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Common bean productivity and micronutrients in the soil-plant system under residual applications of composted sewage sludge

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Abstract: The composted sewage sludge (CSS) is an organic fertilizer that can be used as a source of micronutrients in agriculture. However, there are still few studies with CSS to supply micronutrients for the bean crop. We aimed to evaluate micronutrients concentrations in the soil and their effects on nutrition, extraction, export, and grain yield in response to CSS residual application. The experiment was carried out in the field at Selvíria-MS, Brazil. The common bean cv. BRS Estilo was cultivated in two agricultural years (2017/18 and 2018/19). Experiment was designed in randomized blocks with four replications. The treatments consisted of four CSS doses (5.0, 7.5, 10.0, and 12.5 t ha^{-1}, wet basis), a control without fertilizer application and with conventional mineral fertilizer (CMF) treatments. The available levels of B, Cu, Fe, Mn, and Zn were evaluated in soil samples collected in the layers of 0–0.2 and 0.2–0.4 m. The concentration, extraction, and export of micronutrients in leaf and productivity of common bean were evaluated. The concentration of Cu, Fe and Mn ranged from medium to high in soil. The available levels of B and Zn in the soil increased with the residual rates of CSS, which were statistically not different from the treatments with CMF. The nutritional status of common bean remained adequate. The common bean showed higher requirement for micronutrients in the second year. Leaf concentration of B and Zn were increased with rates of 7.5 and 10.0 t ha^{-1} of CSS. There was greater extraction of micronutrients in the second year. Productivity was not influenced by the treatments, however, it is higher than the Brazilian national average. Micronutrients exported to grains varied between growing years but were not influenced by treatments. We conclude that CSS can be used as an alternative source of micronutrients for common bean grown in winter.

Keywords: *Phaseollus vulgaris* L.; food security; organic fertilizers; plant nutrition; urban waste

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1.Introduction

Brazil is among the world's largest producer of common bean, *Phaseolus vulgaris* L., (FAOSTAT, 2021). The estimated production of common bean was around 1.43 million tons from the planted area of 1.38 million hectares in 2021/2022, reflecting an increase in productivity (CONAB, 2022). Beans are produced and imported in many countries, as they are one of the main sources of protein, rich in macro and micronutrients such as K, Mg, Fe, and Zn, among other benefits (COÊLHO; XIMENES, 2020; VIDAL et al., 2022).

Brazil is producing three crops of common beans annually, vary between regions. The first is rainy season, where common beans are sown between the months of August and November, the second is dry season, where it is sown from November to March and the third is winter or irrigated from April and July (SILVA; WANDER, 2018; NEVES et al., 2021). The production of winter beans requires more technology than crops in appropriate weather conditions with the use of good quality seeds, fertilizers, correctives, and pesticides make it possible to obtain three to five times higher production than sowing times (RICHETTI; ITO, 2015; NEVES et al., 2021).

Common bean cultivation with sprinkler center pivot irrigation is the most common method used by farmers in Brazilian Cerrado region of the Midwest and Southeast states of Brazil (SILVA; WANDER, 2018). It is necessary to overcome the problems of phytosanitary such as pests and diseases as well as climate changes such as water availability and temperature. In addition, soils in this region are under constant weathering, which reduces quality, causing high acidity, less organic matter with low cation exchange capacity (CEC) and anion exchange capacity (AEC) and deficiency of macro and micronutrients (MUMBACH et al., 2018).

Common bean has high requirements in terms of soil fertility due to its short cycle and superficial root system (SOUZA et al., 2011). Common bean requires micronutrients in a small amount but are essential for obtaining productivity gains (CARVALHO et al., 2019; BOARETTO et al., 2022). Thus, adequate nutritional management through correction of acidity of the tropical soils is essential to achieve high gain in the final production of common bean (FAGERIA et al., 2015; GOMEZ-ZAVAGLIA et al., 2020; CORIOLETTI et al., 2021). However, producers face an annual increase in the prices of mineral fertilizers, especially in countries with a high dependence on the imports of fertilizers such as Brazil (ANDA, 2022). Thus, it becomes necessary to search for alternative sources of nutrients to complement mineral fertilization and replace its dependence that has been causing global food insecurity.

The recycling of organic waste in agricultural soils, specifically sewage sludge (SS) is a promising alternative due to its most sustainable final disposal by-product that has been produced on a large scale in urban centers (MATEO-SAGASTA et al., 2015; ABREU et al., 2019). The SS comes from the treatment of effluents and contains high levels of organic matter and plant nutrients that can be used in agriculture as a fertilizer (NASCIMENTO et al., 2020; CHAGAS et al., 2021). Sewage sludge composting has been a strategy to reduce volume of SS and make it safer for application in agricultural areas for its better management (NGUYEN; SHIMA, 2019). The proper treatment of sewage sludge by composting it is called composted sewage sludge (CSS). If CSS meets the criteria established by the Ministry of Agriculture, Livestock and Supply of Brazil in a Normative Instruction No. 61 of July 8, 2020, then it can be registered as a Class B organic fertilizer (Brasil, 2020). Recently, there has been evidence of the agronomic viability of using CSS as an organic fertilizer, especially for supplying P, N, and micronutrients (JAKUBUS; BAKINOWSKA, 2018; PRATES et al., 2020, 2022; ELSALAM et al., 2021; LANNO et al., 2021; SILVA et al., 2022 a,b).

Based on the above, we hypothesized that residual effect of CSS applications would provide micronutrients to the soil in sufficient quantities to maintain nutritional balance of the plants and guarantee the productivity of winter bean as well as reducing the application of mineral fertilizers. Thus, our study evaluated the available levels of micronutrients in the soil and their effects on nutrition, extraction, and export associated with productivity of common bean grown in the soil of Cerrado region.

2. Results

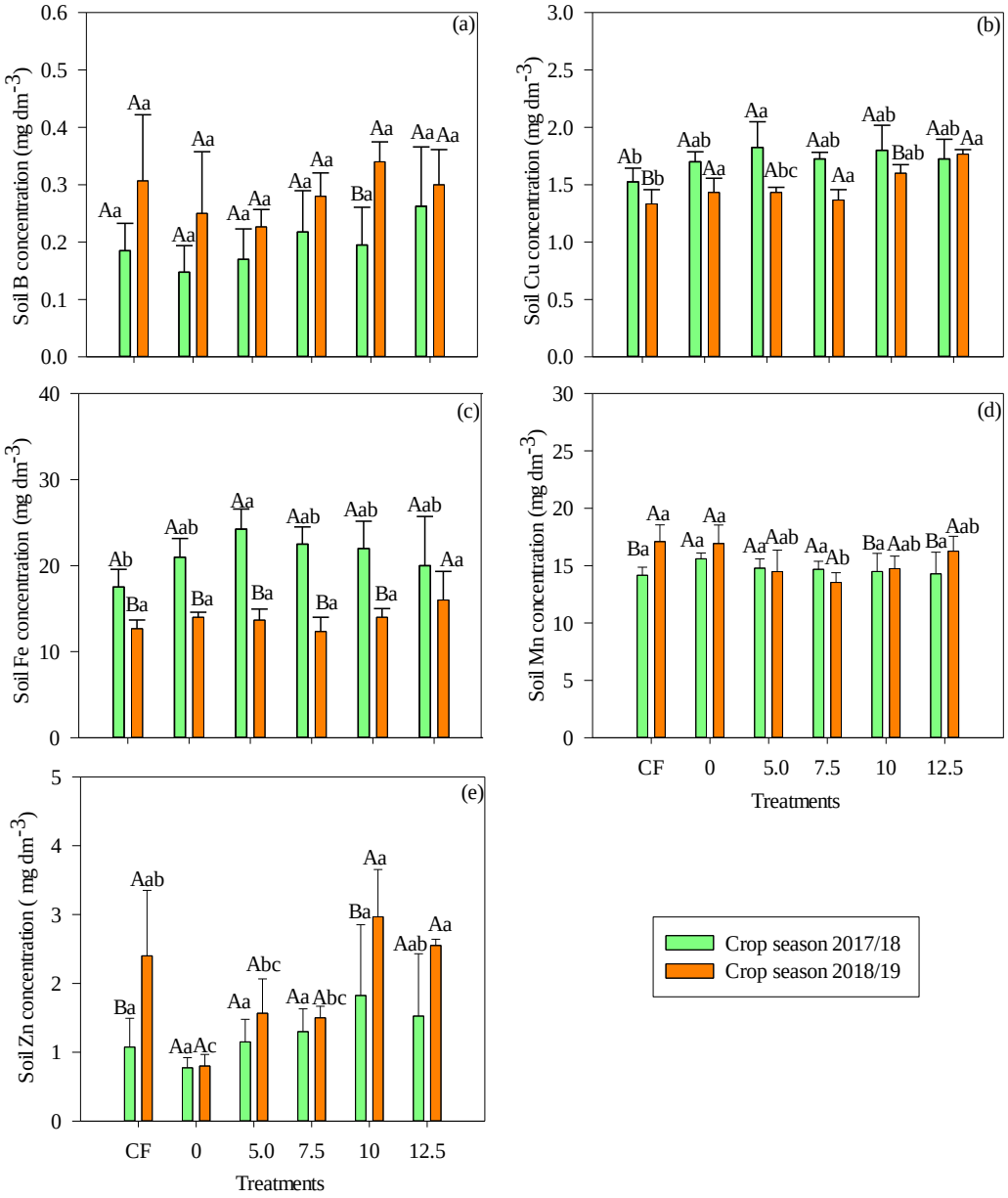
2.1. Soil micronutrients

The cationic micronutrients like Cu, Fe, Mn, and Zn remained higher in available concentrations in the soil when compared to the concentration of anionic micronutrient like B (Figure 1). The concentrations of Cu and Zn in soil were higher at a depth of 0–0.20 m. Such results were also observed in the two agricultural years evaluated (Figures 1b and 1e). It was also noted that the availability of B, Mn, and Zn increased in the soil in the second agricultural year.

In case of the depth of 0.20–0.40 m, only concentrations of Mn and Zn varied between the applied treatments while concentrations of Cu, Fe, Mn, and Zn varied in function of agricultural years (Figure 2). Residual rates of CSS above 7.5, 10.0, and 12.5 Mg ha^{-1} resulted in higher concentrations of B, Cu, Fe, and Zn. In addition, the highest available soil Mn concentration was verified in control treatments and with conventional mineral fertilization. The same results were observed at two depths (0.0–0.20 and 0.20–0.40 m). However, the highest Mn concentration was observed in the control treatments in the 0.20–0.40 m layer. Still at the depth of 0.20–0.40 m, it was found that the levels of B and Zn in the soil were similar in both agricultural years. However, it was possible to notice greater availability of Cu, Fe, and Mn in the soil depth of 0.20–0.40 m for 2017/18 agricultural year.

The limits established by Boaretto et al. (2022) for the interpretation of concentrations of micronutrients in soil for annual crops are described in Figure 1. Thus, it was noted that soil B concentration was increased in the second agricultural year, changing from a low concentration (< 0.2 mg dm^{-3}) for medium (0.2–0.60 mg dm^{-3}) and Cu, Fe, and Mn concentrations showed high levels (Cu: > 0.8; Fe: > 12, and Mn: > 5.0 mg dm^{-3}) in two agricultural years. Except control and the treatment that received conventional mineral fertilization in 2017/18, it was observed that the available soil Zn concentration was considered high (< 1.2 mg dm^{-3}) in both agricultural years. These results proved that the residual CSS rates increased soil fertility by increasing concentrations of B, Cu, Fe, Mn, and Zn.

Considering the residual effect of CSS rates at a depth of 0–0.20 m, the available B and Zn concentrations were linearly increased in the first and second agricultural year, respectively (Figure 3). At a depth of 0.20–0.40 m, there was a linear increase in soil Zn availability in response to the residual effect of applied CSS rates (Figure 4). Although, soil Zn concentrations were increased in both years of study, its response was more expressive in the first agricultural year as compared to the second year.



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Interpretation limits (mg dm-3)(1)					
	B	**Cu**	**Fe**	**Mn**	**Zn**
Low	< 0.20	< 0.30	< 5.00	< 1.50	< 0.60
Medium	0.20–0.60	0.30–0.80	5.00–12.00	1.50–5.00	0.60–1.20
High	> 0.60	> 0.80	> 12.00	> 5.00	> 1.20

138

139 **Figure 1.** Effect of treatments (CF = conventional mineral fertilization and residual application of
140 sewage sludge compost rates in Mg ha^{-1}, wet basis) on available soil micronutrient concentrations
141 (depth 0–0.20 m) after cowpea cultivation common in two agricultural years. Significant differences
142 ($p \leq 0.05$; Tukey test) between treatments (lowercase letters) or agricultural year (uppercase letters)
143 are indicated by different letters. Error bars indicate standard deviation of means (n = 4). (1) Inter-
144 pretation limits of micronutrient availability in tropical and subtropical soils for annual crops
145 (Boaretto et al., 2022).

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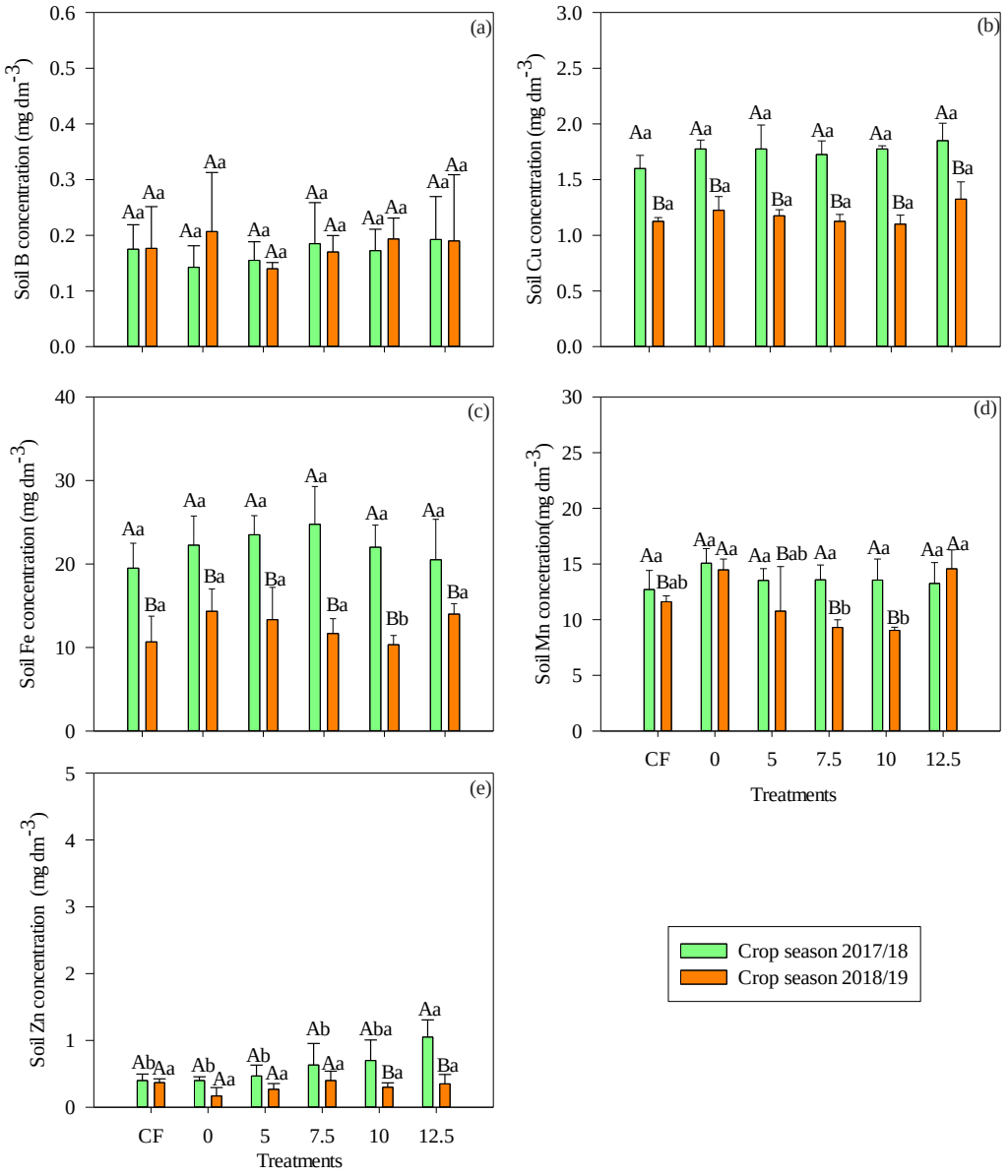
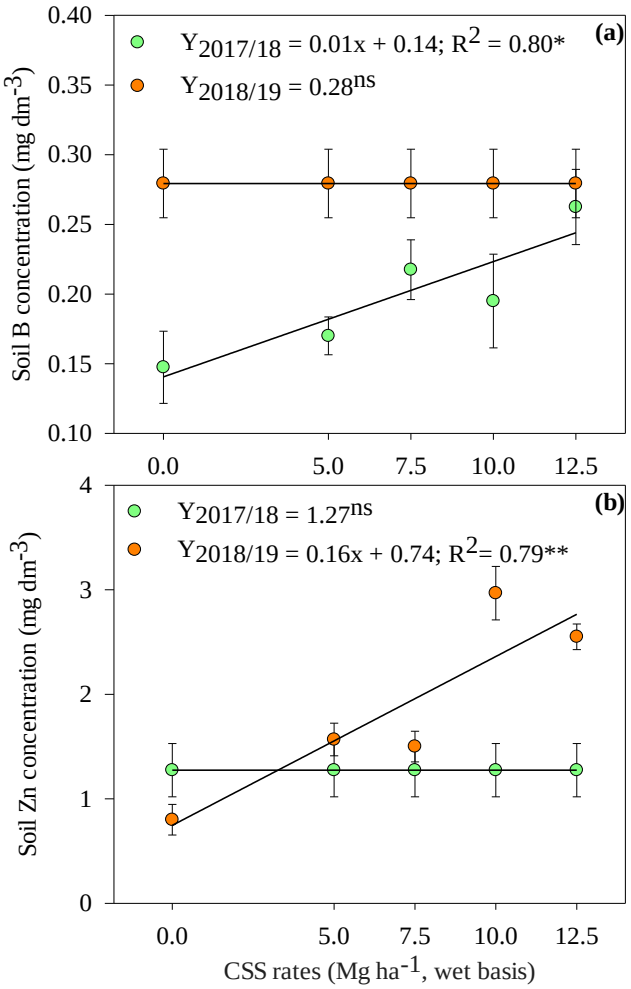
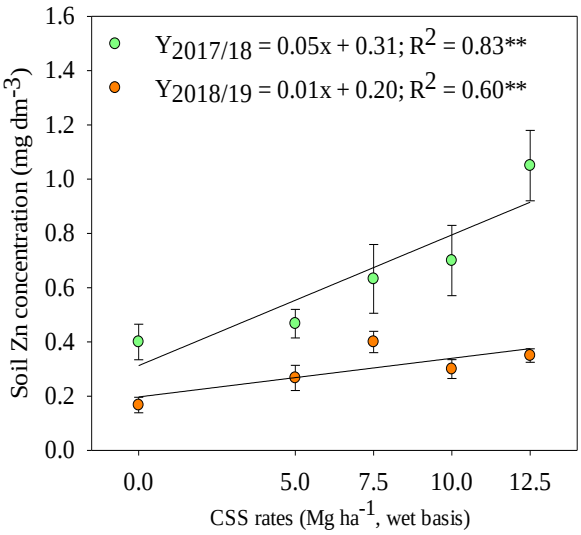


Figure 2. Effect of treatments (CF = conventional mineral fertilization and residual application of sewage sludge compost rates in Mg ha^{-1}, wet basis) on soil available micronutrient concentrations (depth 0.20–0.40 m) after cultivation common bean in two agricultural years. Significant differences ($p \leq 0.05$; Tukey test) between treatments (lowercase letters) or agricultural years (uppercase letters) are indicated by different letters. Error bars indicate standard deviation of means ($n = 4$).



155

156 **Figure 3.** Availability of B (a) and Zn (b) in the soil in the 0 to 0.2 m depth layer after common bean
157 cultivation in response to residual applications of composted sewage sludge (CSS) rates. **, * and ns
158 – Significant at 1 and 5% and not significant, respectively. Error bars indicate the standard deviation
159 of the mean (n = 4).



160

161 **Figure 4.** Soil Zn availability in the 0.2–0.4 m depth layer after common bean cultivation in response
162 to residual application of composted sewage sludge (CSS) rates. ** – Significant at 1%.

163

164 *2.2 Plant*

165 2.2.1. Leaf micronutrient concentrations

166 In the 2017/18 agricultural year, there was a difference between treatments only for
167 leaf Zn concentrations. The treatment with CF and highest rates of CSS were observed
168 with higher leaf Zn concentration. In addition, there was variation in leaf concentration of
169 all micronutrients under the studied treatments in the second year of bean cultivation
170 (2018/19) (Figure 5). In general, the residual rates of CSS provided leaf micronutrients con-
171 centrations similar to the treatment with CF. The control treatments without mineral and
172 organic fertilizer but with application of limestone and agricultural gypsum before the
173 installation of the experiment also provided similar results to CSS and CF.

174 All the treatments tested in the first year of cultivation, it was noted that leaf B con-
175 centration exceeded the proposed limit (26 mg kg^{-1} of B) for common bean crop (Figure 5).
176 However, no symptoms of visual toxicity were observed in the plants in field condition.
177 In the second year, it was noted that the plants with 10 t ha^{-1} of CSS were noted within the
178 appropriate range of leaf B levels. In addition, the plants had high leaf B concentration
179 with the other treatments with CF or CSS. The leaf concentrations of Fe, Cu, Mn, and Zn
180 remained within the range considered adequate for the common bean crop (Figure 5).

181 It was possible to notice a difference in micronutrient concentrations in bean leaves
182 in response to the two agricultural years (Figure 5). Thus, it was also verified that the
183 treatments with CF and residual effect of the first year of CSS were observed with higher
184 leaf B concentration of common bean. The leaf Cu concentration was also higher in the
185 first year of cultivation for the treatments with control, CF, and with residual effect of 5 t
186 ha^{-1} of CSS. There was no variation in Cu concentration for the other treatments as a func-
187 tion of the year of study. Leaf Fe concentrations were higher only in the first year of com-
188 mon bean cultivation under the CF treatment. The leaf Mn concentration of common bean
189 was higher only in the treatment with residual CSS of 7.5 t ha^{-1} in the first and second year
190 of plant cultivation. The leaf Zn concentration was higher in the plants cultivated in the
191 first year of the study within control and 7.5 t ha^{-1} of CSS.

192 Evaluating the residual effect of CSS rates on the leaf micronutrients concentrations,
193 a linear increase in Zn concentrations was observed with application of CSS rates in the
194 first agricultural year (2017/18) (Figure 6a). In addition, leaf B and Cu concentrations were
195 not influenced by the residual effect of CSS rates in the first year (Figures 6b and 6c). In
196 the second agricultural year (2018/19), the residual effect of CSS rates linearly increased
197 leaf B concentration (Figure 6a). Leaf Cu concentration was set to a quadratic adjustment,
198 being observed that the rate of 5.9 t ha^{-1} of CSS (wet basis) provided the highest Cu con-
199 centration (17.70 mg kg^{-1}) in common bean leaves (Figure 6b).

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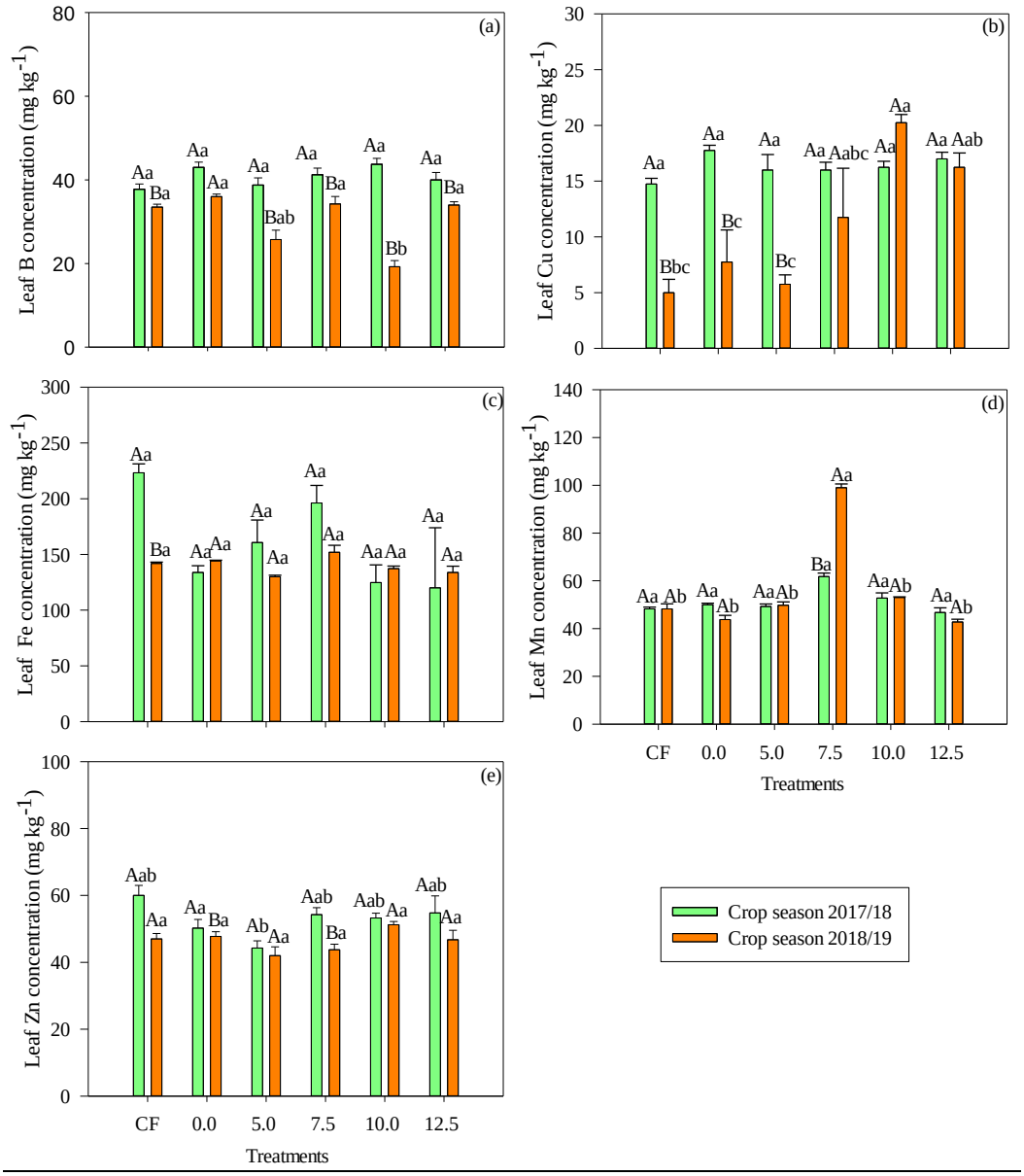

OCR (mg kg-1)(1)				
B	**Cu**	**Fe**	**Mn**	**Zn**
15–26	4–20	40–140	15–100	18–50

Figure 5. Micronutrient concentrations in common bean leaves in response to the effect of treatments (CF = conventional mineral fertilization and residual application of composted sewage sludge rates in Mg ha^{-1}, wet basis) and of the evaluated agricultural years. Significant differences ($p \leq 0.05$; Tukey test) between treatments (lowercase letters) or agricultural year (uppercase letters) are indicated by different letters. Error bars indicate the standard deviation of the mean (n = 4). OCR = optimal concentration range according to (1)Ambrosano et al. (1997b).

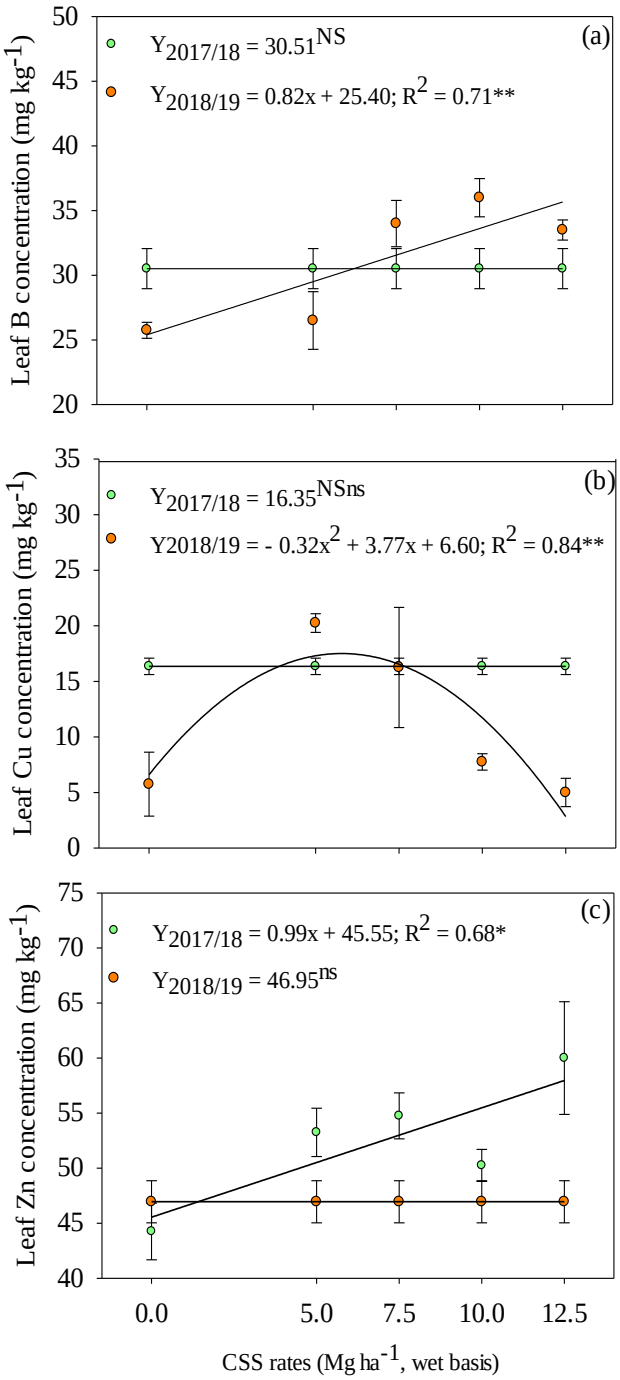

Figure 6. Concentrations of B (a), Cu (b), and Zn (c) in common bean leaf in response to the residual of the application of rates composed of sewage sludge (CSS). **, * and ns – Significant at 1 and 5% and not significant, respectively. Error bars indicate the standard deviation of mean (n = 4).

2.2.2. Extraction and export of micronutrients

Micronutrient extraction by winter bean was significantly influenced by the treatments (Figure 7). The treatments with conventional mineral fertilization showed the highest B extractions in both agricultural years. The concentration of B extraction was ranging from 26.64 g ha^{-1} in 2017/18 agricultural year and 50.02 g ha^{-1} of B in the year agricultural 2018/19 (Figure 7a). It was noted that CSS applications increased shoot B content of common beans plants as compared to control treatment in both agricultural years, with average B contents ranging from 14.17 to 44.28 g ha^{-1}. Hence, the average concentration of extracted B by plants was increased by 5.25 g ha^{-1} in the first year and 20.89 g ha^{-1} in the

second year, which probably come from the correction of acidity through limestone application in the initial phase of the experiment, contributing to higher physiological efficiency of the plant in the extraction from one year to the next.

The extraction of both Fe and Mn was higher in the treatments with conventional mineral fertilization in both agricultural years (Figures 7c and 7d). The Fe extraction was increased by 370.92 and 632.30 g ha^{-1} while Mn extraction was increased by 130.50 and 161.32 g ha^{-1} in the first and second year (Figures 7c and 7d).

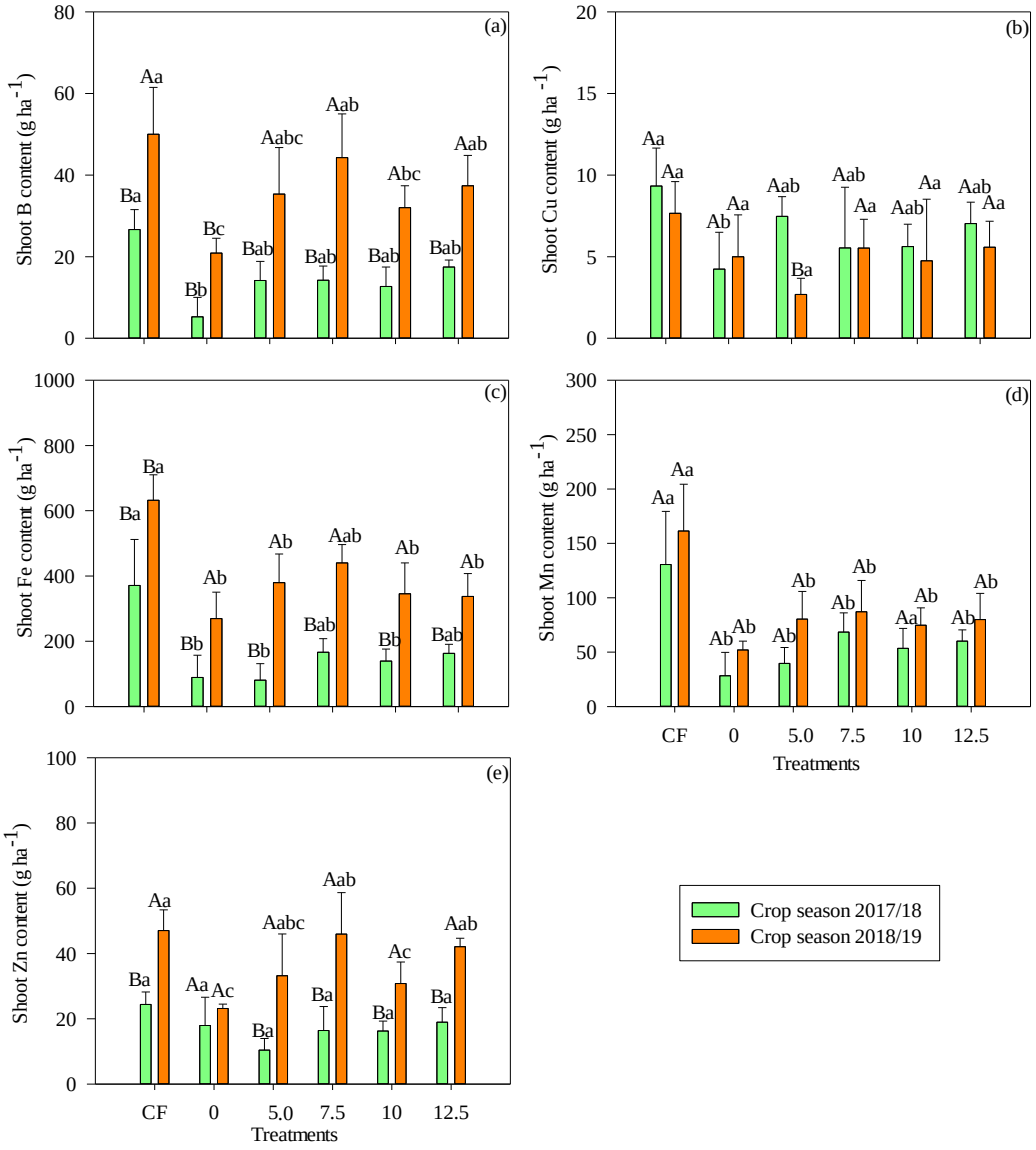

Figure 7. Micronutrient extraction by the common bean crop in response to the effect of treatments (CF = conventional mineral fertilization and residual application of composted sewage sludge rates in Mg ha^{-1}, wet basis) and of the evaluated agricultural years. Means followed by the same letter (lowercase for treatments and uppercase for agricultural years) do not differ from each other by Tukey's test at 5% probability. Error bars indicate the standard deviation of the mean (n = 4).

There were different responses of the extraction of Cu and Zn in both years of bean cultivation (Figures 7b and 7e). The highest Cu extraction was observed in the first year with organic fertilizer application of 5 Mg ha^{-1}, wet basis. The highest amount of Zn was extracted with all treatments except control treatment in the second year of cultivation. However, in both studied years, the treatments with conventional mineral fertilization were observed with the highest extractions of 9.33 g ha^{-1} of Cu in the first year, and 47.02 g ha^{-1} of Zn in the second year. The lowest extraction was observed in control treatments

in the first year of cultivation, with average concentrations of 4.24 g ha^{-1} of Cu (Figure 7b) and 23.17 g ha^{-1} of Zn (Figure 7e). The highest values of Zn extraction was noted with mineral fertilization, which was statistically similar with residual CSS doses in 2018/19 agriculture year (Figure 7e).

The order of micronutrients extracted by the shoot of bean was: Fe > Mn > Zn > B > Cu. The adequate availability of the basic nutritional needs regulate the ability of bean plant to extract nutrients. The extractions of B, Fe, and Mn were increased linearly in the first agricultural year as a function of the application of CSS rates (Figure 8), demonstrating that application of organic fertilizer increased absorption of these nutrients by plants. The CSS rates did not influence the extraction of B, Fe, and Mn in the second year, with average concentrations of 33.99, 354.38, and 74.82 g ha^{-1}, respectively.

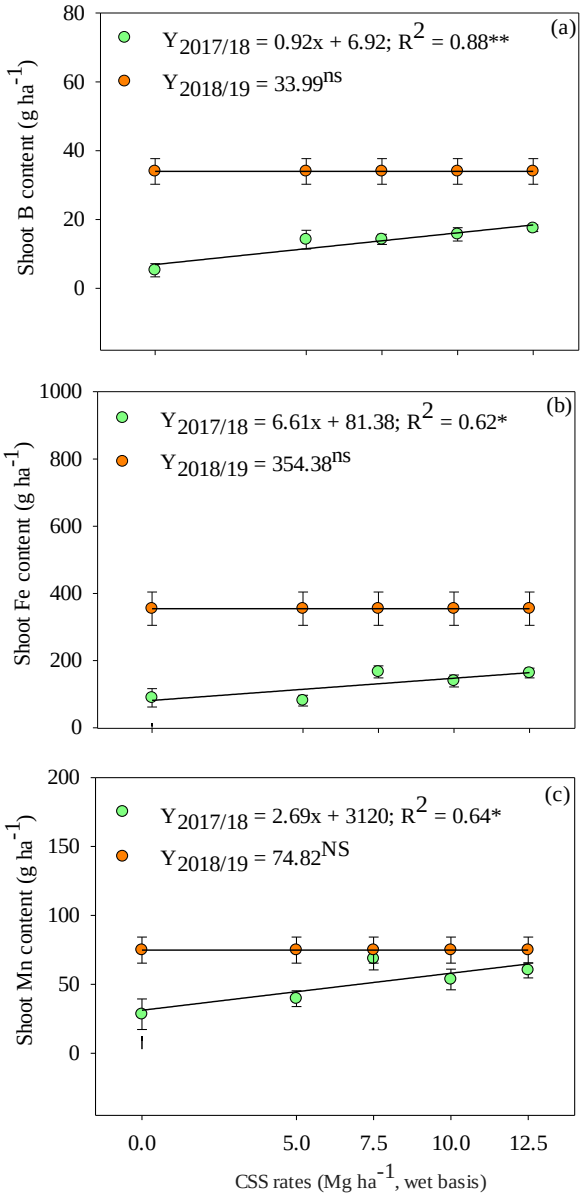

Figure 8. Extraction of B (a), Fe (b), and Mn (c) by common bean crop in response to residual application of sewage sludge compost (CSS) doses. **, * and ns – Significant at 1 and 5% and not significant, respectively. Error bars indicate the standard deviation of the mean (n = 4).

The export of micronutrients carried out by bean plant (Figure 9) indicated that the relationship between treatments and export was significant for B and Cu. The highest exported content of B was recorded in the first year and Cu in the second year of common bean cultivation. There was no significant differences among the control, CSS rates and conventional mineral fertilization for the means of B content. The means of Cu in the first year were not different while there was variation for the export of Cu in the second year, where the highest average (83.86 g ha^{-1}) was observed with application of highest rate of CSS.

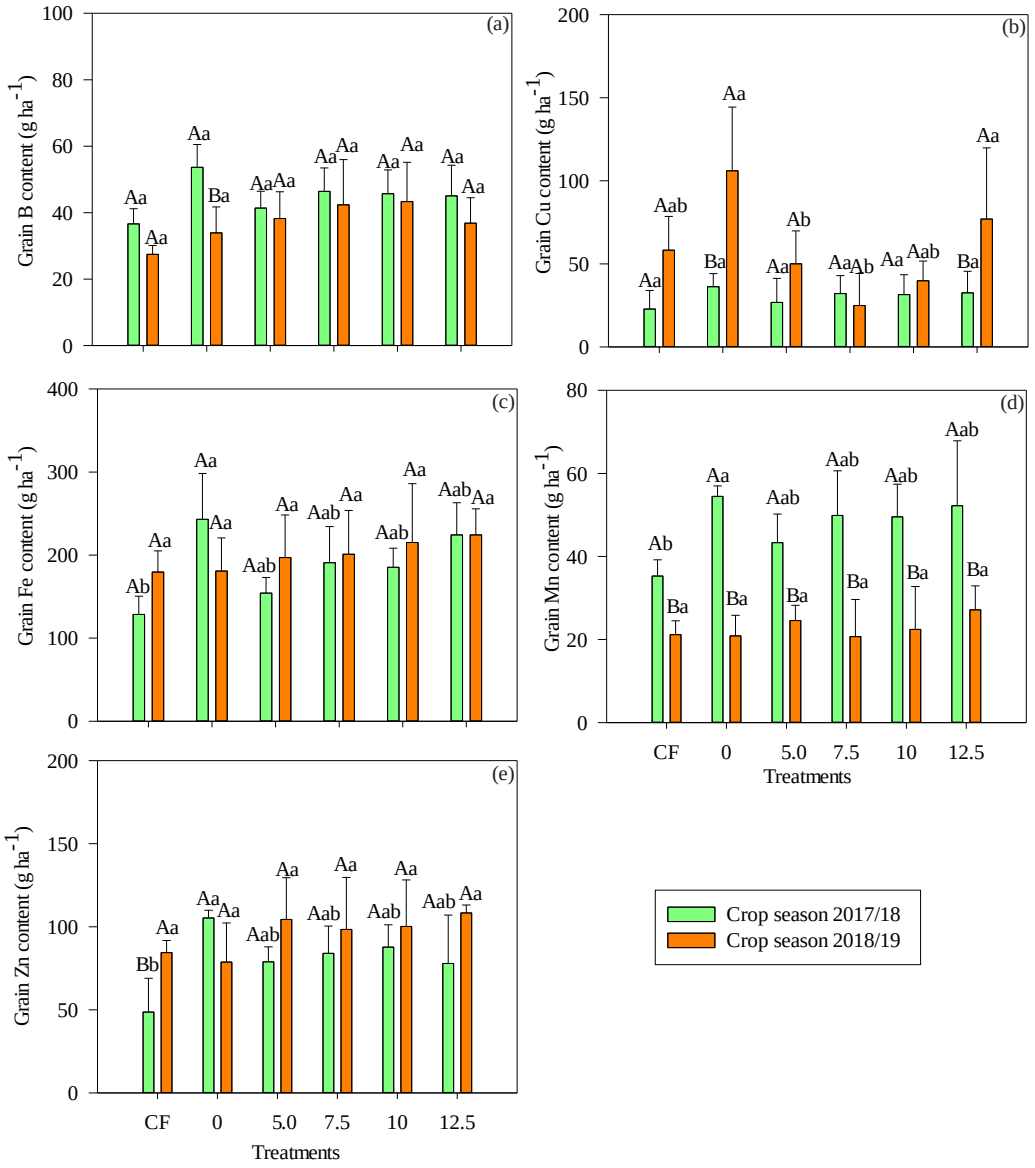

Figure 9. Micronutrients exported by winter common bean grains in response to the effect of treatments (CF = conventional mineral fertilization and residual application of composted sewage sludge rates in Mg ha^{-1}, wet basis) and of the evaluated agricultural years. Means followed by the same letter (lowercase for treatments and uppercase for agricultural years) do not differ from each other by Tukey's test at 5% probability. Error bars indicate standard deviation of the mean (n = 4).

The exported quantities of Fe didn't change in both of the agricultural. The export of B and Zn were significant with the treatments. The export of B showed the highest values in the first year and Zn in the second year. The highest values of Cu were obtained in the

second year of cultivation except the dose of 7.5 t ha^{-1} of CSS, which did not differ from the other treatments. The exports of Mn were different in all treatments while the highest Mn export was noted in the first agricultural year.

The order of micronutrients exported in the winter bean crop had a different behavior in both years, with a decreasing order in 2017/18; Fe > Zn > Mn > B > Cu and in 2018/19; Fe > Zn > Cu > B > Mn. However, most of the micronutrients were exported more by plants treated with CSS application as compared to control and conventional mineral fertilization treatments in the second year.

Comparing the amounts of micronutrients in the grains and shoots, regardless of the year studied, the shoots accumulated more Fe and Mn while grains were characterized by greater accumulations of Fe and Zn. It was noted that common beans exported more Cu in the second agricultural year that ranked this nutrient from the least exported to the third most exported nutrient.

The amount of the export of Fe, Mn, and Zn was linearly increased with increasing CSS rates (Figure 10). However, the increase occurred only in the first year of cultivation of the crop. In the second year, there was no difference in relation to the applied CSS rates and the amount of micronutrients exported. Thus, these results showed the efficiency of CSS in supplying micronutrients to plants, contributing to increase crop productivity in low-consumption agricultural systems.

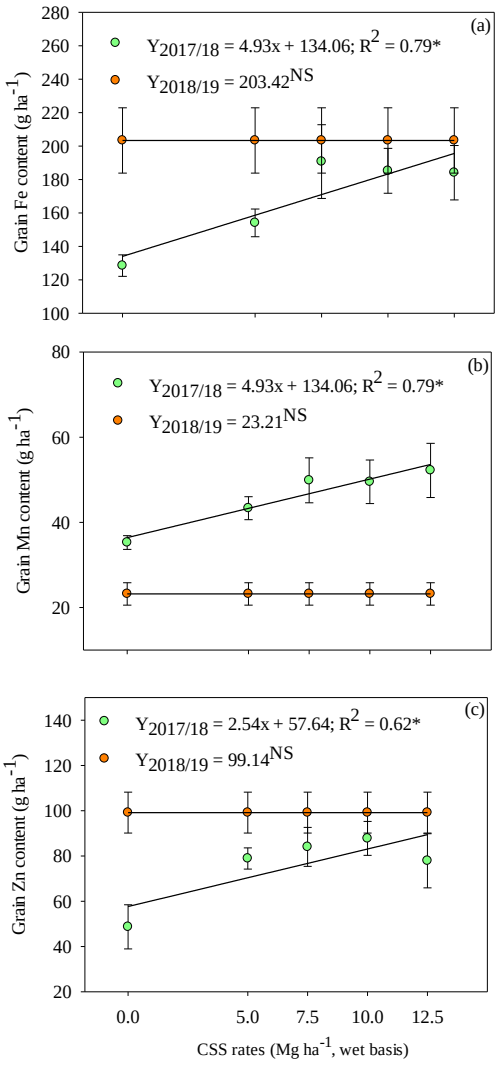

Figure 10. Export of Fe (a), Mn (b), and Zn (c) in common bean grains in response to the residual application of sewage sludge compost (CLE) doses. * and ^{NS} – Significant at 5% and not significant, respectively. Error bars indicate the standard deviation of the mean (n = 4).

2.2.3. Grain productivity

The grain productivity of winter common bean was not influenced by treatments in both agricultural years (Figure 11). The productivity was statistically not different with the treatments of CSS and mineral fertilization.

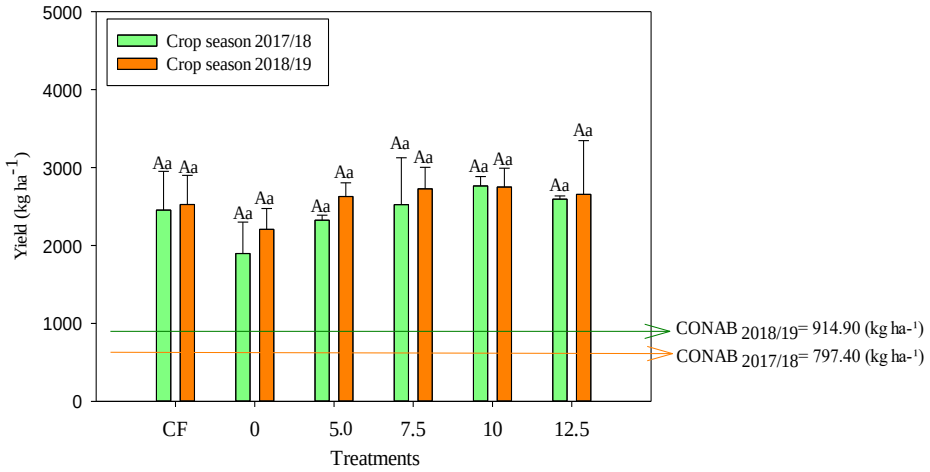

Figure 11. Common bean productivity in response to the effect of applied treatments and years of cultivation of the common bean crop in response to the effect of treatments (CF = conventional mineral fertilization and residual application of rates of composted sewage sludge in Mg ha^{-1}, wet basis) and the evaluated agricultural years. Means followed by the same letter (lowercase for treatments and uppercase for agricultural years) do not differ from each other by Tukey's test at 5% probability. Error bars indicate the standard deviation of the mean (n = 4). The orange and green arrows indicate the national productivity of the second-crop bean crop grown in the 2017/18 (CONAB, 2019) and 2018/19 (CONAB, 2019) agricultural years, respectively.

The results of this research showed that residual effect of the application of CSS rates can be considered a viable alternative in cultivation of winter bean. In the first agricultural year, grain yield was linearly increased in response to the residual effect of CSS application (Figure 12). In the second year of bean cultivation, there was no influence of the residual rates of CSS on plant productivity, with an average value of 2594 kg ha^{-1} being observed.

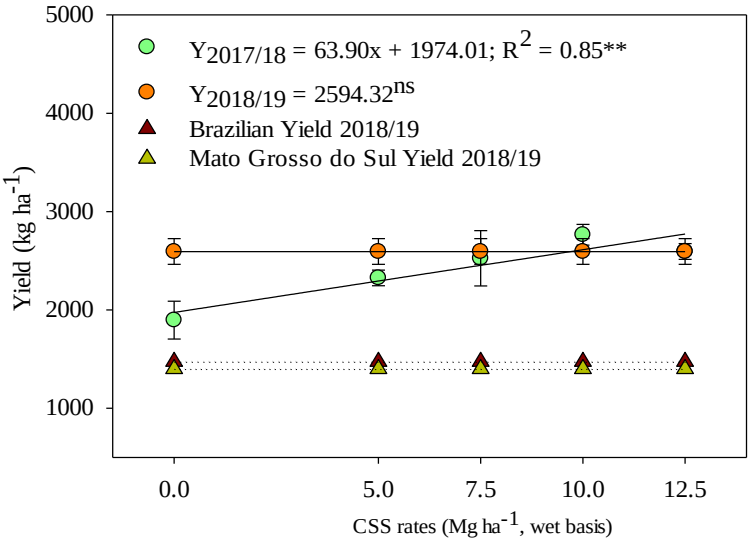

Figure 12. Yield of common bean in response to residual application of composted sewage sludge (CSS) rates. ** and ns – Significant at 1% and not significant, respectively. Productivity averages of color bean second crop (CONAB, 2019).

3. Discussion

The soil cationic micronutrients such as Cu, Fe, Mn, and Zn remained in higher concentrations when compared to the anionic B. This behavior normally observed in the soils with intense weathering, after residual accumulation of CSS. The increase in soil organic matter influences the increase in B levels, which is very dynamic in the profile and subject to leaching in the soil (YAMADA, 2016) as indicated in the soil of present study (Figure 1).

The concentrations of B and Zn were increased at the soil depth of 0.0–0.20 m while all the studied micronutrients were increased at the depth of 0.20–0.40 m, when compared with the initial contents obtained in the soil (Table S1). This fact demonstrated the ability of organic fertilizer to supply these micronutrients to the soil except soil Cu concentration, which was reduced in the second year. Among the studied micronutrients, soil Zn concentration was increased in both of the evaluated depths, as it also occurred in the study by Silva et al. (2022), who evaluated the changes in chemical properties of the soil after CSS application in sugarcane cultivation in Cerrado soil. Several other studies being reported that residual CSS improve soil fertility in term of supply of micronutrients like B, Cu, Fe, Mn, and Zn in legumes cultivation (PRATES et al., 2020; ELSALAM et al., 2021).

Leaf B concentration is an important factor that was remained above the appropriate levels unlike the other micronutrients that remained within adequate ranges in the leaf however, no symptoms of toxicity were observed in beans (Figure 5). As in the study by Prates et al. (2022), who reported that leaf B concentration was increased with residual rates of CSS but still no toxicity was seen in the plant with B concentration above the recommended values in the literature (AMBROSANO et al., 1997b). The improvement in biochemical and physiological processes might help the plants to improve the tolerance mechanisms in response to the excess of these micronutrients in soil (MENDOZA-CÓZATIL et al., 2011). The present study indicated that there were leaf micronutrients concentrations were increased with CSS. However, there was no increase in the leaf micronutrient concentrations in relation to the application of mineral fertilizer and the control treatment. Bertolazi et al. (2017) in their study with the initial cultivation of eucalyptus and Prates et al. (2020) with the soybean crop under the application of different CSS rates. In the case, soil Zn concentartion had a significant increase (high concentrations) with the application of CSS, which demonstrated that the absorption of micronutrients is related to soil-plant interactions and that govern the competitive/inhibitory processes (PRATES et al., 2022).

Synthetic and mineral fertilizers are the most common sources of micronutrients. A wide range of these fertilizers are commercially available, so it is very easy to find a suitable product to meet the needs of plants. However, these fertilizers are very expensive and imported. In addition, the principles of sustainable agriculture and environmental protection, farmers are paying more attention to the possibility of using organic fertilizers, which are in line with consumer expectations as well as reducing exploitation of mineral sources and lower production cost (JAKUBUS AND GRACZYK, 2020).

Organic fertilizers guarantee a gradual release of nutrients, maintaining their positive balance for a long period of time. Jakubus and Bakinowska (2018) indicated that the systematic application of organic fertilizers in the long term could not only results in an increase in soil organic matter, but also increasing the available amounts of micronutrients to plants as presented in the current experiment (Figure 6 and 7). Thomas et al. (2019) listed the positive aspects related to the use of recycled organic waste as agricultural fertilizers. In this sense, an interesting alternative to commonly used mineral fertilizers can be provided by compost prepared from sewage sludge as proved in the present experiment.

The increase in concentrations of micronutrients in shoot of common beans evidenced the supply of B by the compost applications (Figure 5), initially, the soil had average levels in the experimental area (supplymentary Table 1). It is known that the accumulation of micronutrients by plants is strictly related to their available contents in soil and

379 the applied correctives (JAKUBUS; GRACZYK, 2020). Furthermore, B plays a key role in
380 plant metabolism, including cell wall formation and stability, which maintains membrane
381 integrity, sugar and energy activation, pollination, pod fixation, and increased grain yield
382 per plant, resulting in higher productivity (LANDI et al, 2019; PEREIRA et al., 2021).
383 In general, the values obtained in the extraction of micronutrients in the present
384 study were lower than those found in the previous study (Figure 7). Perez et al. (2013)
385 evaluated different doses and times of nitrogen fertilization via mineral fertilizer (60 kg
386 ha^{-1} pre-sowing; 60 kg ha^{-1} at V4 stage; 60 kg ha^{-1} at pre-sowing + 60 kg ha^{-1} in coverage)
387 in bean crop in a no-tillage system and observed that mineral fertilizer increased micro-
388 nutrient exportation to the plants. In addition, the more macronutrients application fulfill
389 greater demand of plants for micronutrients, especially the cultivars that can express high
390 productive potential (FERNANDES et al., 2013; FAGERIA et al., 2014).
391 The compounds prepared from sewage sludge are characterized by higher Fe and
392 lower Mn concentrations (JAKUBUS AND GRACZYK, 2020). These results are similar to
393 those observed by Prates et al. (2022). These authors suggest that application of CSS pro-
394 motes an adequate concentration of micronutrients, avoiding deficiencies while reducing
395 toxicity problems in Cerrado soil (Figure 8 and 9).
396 The results obtained in the first agricultural year corroborated the work of Fageria et
397 al. (2007) and Fernandes et al. (2013), who evaluated the export of micronutrients in com-
398 mon bean with doses of mineral fertilizers. It was noted that crop exported more Cu in
399 the second agricultural year, ranking the least exportated nutrient by bean plant to be the
400 third most exported (Figure 9). Phageriaet al. (2007) evaluated three doses of limestone (0,
401 12, and 24 Mg ha^{-1}) and seven doses of B (0, 2, 4, 8, 12, 16, and 24 kg ha^{-1}) in common bean
402 reported the lowest Cu exported values in both shoots and grains.
403 Silva et al. (2021) evaluated the effect of sewage sludge application on shoot biomass,
404 productivity, and soil and plant nutrient concentration in three successive maize crops.
405 These authors obtained similar results to the present study regarding the availability of
406 micronutrients. Rodrigues et al. (2017) also highlighted that the availability of micronutri-
407 ents increases use efficiency of biosolids in agriculture. Furthermore, Prates et al. (2020)
408 evaluating the effect of applying CSS in low fertility soils in the Cerrado region, concluded
409 that CSS could be an excellent alternative to mineral fertilization as a source of micronu-
410 trients for soybean cultivation.
411 Common bean productivity exceeded the Brazilian average in both studied years,
412 with an average of 1,268 kg ha^{-1} in 2017/18 crop, and 1,474 kg ha^{-1} in 2018/19 crop (Figure
413 11 and 12). It was observed that productivity of the current study was 101 and 82% higher
414 than the average Brazilian productivity in the first and second common bean harvest (Fig-
415 ure 11). Using this general average of the treatments with CSS application, it was also
416 noted that present productivity surpassed the other studies as well, such as those by San-
417 drini et al. (2019) whos common bean productivity was 2,329 kg ha^{-1} as a function of ni-
418 trogen application rates. In addition, Prates et al. (2020) reported a linear increase in soy-
419 bean productivity with application of CSS rates in the first year of soybean cultivation. As
420 verified in the present study for winter bean, some previous studies have already reported
421 that CSS is capable of being an alternative source of micronutrients and increasing produc-
422 tivity of several crops (e.g., sugarcane, soybean and maize) while completely eliminating
423 the use of mineral fertilizers in some situations (PRATES et al., 2020; PRATES et al., 2022;
424 SILVA et al., 2022). However, it is essential to monitor micronutrient levels in the soil-
425 plant system, always aiming to maintain the levels of these nutrients above the critical
426 levels established for each type of soil and agricultural region. Still, it is important to assess
427 the availability of macronutrients in the soil, favoring the nutritional balance for all nutri-
428 ents and maintaining crop productivity.
429
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431

4. Materials and Methods

4.1. Site description

The current study was carried out under field conditions in agricultural years of 2017/18 and 2018/19 at Selvíria-MS, Brazil (Figure 13). The region has an annual average rainfall of 1,370 mm, temperature of 24.5 °C and relative humidity of 75%, thus, it has charactrized as rainy summers and dry winters by the Aw climate according to Köppen classification, (LOMBARDI NETO AND DRUGOWICH, 1994). The monthly data regarding maximum and minimum temperatures, relative humidity and rainfall were collected throughout the experimental period (Figure 14).

The soil of experimental area was classified as a Rhodic Haplodox (Soil Survey Staff, 2014), presenting physical and chemical attributes as described in Supplementary Table 1.

Each experimental unit consisted of seven rows of bean crops (spaced 0.45 m apart) of 10 meters in length, totaling 31.5 m² per plot and 1,260 m² of total experimental area. The useful area of the plot for the evaluations consisted of the three central lines, 2.5 m from each end being eliminated as a border, totaling approximately 7.0 m².

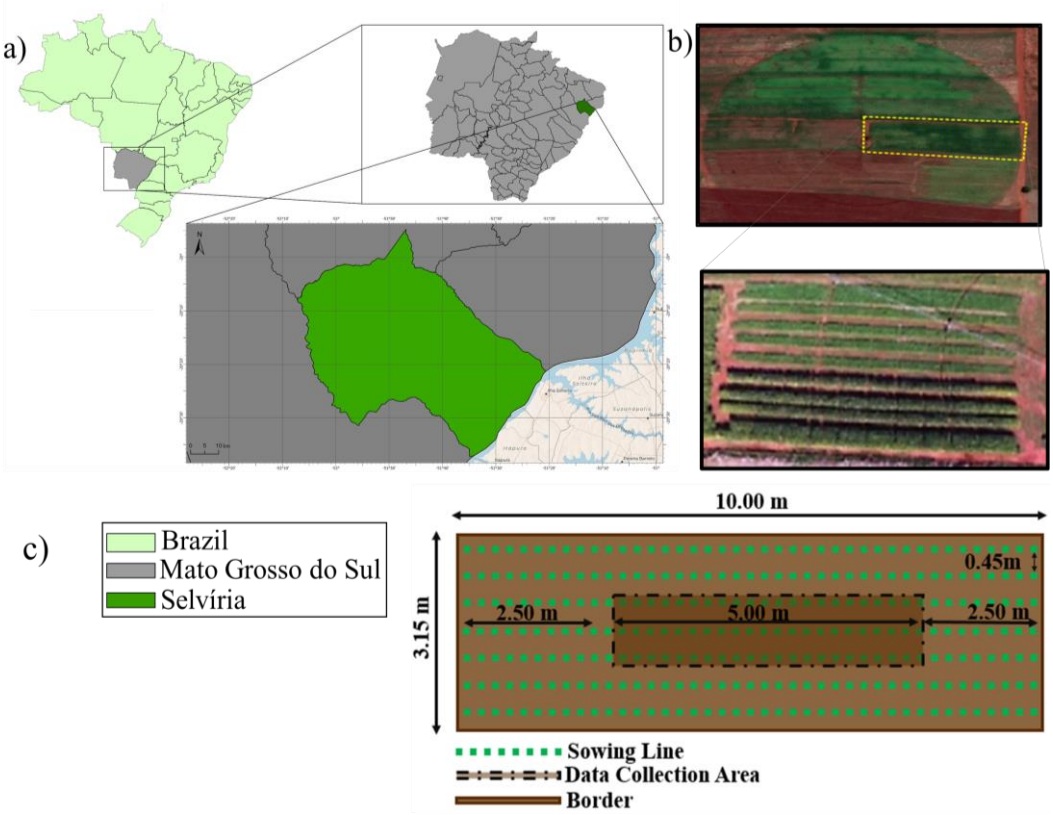

Figure 13. Experimental area located in the municipality of Selvíria at: 20°20'35" S, 51° 24'04" W; 358 m altitude; Mato Grosso do Sul State – MS, Brazil (a); aerial view of the entire experimental area and plots (b); schematic representation of a single plot with the individuation of the "useful area" for collecting soil and plant data (c).

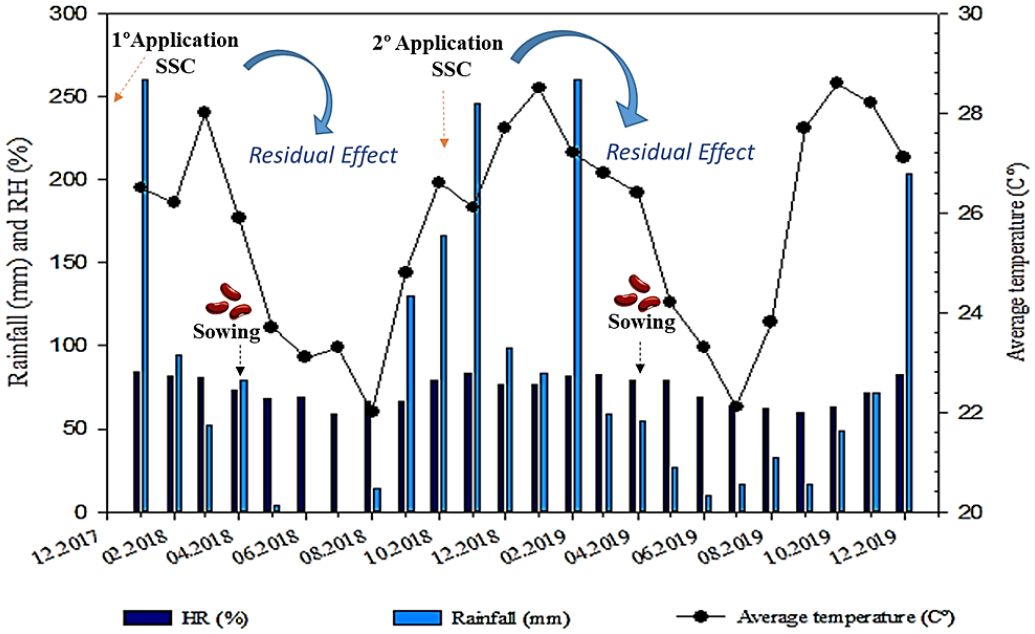

Figure 14. Rainfall, relative humidity (HR) and average temperatures during common bean cultivation in the 2017/18 and 2018/19 growing seasons. Data were collected from the meteorological station of the Faculty of Engineering of Sao Paulo State University, Ilha Solteira, Brazil.

4.2. Experimental design and treatments

A randomized block design with split plots was adopted with six main and two secondary treatments in four replications. The six main treatments were consisted of four rates of composted sewage sludge – CSS (5.0, 7.5, 10.0, and 12.5 Mg ha^{-1}, wet basis), a control treatment (without application of CSS or mineral fertilizers) and a treatment with conventional mineral fertilizer. The two agricultural years (2017/18 and 2018/19) of common bean growing were used as a secondary treatment. The beans cultivation, treatments and conduct of the experiment were kept the same for both years, aiming to compare the response to residual effect of CSS applications.

4.3. Obtaining and characterizing sewage sludge compost

The CSS was obtained from the composting of sewage sludge generated at the wastewater treatment plant in the municipality of Jundiaí, SP, Brazil. The process consists of turning over and drying the material at the same time using a forced aeration system for three consecutive months. The chemical and microbiological characterization of CSS was carried out (Supplementary Table 2), as recommended by Conama Resolution No. 498 (CONAMA, 2020).

4.4. Installation and development of the study

The initial preparation of the area was carried out by scarification in September 2017. Based on the results of the soil fertility assessment, the area was applied with 2.2 Mg ha^{-1} of limestone, aiming to raise base saturation to 70%, and then 1.8 Mg ha^{-1} of agriculture gypsum was applied on a surface without incorporation (RAIJ et al., 1997).

The common bean (*Phaseolus vulgaris* L.), cv. BRS Estilo was used as a test plant. Beans plants were cultivated in the winter of 2017/18 and 2018/19 growing years. A desiccation of the vegetation cover was carried out with the application of herbicides Verdict R (37.41 g ha^{-1} active ingredient-ai) and Gramoxone (300 g ha^{-1} ai) were used. The application of CSS was carried out in rice cultivation with two consecutive applications prior to common bean in the experimental area. The CSS was manually distributed over the total area within each experimental plot.

Before sowing the crop, the seeds were treated using fungicides thiophanate methyl + pyraclostrobin (5 g + 45 g ai per 100 kg of seed) and insecticide fipronil (50 g ai per 100 kg of seed). Bean seeds primed with solution of cobalt and molybdenum-CoMo (39.21 mL) and *Rhizobium tropici* (80 g of inoculant for each 50 kg of seed) together with a 60 mL sucrose solution to stimulate nodulation.

Aiming to evaluate micronutrients in soil and in plant, it was decided to perform mineral fertilization with CSS to supply macronutrients. For the purpose, chemical analysis of the soil and recommendations in Bulletin-100 (RAIJ et al., 1997) were taken into account. A rate of 400 kg ha^{-1} of NPK fertilizer (04–20–20), corresponding to 16 kg ha^{-1} of N, 80 kg ha^{-1} of P_2O_5 and 80 kg ha^{-1} of K_2O was applied in both growing seasons of common beans. The plots referring to the treatment with conventional mineral fertilization were applied with 1.0 kg ha^{-1} of boron using boric acid (H_3BO_3) in the first year (2017/18) while soil B level was adequate in the agricultural year (2018/19).

The cover fertilization in common bean crop was carried out according to the recommendations of Ambrosano et al. (1997a). A total of 90 kg ha^{-1} of N (via urea) was applied to the plots that received conventional mineral fertilization. This dose (90 kg ha^{-1}) was split, applied 50.0 and 40.0 kg ha^{-1} of N at 15 and 30 days after sowing (DAS) respectively. In addition, treatments that received CSS was applied with 50 kg ha^{-1} of N (in the form of urea) at 15 DAS. The distribution of mineral fertilizers was carried out on the soil surface without incorporation approximately 0.08 m from the sowing lines in order to avoid contact between fertilizer and plants. After the applications, the area was irrigated by sprinkler (central pivot) with a 14 mm blade.

4.5. Soil and Plant Analysis

4.5.1. Available levels of micronutrients in the soil

Soil samples were collected from 0–0.20 and 0.20–0.40 m deep within the useful area of each plot at the end of the crop cycle. Five random subsamples were collected per plot to compose a composite sample. These samples were taken with the aid of a mechanical sampler. Afterwards, the samples were air-dried, crushed and passed through a sieve with a 2 mm mesh opening, packed in identified polyethylene bags, and stored in a dry chamber until the time of analysis.

The available concentrations of Cu, Fe, Mn and Zn in the soil were obtained using a DTPA chemical extractor at pH 7.3 (ABREU; ANDRADE, 2001), quantified by an inductively coupled plasma atomic emission spectrometry (ICP-AES) – Model Varian Vista-MPX, Varian, CA, USA, with respective wavelengths in nm: Cu = 324.7; Fe = 259.9; Mn = 257.6, and Zn = 206.2. The detection limit for the analyzed elements was established by reading blank sample (washed sand) seven times and calculated by the formula: LD = 3.s, where "s" is the standard deviation. The concentration of B in the soil was evaluated by means of extraction with barium chloride and heating with a microwave oven and quantified in a UV-VIS spectrophotometer (Model Varian Cary-50, Varian, Victoria, Australia) at 420 nm (ABREU et al., 2001).

4.5.2. Nutritional parameters of bean culture

The nutritional status was evaluated during R6 stage (flowering) of common bean, grown in the 2017/18 and 2018/19 cropping seasons. The third leaf with petiole was randomly collected from 10 plants per plot, as described by Ambrosano et al. (1997b). After being washed, the samples of each plot of the field were dried in an oven with forced air circulation at a temperature of 65°C for 72 h, and crushed in a Willey-type mill. This same material was submitted to wet digestion with nitric acid (HNO_3) and perchloric acid ($HClO_4$) (MALAVOLTA et al., 1997) for the determination of Cu, Fe, Mn and Zn concentrations and dry digestion (muffle incineration) for the determination of B.

4.5.3. Export of micronutrients and grain yield

To estimate grain yield, all plants in the useful area were harvested and manually threshed to avoid losses, weighed and, calculations were performed with extrapolation to kg ha^{-1} and corrected for 13% moisture content (SABUNDJIAN et al., 2016). Samples of these grains were taken for the analysis of micronutrient contents and exported amounts of these nutrients per area.

4.6. Statistical analysis

All data were initially tested for normality using Shapiro and Wilk (1965) test and Levene's homoscedasticity test ($p \leq 0.05$), which showed the normal distribution ($W \geq 0.90$) of the data. The results obtained were subjected to analysis of variance, applying the Tukey test ($p \leq 0.05$) to compare main treatments (CSS rates, control and conventional fertilization) and secondary treatments (growing years 2017/18 and 2018 /19). Also, polynomial regression were performed for the effects of CSS rates, using control plot as zero rate. Statistical analysis was performed using the R studio (2023) software.

5. Conclusions

Conventional mineral fertilization and residual application of CSS rates provided similar results for all evaluated variables (yield, extraction, and export of micronutrient content in leaf and soil) in the present study. By comparing the agricultural years, it was possible to notice variation within each production cycle. However, there is still no pattern between the analyzed variables and requiring long-term studies. The concentrations of micronutrients in the leaves and in soil were observed within the adequate limits. Therefore, it is possible to notice that the residual effect of CSS application was able to supply the nutrients in amounts necessary for a better development of winter bean cultivated in the Cerrado region. Thus, we concluded that CSS can be used as an organic fertilizer to supplement micronutrients, in particular can increase the levels of B and Zn in soil-plant system.

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Data Availability Statement: The information and database for this research are currently not on a platform or website. They can be provided by the corresponding author.

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