area, sugarcane productivity in tons of stalks per hectare (STY), total recoverable sugar (TRS), sugar productivity in tons of sugar per hectare (TSH), sucrose percentage in cane (Pol%) and °Brix in response to applied composted sewage sludge doses (0.0, 2.5, 5.0, and 7.5 Mg ha$^{-1}$, on a wet basis).

| Variables | Equation | $R^2$ | *Test F* |
|---|---|---|---|
| Leaf area | $\hat{y} = 0.05$ | 0.96 | 2.80 $^{ns}$ |
| STY | $\hat{y} = -1.283x^2 + 14.35x + 45.32$ | 0.52 | 7.15 ** |
| TRS | $\hat{y} = 160.67$ | 0.91 | 0.41 $^{ns}$ |
| TSH | $\hat{y} = -0.200x^2 + 2.27x + 7.26$ | 0.51 | 6.69 ** |
| Pol% | $\hat{y} = 19.25$ | 0.80 | 0.38 $^{ns}$ |
| °Brix | $\hat{y} = 22.05$ | 0.99 | 0.01 $^{ns}$ |

** and $^{ns}$—Significant at 1% probability and not significant, respectively.

Application of CSS with or without mineral fertilizer increased CEC and Ca concentrations in soil [26]. In this sense, it is possible to verify a positive correlation (*r* = 0.97 **) between these variables, showing that CSS application can increase Ca concentrations in surface soil layers while also increasing CEC. The positive correlation of CEC could also be observed with Mg (*r* = 0.92 **), SB (*r* = 0.99 **), P (*r* = 0.74 **), Cu (*r* = 0.71**), and Zn (*r* = 0.74 **) (Figure 6a). The positive correlations for soil Zn concentration (Figure 6a,b) indicated that CSS increased this nutrient in soil. It is known that this nutrient contributes significantly to final productivity of sugarcane crop [51].




(**a**) (**b**)

**Figure 6.** Heat map showing Pearson correlations between soil chemical attributes (OM—organic matter, pH—active acidity, H + Al—potential acidity, Al—exchangeable aluminum, SB—sum of bases, CEC—cation-exchange capacity, and BS—base saturation), soil nutrient concentrations (P—phosphorus, K—potassium, Ca—calcium, Mg—magnesium, S—sulfur, B—boron, Cu—copper, Fe—iron, Mn—manganese, and Zn—zinc) in 0.0–0.25 m (**a**), and 0.25–0.50 m (**b**) deep soil layers, and tons of stalk per hectare (STY), total recoverable sugar (TRS), sugar productivity in tons of sugar per hectare (TSH), sucrose percentage in cane (Pol%), and °Brix, in response to treatments studied: T1: control—without application of composted sewage sludge (CSS) and mineral fertilizer (MF); T2: 100% of the recommended MF for sugarcane; doses of CSS (Mg ha$^{-1}$, wet basis) = T3: 2.5; T4: 5.0; T5: 7.5; doses of CSS (Mg ha$^{-1}$, on a wet basis) + MF with NPK (kg ha$^{-1}$) = T6: 2.5 + 50%; T7: 5.0 + 50%; T8: 7.5 + 50%; T9: 2.5 + 100%; T10: 5.0 + 100%; T11: 7.5 + 100%.

Compared findings by Silva et al. [26], we observed a significant increase in P concentration (up to 18.6 times) after the experiment, demonstrating the potential of CSS to supply P to soil. The positive correlation of P concentrations with other soil attributes demonstrated the supply of nutrients via CSS with or without mineral fertilization provided better productivity (Figure 5). These benefits are related to the effect of P on rooting, tillering and absorption of other nutrients [52]. In the 0.0–0.25 m depth layer, sugarcane productivity was influenced by soil Ca, Mg, K, Cu, Mn, and Zn concentrations (Figure 6a). There was also a positive correlation with Ca, Mg, S, and Zn concentrations and sugarcane productivity in subsurface soil layer (Figure 6b).

Negative correlations were also observed for potential acidity, exchangeable aluminum, and aluminum saturation. These findings showed that CSS doses can lead to higher soil pH, which provides better conditions for root development and consequently, greater absorption of nutrients by roots. At a depth of 0.25–0.50 m (Figure 6b), a positive correlation was observed between Ca and Mg ($r$ = 0.66 **), CEC ($r$ = 0.86 **), and SB ($r$ = 0.96 **).

Regarding morphological, technological, and productivity attributes of sugarcane (Figure 6a,b), a positive correlation was observed for TRS, POL, and BRIX. There was also a positive correlation for stem length and leaf area.

Overall, the study demonstrated that CSS can be a sustainable nutrient management option in sugarcane seedling nurseries, resulting in greater crop productivity at lower MF rates. However, additional research must be conducted to understand the impact of CSS on other pivotal soil aspects. From this perspective, future studies must investigate additional parameters, such as enzymatic activities. Indeed, with its ability to represent the cumulative effect of past management practices, enzyme activity can be a helpful tool for further improving our knowledge on CSS soil application for sugarcane production [53]. As a matter of fact, while physical–chemical properties usually change over decades, biochemical activities, such as soil enzymes, respond more quickly even to small soil changes, thus providing pivotal information [54,55]. Therefore, we suggest that future investigation on this topic should also focus on soil enzyme activities, thus providing additional suitable indications about soil quality.

## 4. Conclusions

Morphological variables (stem length, stem diameter, plant height, leaf area, and number of tillers) were not influenced by CSS application doses. The same behavior was observed for technological variables (Brix, ATR, and Pol). However, the application rate of 5.0 Mg ha$^{-1}$ of CSS associated with 50% MF was observed with higher productivity of TSH. The application rates of 5.0 and 7.5 Mg ha$^{-1}$ of CSS (wet base) with or without MF increased sugarcane productivity. Our results suggest that the application of CSS in sugarcane nursery areas can be a viable and sustainable strategy to provide adequate amounts of nutrients for sugarcane, increasing productivity and reducing use of mineral fertilizers. Considering Brazil is the second largest importer of mineral fertilizers in the world, the use of CSS as an alternative fertilizer for sugarcane can supports sustainable agriculture in the region.

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