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Regenerative Farming with Organic Fertilizer and Biologics: A New Approach to Enhancing Soybean Yield and Soil Chemical Quality

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Abstract

Composted sewage sludge (CSS) applications and the use of plant growth-promoting bacteria (PGPB) are emerging as sustainable alternatives in tropical agriculture. However, no studies have validated the combined use of these practices. This study aimed to evaluate the residual effect of three CSS applications on soil fertility (0.0–0.2 m and 0.2–0.4 m layer), plant nutrition, morphological and yield components, and grain yield and quality of soybean, with and without co-inoculation of *Bradyrhizobium japonicum* combined with *Azospirillum brasilense*, under a no-tillage system (NTS) in the Cerrado region. The field experiment was conducted over a six-year period in Selvíria, Mato Grosso do Sul, Brazil. This research was evaluated during the 2022/23 first cropping season. The experimental design was a randomized complete block with four replicates, arranged in a 5 × 2 + 1 factorial scheme, consisting of five cumulative CSS rates (0.0, 15.0, 22.5, 30.0, and 37.5 Mg ha^{-1}, wet basis), with and without co-inoculation of *A. brasilense*, plus an additional control treatment with conventional mineral fertilization (CMF). The residual effect of the cumulative CSS rates improved soil fertility in both layers, similarly to CMF, regardless of co-inoculation. Co-inoculation with *Bradyrhizobium japonicum* and *Azospirillum brasilense* did not influence the soybean variables assessed. We found that the 24.7 Mg ha^{-1} CSS accumulated rate yielded the highest soybean yield (4990 kg ha^{-1}). CSS can be used as an organic fertilizer in soybean cultivation, helping to improve the efficiency of mineral fertilizers while ensuring environmentally friendly disposal of municipal sewage sludge.

Keywords: *Glycine max* L.; bioinputs; composting; circular economy; soil fertility; food security

1. Introduction

Soybean [*Glycine max* (L.) Merrill] currently accounts for approximately 50% of Brazil's grain production, with an estimated output of 166 million tons in the 2024/2025 growing season, an increase of 18 million tons (12.7%) compared to the previous season [1,2]. This crop plays a strategic role in food security and the global economy, serving as a raw material for producing essential food products, biofuels, and animal feed [2].

Brazil is the world's fourth-largest producer of food. With the expansion of agriculture and the challenges related to domestic production and the procurement of imported fertilizers, adopting sustainable agricultural management practices has emerged as a solution to mitigate such socioeconomic and environmental issues [3]. Sewage sludge (SS) is a viable option, as it is an urban residue originating from effluents of municipal wastewater treatment plants (WWTPs), rich in organic matter and nutrients [4,5]. Estimates indicate Brazil produces approximately 150,000 to 220,000 metric tons of SS dry matter annually [6]. Through the thermophilic composting process, SS is converted into composted sewage sludge (CSS) [7], which enables its use in agriculture and allows it to be registered as an organic fertilizer [8]. CSS can partially replace mineral fertilizers [9].

Promising results have been observed in increasing soil fertility and crop yields through the use of CSS as a compound organic fertilizer. Recent studies have shown that sequential CSS applications over multiple growing seasons, with or without supplemental mineral fertilization, promoted nutrient cycling, increased soil pH, base saturation, and cation exchange capacity (CEC), as well as raised macro- and micronutrient levels in both soil and plants [10–14].

In emerging technologies aimed at regenerative, increasingly sustainable, and low-carbon agriculture, research on bioinputs has gained prominence, particularly in the form of inoculation with plant growth-promoting bacteria (PGPB). Recent studies have highlighted the benefits of PGPB (co)inoculation for soybean nutrition and agronomic performance, the reduction/optimization of mineral fertilizer inputs, as well as improvements in grain quality and soil health [15–22].

Although the positive effects of PGPB and CSS are already well known, no studies have yet evaluated crop production under a no-tillage system (NTS) and the combined influence of these two technologies. Therefore, the results will help validate the feasibility of using CSS with PGPB, which will directly influence mineral fertilizer consumption and impact the Brazilian agribusiness sector. Based on this premise, we established the following hypotheses for this research: the residual effect of CSS fertilization combined with inoculation/co-inoculation (in the sowing furrow) with *Bradyrhizobium japonicum* and *Azospirillum brasilense* will improve soil fertility levels and result in higher soybean grain yield. To this end, we evaluated the residual effects of CSS application rates combined with PGPB, compared to conventional mineral fertilization, monitoring changes in soil chemical properties and their implications for soybean grain yield in a crop rotation system under NTS in *Cerrado* soil after six years of management.

2. Materials and Methods

2.1. Local and Experimental Setup

The field experiment was conducted over six growing seasons in Selvíria (20°22′ S, 51°22′ W), Mato Grosso do Sul, Brazil, at an altitude of approximately 335 m (Figure 1). The region has an average annual rainfall of 1370 mm, an average temperature of 24.5 °C, and a relative air humidity of 75% (Figure 2). According to the Köppen–Geiger classification [23], the regional climate is aw-type, characterized by rainy summers and dry winters [24].

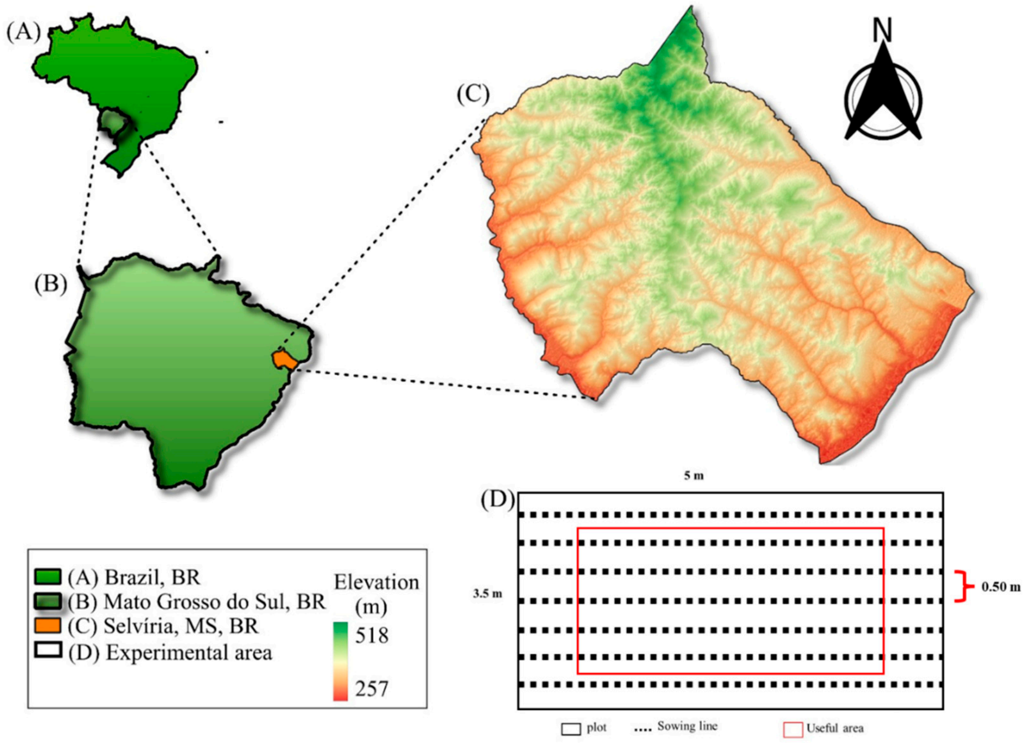

Figure 1. Study site: municipality of Selvíria, Mato Grosso do Sul, Brazil (**A**–**C**) and characterization of the area and experimental unit (**D**).

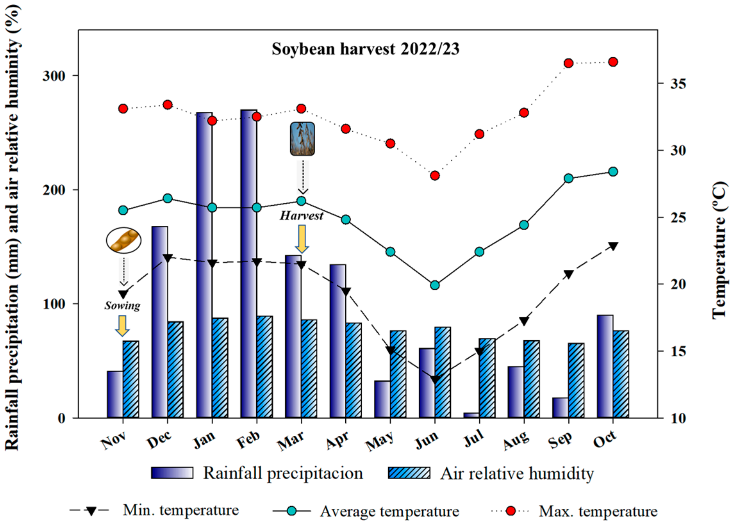

Figure 2. Rainfall, relative humidity, and minimum, average, and maximum air temperature (Selvíria, Mato Grosso do Sul, Brazil, 2022/23). Information provided by the Clima Agrometeorological Station, Ilha Solteira, SP, Brazil.

The soil was classified as a Rhodic Hapludox [25]. During the 2017/18 and 2018/19 growing seasons, rice (*Oryza sativa* L.) and common bean (*Phaseolus vulgaris* L.) were grown in succession in the experimental area under conventional tillage and center-pivot irrigation. Subsequently, a no-tillage system (NTS) was implemented. In 2019/20, marandu palisadegrass (*Urochloa brizantha* cv. Marandu) was grown in the first crop season, followed by maize (*Zea mays* L.) in the second crop. In the first crop season of 2020/21, marandu palisadegrass was again cultivated, while in the second crop season, a mix of Sunn hemp (*Crotalaria juncea*), forage radish (*Raphanus sativus*), and pearl millet (*Pennisetum glaucum*) was sown. In the 2021/22 crop season, maize was cultivated, followed by wheat in the subsequent season. In the 2022/23 growing season, soybean was grown (Figure 3).

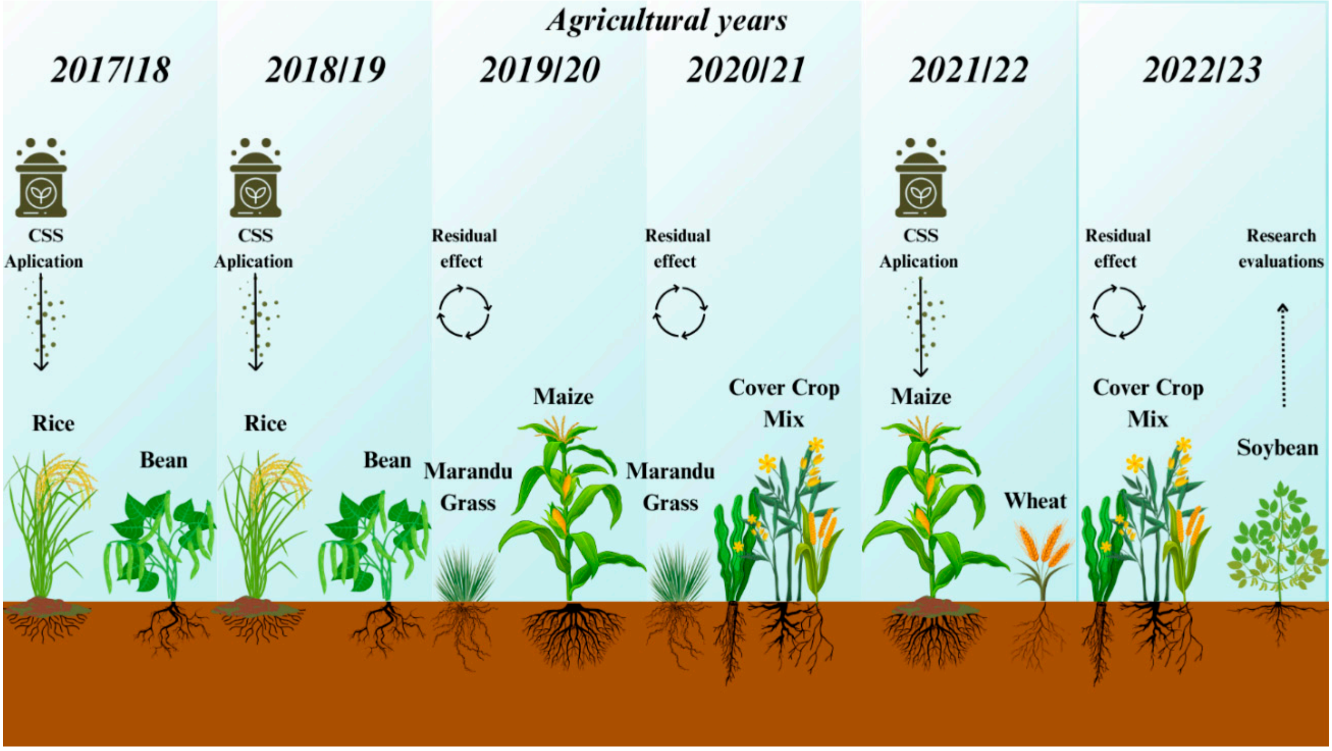

Figure 3. Timeline showing the application of composted sewage sludge (CSS) and the crop rotation management system over the crop years. “Mix” = forage radish, Sunn hemp, and pearl millet.

2.2. Experimental Design and Treatments

The experimental design was a randomized complete block with four replications. Treatments were arranged in a 5 × 2 + 1 factorial scheme, consisting of five residual cumulative rates from three applications of CSS (0.0, 15.0, 22.5, 30.0, and 37.5 Mg ha^{-1}, wet basis) (Table 1), with and without co-inoculation of *Azospirillum brasilense* strain Ab-V5, using the commercial inoculant Aufix (guaranteed 2×10^8 colony-forming units—CFU mL^{-1}) applied in the sowing furrow, and an additional treatment with mineral fertilizer application in soybean cultivation. All treatments were inoculated with *Bradyrhizobium japonicum* strains SEMIA 5079 and 5080, using the Brafix inoculant (guaranteed 1×10^9 CFU mL^{-1}). Inoculants were applied at the doses and spray volumes recommended by the manufacturer (NOAA Agricultural Science and Technology, Patos de Minas, Brazil).

Table 1. Chemical and microbiological composition of composted sewage sludge samples (Mean ± standard deviation; *n* = 3).

Characteristics	**Unit**	**2017/18**	**2018/19**	**2021/22**	**Allowed Value** (1)
Chemical			Dry basis		
pH ($CaCl_2$)	- (3)	7.0 ± 0.1	7.3 ± 0.1	8.0 ± 0.4	-- (2)
Moisture (60–65 °C)	%	41.0 ± 0.3	34.4 ± 0.5	36.7 ± 0.1	--
Total Moisture	%	45.5 ± 0.2	35.8 ± 0.6	38.2 ± 0.1	--
Total Organic Matter	g kg^{-1}	308.7 ± 10.0	255.0 ± 7.4	200.0 ± 26.8	--
CEC	$mmol_c$ kg^{-1}	520.0 ± 20.0	--	263.3 ± 81.4	--
C/N	-	12.0 ± 0.8	9.0 ± 0.6	11.00 ± 3.5	--
N Total	g kg^{-1}	13.9 ± 0.2	15.3 ± 1.5	10.7 ± 3.0	--
P Total	g kg^{-1}	12.3 ± 1.4	14.1 ± 0.00	16.5 ± 4.5	--
S Total	g kg^{-1}	4.8 ± 0.3	8.4 ± 1.4	7.3 ± 0.9	--
Na	mg kg^{-1}	3930 ± 32.0	3915 ± 41.2	--	--
K	g kg^{-1}	6.0 ± 2.2	8.2 ± 0.4	4.7 ± 2.8	--
Ca	g kg^{-1}	19.4 ± 4.4	31.1 ± 1.1	41.7 ± 17.4	--
Mg	g kg^{-1}	5.2 ± 0.5	9.9 ± 0.2	11.3 ± 2.2	--
As	mg kg^{-1}	3.2 ± 1.8	--	3.3 ± 1.1	20.0
B	mg kg^{-1}	94.0 ± 4.5	94.0 ± 4.6	--	--
Cd	mg kg^{-1}	1.00 ± 0.1	--	1.0 ± 0.4	3.0
Cu	mg kg^{-1}	237.0 ± 16.5	191.2 ± 5.8	246.3 ± 69.0	--
Pb	mg kg^{-1}	18.1 ± 1.6	--	17.6 ± 0.7	150.0
Cr	mg kg^{-1}	54.3 ± 1.8	--	64.4 ± 1.0	--
Fe	mg kg^{-1}	16,400 ± 1300	14,708 ± 249	12,405 ± 522	--
Mn	mg kg^{-1}	246 ± 37.0	310.0 ± 15.0	591.0 ± 89.1	--
Hg	mg kg^{-1}	0.2 ± 0.1	--	0.1 ± 0.1	1.0
Mo	mg kg^{-1}	5.2 ± 0.2	--	6.6 ± 2.4	--
Ni	mg kg^{-1}	26.5 ± 0.5	--	23.3 ± 4.6	70.0
Zn	mg kg^{-1}	456.0 ± 8.0	684.0 ± 7.2	1083.0 ± 339.5	--
Microbiological					
Salmonella sp.	NMP/10 g	Absent	Absent in 10 g of DM		
Thermotolerant coliforms	NMP/g	0	1000.0		
Viable helminth eggs	Eggs/g of ST	0.12	1.0		

(1) Normative Instruction No 7 MAPA [8]. (2) Not determined. (3) Dimensionless. NMP = Most probable number. CEC: Cation exchange capacity. No composted sewage sludge was applied in the 2019/20 and 2020/21 growing seasons. The residual effect of the organic fertilizer applications was evaluated instead.

2.3. Acquisition and Characterization of Composted Sewage Sludge

The composted sewage sludge (CSS) was obtained in the municipality of Jundiaí, São Paulo State, Brazil, and classified as a Class B compound organic fertilizer, registered with the Ministry of Agriculture, Livestock, and Food Supply (MAPA) [8]. It was produced through thermophilic composting of various urban organic residues. The primary raw material component is municipal sewage sludge, accounting for approximately 70% of the mass. In addition to sewage sludge, the composting process also included sludges from wastewater treatment systems of agro-industrial facilities, such as breweries and food processing plants, along with pre- and post-consumer fruit, vegetable, and leafy green residues (source-separated and selectively collected), as well as waste from unusable processed food products, among others. Composting was conducted in a forced-aeration system for three consecutive months to reduce the pathogen load and increase solid biomass, resulting in a moisture content of approximately 40%. Furthermore, gypsum and limestone (4% by mass) were added to reduce aluminum saturation and to increase porosity and pH.

Six samples were collected from different locations to characterize the CSS applied in the three growing seasons. The following chemical attributes were analyzed: pH, CEC, OM, organic C, moisture, As, Ba, B, Cd, Ca, Cr, Cu, Fe, Hg, Mg, Mn, Mo, N, Na, Ni, P, Pb, S, Se, and Zn; as well as microbiological parameters (thermotolerant coliforms, *Salmonella* sp., and viable helminth eggs), following the guidelines established in CONAMA Resolution No. 375 [26]. The material was deemed suitable for this study (Table 1).

2.4. Experiment Implementation

The present study commenced in the 2017/18 growing season and was completed in the 2022/23 first cropping season, during which soybean evaluations were conducted, in other words, the study is based on data from a single growing season in response to residual CSS application rates. Before setting up the experiment and applying the treatments for the first time, soil samples were collected from the 0.0–0.2 m and 0.2–0.4 m layers for physical [27] and chemical characterization [28] (Table 2).

Table 2. Characterization of chemical [(1)] and physical [(2)] attributes of soil samples collected at the beginning (2017/18) of the experiment (Mean ± standard deviation; *n* = 3).

Attribute	**Unit**	**Soil Layer**	
		0.0–0.2 m	**0.2–0.4 m**
pH ($CaCl_2$)	- [(3)]	4.5 ± 0.1	4.7 ± 0.1
Organic matter	g kg^{-1}	19 ± 1.2	14 ± 0.6
P	mg kg^{-1}	16 ± 0.6	9 ± 0.00
K	$mmol_c$ kg^{-1}	1.7 ± 0.2	0.7 ± 0.2
Ca	$mmol_c$ kg^{-1}	13 ± 0.6	11 ± 0.6
Mg	$mmol_c$ kg^{-1}	12 ± 1.0	10 ± 0.0
Aluminum	$mmol_c$ kg^{-1}	4 ± 0.0	2 ± 0.6
H + Al	$mmol_c$ kg^{-1}	37 ± 2.3	32 ± 1.7
SB	$mmol_c$ kg^{-1}	27.0 ± 1.7	22.1 ± 0.7
S-SO_4	mg kg^{-1}	15 ± 0.6	8 ± 0.6
CEC	$mmol_c$ kg^{-1}	63.7 ± 0.8	54.1 ± 2.4
BS	%	42 ± 3.2	41 ± 0.6
m	%	13 ± 1.0	9 ± 2.3
B	mg kg^{-1}	0.2 ± 0.1	1.4 ± 0.1
Cu (DTPA)	mg kg^{-1}	1.8 ± 0.1	7.7 ± 0.1
Fe (DTPA)	mg kg^{-1}	15.0 ± 0.6	8.0 ± 0.6
Mn (DTPA)	mg kg^{-1}	18.8 ± 0.1	7.3 ± 0.7
Zn (DTPA)	mg kg^{-1}	0.6 ± 0.1	0.2 ± 0.0
Particle size distribution		0–0.4 m	
Sand (>0.05 mm)	g kg^{-1}	553 ± 12.86	
Silt (>0.002 e <0.05 mm)	g kg^{-1}	81 ± 3.21	
Clay (<0.002 mm)	g kg^{-1}	372 ± 19.05	
Texture	-	Clayey	

[(1)] [28]. [(2)] [27]. [(3)] Dimensionless. SB = Sum of bases. CEC = Cation exchange capacity. BS = Base saturation. *m* = Aluminum saturation.

For the initial preparation of the experimental area, chiseling was performed to a depth of 0.3 m. Based on the soil fertility results, liming (2.2 Mg ha^{-1}) was carried out using agricultural limestone with an effective calcium carbonate equivalent (ECCE) of 80%, three months before the start of the 2017/18 first cropping season, aiming to raise base saturation to 70%. Half of the dose was applied before plowing, and the other half before harrowing the area. Subsequently, 1.8 Mg ha^{-1} of agricultural gypsum was applied on the surface without incorporation [29]. CSS applications were performed on the entire area without incorporation, in the days preceding crop sowing, during the 2017/18, 2018/19, and 2021/22 first cropping seasons, with varying material moisture levels (Table 1).

Soybean was grown in the 2022/23 first cropping season, with varying material moisture levels (November to March) under the residual effect of three CSS applications, as previously described. The soybean cultivar used was HO Pirapó IPRO (HO Genetics, Goiânia, Brazil), characterized by an indeterminate growth habit, a relative maturity group (RMG) of 6.4, and high yield potential, as well as considerable seed weight and excellent branching, along with resistance to major diseases and nematodes [30]. The plot area was 17.5 m^2, with the functional area consisting of five central rows and three central meters in length, excluding one meter from each end.

Sowing was carried out with a row spacing of 0.5 m, and to ensure proper soybean seedling emergence, a plant population of 320,000 plants ha^{-1} was used, as recommended for the crop. In the plots, co-inoculation with *Azospirillum brasilense* was performed at a rate of 100 mL ha^{-1} on the day of sowing, applied to the soil over the seed row after furrow closure, using liquid inoculants based on pure bacterial cultures [31]. Basal and topdressing fertilization were applied only to the plots in the conventional mineral fertilization (additional) treatment, following the recommendations of Raij et al. [29]. Basal fertilization supplied 30 kg ha^{-1} of N (urea—45% N) and 40 kg ha^{-1} of K_2O (potassium chloride—60% K_2O). Topdressing was carried out 30 days after sowing, in a single application, at a rate of 40 kg ha^{-1} of K_2O as KCl [32]. Pest and disease management was performed according to technical recommendations for soybean cultivation in the region. According to the crop requirements, 14 mm of water was applied through supplemental irrigation using a center-pivot system.

2.5. Laboratory and Field Analyses

At the end of the soybean growing cycle, soil sampling was conducted in the interrows, collecting 10 simple soil samples per layer. After homogenization, a fraction was taken to form a composite sample for each plot at two soil horizons (A_{p1}: 0.0–0.2 m; A_{p2}: 0.2–0.4 m) to evaluate soil chemical properties: organic matter (OM), pH, cation exchange capacity (CEC), $H^+ + Al^{3+}$, Al, sum of bases (SB), base saturation (BS), N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn [28].

Soil pH was determined in a 0.01 mol L^{-1} $CaCl_2$ solution at a soil-to-solution ratio of 1:2.5. Organic matter was determined after oxidation with $K_2Cr_2O_7$ in the presence of H_2SO_4. Exchangeable aluminum (Al^{3+}) was extracted with 1 mol L^{-1} KCl. Available phosphorus (P), exchangeable potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) were extracted using ion-exchange resin. Potential acidity ($H^+ + Al^{3+}$) was estimated by the SMP pH method. Sulfur was extracted using a 0.01 mol L^{-1} $Ca(H_2PO_4)_2$ solution. Cation exchange capacity (CEC) at pH 7.0 and base saturation (BS) were calculated. The available Cu, Fe, Mn, and Zn contents were determined using DTPA extraction at a pH of 7.3 [33]. Boron content was assessed through extraction with barium chloride [34].

All plants from the plot's functional area were harvested, threshed, and weighed. The results were then extrapolated to kg ha^{-1} and corrected to a moisture content of 13% (wet basis).

2.6. Statistical Analysis

All statistical procedures were performed in R version 4.3.0 [35]. All data were initially checked for normality (Shapiro–Wilk test) and homogeneity of variance (Levene's test) to validate the assumptions required for subsequent analyses. A factorial ANOVA was then performed to evaluate the main and interactive effects of CSS rates and co-inoculation with *Azospirillum brasilense* on all measured variables. When significant main effects of CSS and co-inoculation treatments were identified ($p \leq 0.05$), mean comparisons were conducted using Tukey's test. Differences between CSS treatments and the mineral fertilizer control were further analyzed using Dunnett's test. For variables with significant quantitative relationships, polynomial (second-degree) regression models were fitted to describe the response to increasing CSS rates. Model assumptions, including linearity, homoscedasticity, independence, and normality of residuals, were assessed both graphically and with diagnostic tests. The selection of the best model was based on adjusted R^2 and residual patterns. Non-significant interaction terms were excluded to enhance model parsimony and clarity in interpretation. This transparent approach ensures that analytical results are robust, thoroughly reproducible, and aligned with established standards in agricultural research.

3. Results and Discussion

3.1. Soil Chemical Properties

CSS rates influenced pH, SB, and CEC in both soil layers, and base saturation (BS) only in the surface layer (Table 3). A linear increase was observed for pH (Figures 4a and 5a), SB (Figures 4b and 5b), CEC (Figures 4c and 5c), and BS (Figure 4d) at both soil layers. In the surface layer, pH values ranged from 5.2 to 5.6, SB from 31.1 to 42.5 $\text{mmol}_c\ \text{kg}^{-1}$, CEC from 48.4 to 57.5 $\text{mmol}_c\ \text{kg}^{-1}$, and BS from 64.3% to 73.4%. In the subsurface layer, values ranged from 5.0 to 5.4 for pH, 25.5 to 33.8 $\text{mmol}_c\ \text{kg}^{-1}$ for SB, and 43.6 to 50.4 $\text{mmol}_c\ \text{kg}^{-1}$ for CEC (Table 3). Considering both soil layers, after soybean cultivation, there was an increase in OM, pH, SB, and BS values, and a decrease in potential acidity ($H^+ + Al^{3+}$), compared to the soil chemical characterization before the experiment setup (Table 2).

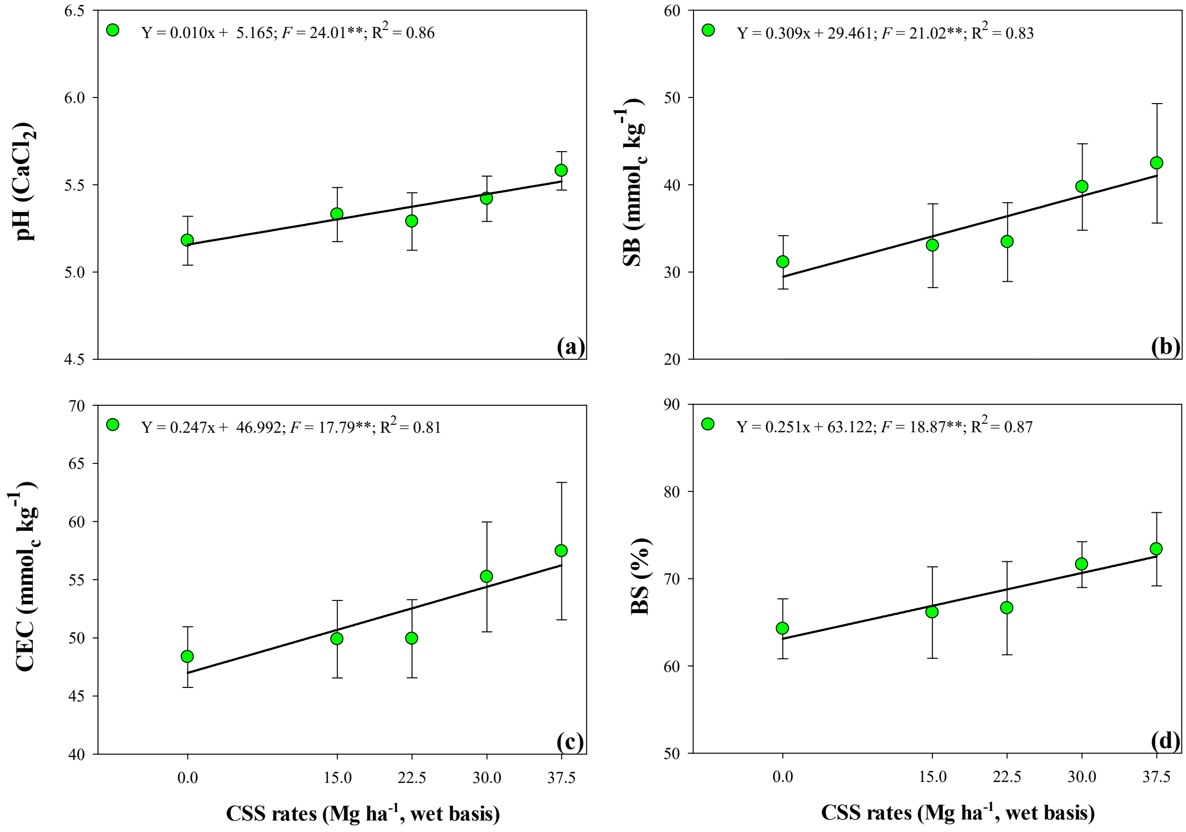

Figure 4. Soil pH (**a**), sum of bases—SB (**b**), cation exchange capacity—CEC (**c**), and base saturation—BS (**d**) in the 0.0–0.2 m layer after soybean cultivation in response to cumulative composted sewage sludge (CSS) rates. **—Significant at the 1% probability level. Error bars stand for the St. Err. of the mean.

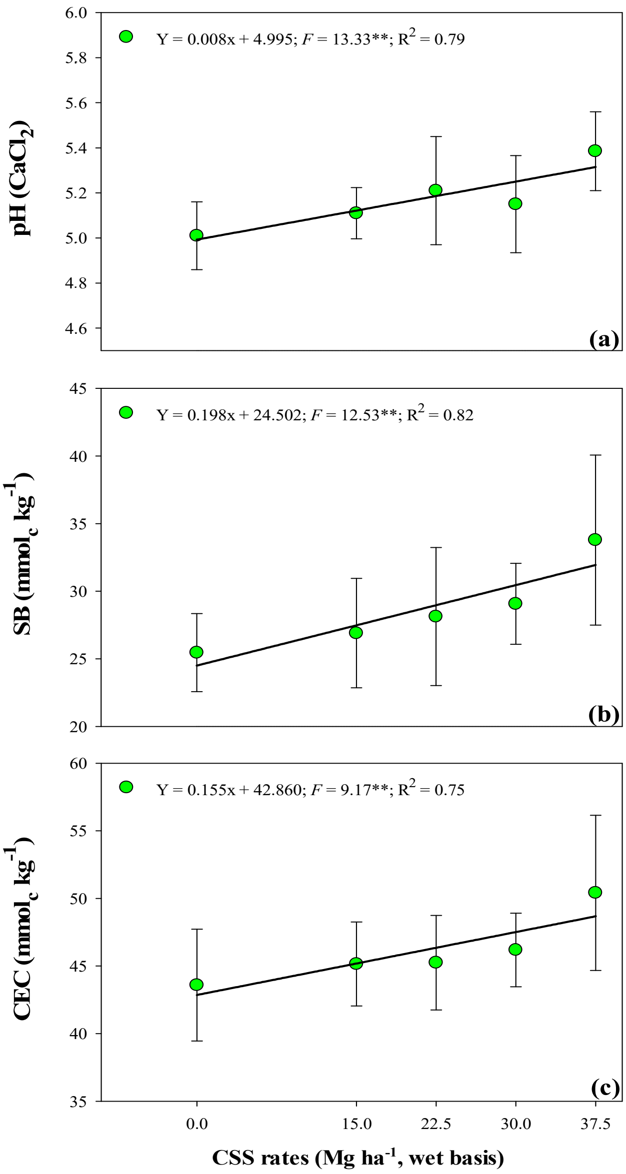

Figure 5. Soil pH (**a**), sum of bases—SB (**b**), and cation exchange capacity—CEC (**c**) in the 0.2–0.4 m layer after soybean cultivation in response to cumulative composted sewage sludge (CSS) rates. **—Significant at the 1% probability level. Error bars stand for the St. Err. of the mean.

Active acidity (pH) classes shifted from high acidity (4.4–5.0) (Table 2) to low acidity (5.6–6.0) at the 37.5 Mg ha^{-1} CSS rate in the surface layer, and to medium acidity (5.1–5.5) for the remaining CSS rates in both soil layers analyzed (Table 3) [36]. These changes occur due to the neutralizing effect of the product, which also acts similarly to a soil acidity corrective, based on its properties and chemical composition (Table 1). Furthermore, the soil's capacity to retain and exchange ions, buffer acidity, and maintain nutrient concentrations in the soil solution and solid phase is strongly influenced by the organic matter content, chemical nature, and bioactivity. Therefore, CSS serves as a conditioner for various soil chemical attributes [37,38].

These results show that CSS was able to maintain adequate levels of soil attributes (pH, SB, CEC, BS, and H^+ + Al^{3+}), which can be explained by the addition of exchangeable cations such as Ca^{2+} and Mg^{2+} through CSS application, along with K^+ released from crop residues in the rotation system. When meeting specific quality requirements and relevant regulations, organic fertilizers based on sewage sludge (CSS) can be used to increase soil

OM, supply nutrients, and condition various soil properties, thereby improving the plant growth environment [37,38].

Table 3. Effect of treatments on organic matter (OM), pH, H + Al, sum of bases (SB), cation exchange capacity (CEC), and base saturation (BS) after soybean cultivation.

Treatments	**OM**	**pH $_{CaCl2}$**	**H + Al**	**SB**	**CEC**	**BS**
	— g kg^{-1} —		**————— mmol$_c$ kg^{-1}**		**—————**	**%**
			0.0–0.2 m			
Mineral fertilization	18.00	4.70	22.25	26.37 $^{\blacktriangle}$	48.62 $^{\blacktriangle}$	54.00
CSS rates (Mg ha^{-1}) (1)						
0.0	18.12	5.18	17.25	31.10 $^{\blacktriangle}$	48.35 $^{\blacktriangle}$	64.25
15.0	18.62	5.34	16.87	33.01 $^{\blacktriangle}$	49.89 $^{\blacktriangle}$	66.12
22.5	18.87	5.30	16.50	33.42 $^{\blacktriangle}$	49.92 $^{\blacktriangle}$	66.62
30.0	19.50	5.42	15.50	39.74 $^{\bullet}$	55.24 $^{\blacktriangle}$	71.62
37.5	19.00	5.60	15.00	42.45 $^{\bullet}$	57.45 $^{\bullet}$	73.37
Co inoculation						
With *A. brasilense* (2)	18.95	5.35	16.50	35.47	51.97	67.90
Without *A. brasilense*	18.70	5.38	15.95	36.41	52.36	68.90
F Test						
CSS rates (R)	1.76 ^{NS}	6.98 **	2.64 ^{NS}	6.30 **	5.46 **	5.45 **
Co inoculation (C)	0.54 ^{NS}	0.24 ^{NS}	1.12 ^{NS}	0.29 ^{NS}	0.07 ^{NS}	0.45 ^{NS}
R *x* C	0.16 ^{NS}	1.83 ^{NS}	1.39 ^{NS}	0.83 ^{NS}	0.78 ^{NS}	0.57 ^{NS}
CV (%)	5.74	3.02	9.81	15.67	9.20	7.04
			0.2–0.4 m			
Mineral fertilization	17.00	4.70	23.00	22.17 $^{\blacktriangle}$	45.17	49.25
CSS rates (Mg ha^{-1})						
0.0	16.12	5.01	18.12	25.46 $^{\blacktriangle}$	43.59	58.25
15.0	17.00	5.11	18.25	26.90 $^{\blacktriangle}$	45.15	59.62
22.5	16.87	5.21	17.12	28.12 $^{\blacktriangle}$	45.25	62.12
30.0	16.87	5.15	17.12	29.06 $^{\blacktriangle}$	46.19	62.75
37.5	17.37	5.39	16.62	33.79 $^{\bullet}$	50.41	66.25
Co inoculation						
With *A. brasilense*	17.05	5.12	17.80	28.03	45.83	60.75
Without *A. brasilense*	16.65	5.22	17.10	29.30	46.40	62.85
F Test						
CSS rates (R)	2.21 ^{NS}	4.23 **	0.97 ^{NS}	3.83 *	3.04 *	2.64 ^{NS}
Co inoculation (C)	2.14 ^{NS}	2.73 ^{NS}	1.20 ^{NS}	0.77 ^{NS}	0.18 ^{NS}	1.52 ^{NS}
R *x* C	1.47 ^{NS}	1.54 ^{NS}	1.77 ^{NS}	0.40 ^{NS}	0.08 ^{NS}	0.93 ^{NS}
CV (%)	5.12	3.73	11.28	16.28	9.08	8.87

*, **, and ^{NS}—indicate significance at $p \leq 0.05$, $p \leq 0.01$, and not significant, respectively. Significant differences ($p \leq 0.05$; Dunnett's test) between treatments are indicated by different symbols $^{\blacktriangle}$ and $^{\bullet}$ following the means within the same column. (1) CSS: Composted sewage sludge, wet basis. (2) *Azospirillum brasilense*.

Tropical soils are characterized by low CEC and BS and high availability of Al^{3+} and Mn^{2+} [39]. Soil acidification can result from the weathering of parent material with low concentrations of exchangeable bases (K^{+}, Ca^{2+}, and Mg^{2+}) [40,41], from leaching throughout the soil profile [42], or from inadequate agricultural practices associated with excessive use of nitrogen fertilizers [43,44]. Silva et al. [12] reported that CSS affects soil attributes in surface layers, as they found significant results for pH, SB, CEC, and BS in sandy soil, with the highest values obtained at CSS rates between 5.0 and 7.5 Mg ha^{-1}.

However, similar to the present study, they did not observe significant changes in soil OM content.

Organic matter management is essential for agricultural sustainability in tropical soils because it increases CEC, which is typically low in this soil type [45–47]. The application of CSS, especially at higher rates, promotes an increase in soil pH values and enhances OM content [47].

When comparing the treatment that received mineral fertilization with the cumulative CSS rates, differences were observed only for SB in both soil layers and for CEC in the surface layer, with the highest means recorded in the treatment that received the highest CSS rate (37.5 Mg ha^{-1}) (Table 3).

Co-inoculation with *A. brasilense* did not influence soil chemical properties after soybean harvest. This result may be related to the low inoculant dose used (100 mL ha^{-1}), the possible high native population of *A. brasilense* in the soil, which could reduce the likelihood of a co-inoculation response because of competition intraspecific, or the fact that PGPB perform less effectively at pH < 5.4 ($CaCl_2$). Although the pH remained within this range in some CSS rates, this suggests that this parameter alone was not a limiting factor [48,49]. It is known that inoculation with *A. brasilense* can stimulate P solubilization, indole-3-acetic acid production, 1-aminocyclopropane-1-carboxylate deaminase activity, and the exudation of organic acid anions and siderophores [50,51]. The carboxylates produced could form soluble complexes with metallic cations [52]. Therefore, the bacterium can alleviate Al stress by forming Al-siderophore complexes, reducing H^+ + Al^{3+} and adjusting the pH toward the optimal survival range [53], thereby enhancing plant P uptake.

3.2. Soil Nutrient Contents

CSS rates influenced the contents of Ca, Mg, P, Cu, Mn, and Zn in both layers, as well as S content in the subsurface layer (Tables 4 and 5).

Soil Ca (Figures 6a and 7a), Mg (Figures 6b and 7b), P (Figures 6c and 7c), Cu (Figures 8a and 9a), and Zn (Figures 8c and 9c) contents showed a linear increase in both soil layers analyzed as CSS rates increased, with the same trend observed for S content in the subsurface layer (Figure 7d). The opposite was observed for Mn, which decreased linearly with increasing CSS rates in both soil layers (Figures 8b and 9b).

When comparing mineral fertilization with CSS rates (Tables 4 and 5), differences were observed for Ca, Mg, P, Cu, and Zn contents in both soil layers, with the highest values of these nutrients recorded at the highest CSS rate (37.5 Mg ha^{-1}). At this same rate, the lowest Mn content was observed in the surface layer, differing significantly from the control (Tables 4 and 5). The residual effect of CSS applications, at the highest rate, supplied the soil with up to 23.8 mmol$_c$ kg^{-1} of Ca, 17.25 mmol$_c$ kg^{-1} of Mg, and 15.8 mg kg^{-1} of P in the surface layer, and 19.8 mmol$_c$ kg^{-1} of Ca, 12.8 mmol$_c$ kg^{-1} of Mg, and 15.8 mg kg^{-1} of P in the subsurface layer (Table 4). Regarding micronutrients, the highest CSS rate (37.5 Mg ha^{-1}) resulted in 2.2 mg kg^{-1} of Cu and 4.2 mg kg^{-1} of Zn in the surface layer, and 2.0 mg kg^{-1} of Cu and 2.7 mg kg^{-1} of Zn in the subsurface layer.

In the 2017/2018 growing season, nutrient contents in the surface layer were classified as low for B, medium for K, P, and Zn, and high for Ca, Mg, S, Cu, Fe, and Mn [36] (Table 2). For the experiment, after five years of cultivation, it was observed that in the surface layer, at the highest cumulative CSS rate (37.5 Mg ha^{-1}), P content is now classified as medium. Sulfur content also remains in this class, with values of 16.0–40.0 and 5.0–10.0 mg kg^{-1}, respectively, under the residual effect of the highest cumulative CSS rates [36]. In contrast, Ca (4.0–7.0 mmol$_c$ kg^{-1}) and Mg (5.0–8.0 mmol$_c$ kg^{-1}) contents exceeded these classification ranges at all CSS rates (Table 4), remaining in the high category but at higher levels compared to the initial contents of these nutrients (Table 2).

Table 4. Effect of treatments on soil K, Ca, Mg, P, and S contents at two soil layers after soybean cultivation.

Treatments	**K**	**Ca**	**Mg**	**P**	**S**
	mmol$_c$ kg^{-1}			**mg kg^{-1}**	
			0.0–0.2 m		
Mineral fertilization	1.62	14.75 ▲	10.00 ▲	24.75 ▲	8.25
CSS rates (Mg ha^{-1}) (1)					
0.0	1.22	18.12 ▲	11.75▲	5.50 •	8.25
15.0	1.39	18.00 ▲	13.62 •	11.87 •	9.12
22.5	1.67	17.87 ▲	13.87 •	12.25 •	8.50
30.0	1.49	21.87 •	16.37 •	14.87 •	8.50
37.5	1.45	23.75 •	17.25 •	19.75 ▲	9.37
Co inoculation					
With *A. brasilense* (2)	1.52	19.50	14.45	12.10	8.75
Without *A. brasilense*	1.36	20.35	14.70	13.60	8.75
F Test					
CSS rates (R)	1.15 ^{NS}	6.00 **	6.63 **	10.83 **	2.45 ^{NS}
Co inoculation (C)	1.38 ^{NS}	0.73 ^{NS}	0.10 ^{NS}	1.14 ^{NS}	0.00 ^{NS}
R *x* C	0.33 ^{NS}	0.98 ^{NS}	0.70 ^{NS}	2.19 ^{NS}	0.42 ^{NS}
CV (%)	29.43	16.14	17.25	31.91	9.89
			Interpretation limit (3)		
Very low	-- (4)	-- (4)	-- (4)	<7.0	-- (4)
Low	<1.6	<4.0	<5.0	7.0–15.0	<5.0
Medium	1.6–3.0	4.0–7.0	5.0–8.0	16.0–40.0	5.0–10.0
High	3.1–6.0	>7.0	>8.0	>41.0–80.0	>10.0
Very high	>6.0	-- (4)	-- (4)	>80.0	-- (4)
			0.2–0.4 m		
Mineral fertilization	1.42	12.75 ▲	8.00 ▲	15.25 ▲	9.25
CSS rates (Mg ha^{-1})					
0.0	1.08	14.50 ▲	9.87 ▲	4.50 •	7.62
15.0	1.15	14.50 ▲	11.25 •	9.12 •	9.25
22.5	1.26	15.00 ▲	11.50 •	8.62 •	8.75
30.0	1.31	15.37 ▲	12.37 •	10.25 •	9.25
37.5	1.29	19.75 •	12.75 •	15.75 ▲	9.87
Co inoculation					
With *A. brasilense*	1.24	15.40	11.25	9.35	8.80
Without *A. brasilense*	1.20	16.25	11.85	9.95	9.10
F Test					
CSS rates (R)	0.70 ^{NS}	4.79 **	2.79 *	17.70 **	5.59 **
Co inoculation (C)	0.15 ^{NS}	0.87 ^{NS}	1.00 ^{NS}	0.49 ^{NS}	0.89 ^{NS}
R *x* C	0.40 ^{NS}	0.25 ^{NS}	0.60 ^{NS}	2.29 ^{NS}	2.68 ^{NS}
CV (%)	26.29	18.48	16.89	26.76	11.20

*, **, and ^{NS}—indicate significance at $p \leq 0.05$, $p \leq 0.01$, and not significant, respectively. Significant differences ($p \leq 0.05$; Dunnett test) between treatments are indicated by different symbols ▲ and • following the means within the same column. (1) CSS: Composted sewage sludge, wet basis. (2) *Azospirillum brasilense*. (3) [36]. (4) Values not established.

Analyzing soil K^+ content, no changes were observed in the interpretation classes [36], except for the intermediate CSS rate (22.5 Mg ha^{-1}) in the surface layer, where the content shifted from low (<1.6 mmol$_c$ kg^{-1}) to medium (1.6–3.0 mmol$_c$ kg^{-1}) (Table 4). Regarding micronutrients, all increased to the high-response class [36] in both soil layers, except for B, which remained between 0.2 and 0.6 mg kg^{-1}, altering the interpretation classes to medium (0.21–0.60 mg kg^{-1}) in both soil layers at all CSS rates applied (Table 5).

Table 5. Effect of treatments on soil B, Cu, Fe, Mn, and Zn contents at two layers after soybean cultivation.

Treatments	**B**	**Cu**	**Fe**	**Mn**	**Zn**
			mg kg^{-1}		
			0.0–0.2 m		
Mineral fertilization	0.31	1.77 ▲	21.75	18.70 ▲	2.32 ▲
CSS rates (Mg ha^{-1}) (1)					
0.0	0.22	1.70 ▲	18.25	18.67 ▲	0.91 •
15.0	0.22	2.04 ▲	19.75	16.59 ▲	2.80 ▲
22.5	0.26	2.02 ▲	19.87	15.81 ▲	2.91 ▲
30.0	0.32	2.20 •	18.75	14.58 •	3.72 •
37.5	0.26	2.24 •	17.75	13.75 •	4.21 •
Co inoculation					
With *A. brasilense* (2)	0.25	1.98	18.65	15.73	2.68
Without *A. brasilense*	0.26	2.10	19.10	16.01	3.14
F Test					
CSS rates (R)	2.26 ^{NS}	4.66 **	0.74 ^{NS}	6.85 **	13.58 **
Co inoculation (C)	0.15 ^{NS}	1.86 ^{NS}	0.22 ^{NS}	0.18 ^{NS}	2.31 ^{NS}
R *x* C	1.16 ^{NS}	0.93 ^{NS}	1.19 ^{NS}	2.35 ^{NS}	1.02 ^{NS}
CV (%)	28.33	13.80	15.97	12.83	33.86
			Interpretation limit (3)		
Low	0–0.20	0–0.2	0–4.0	0–1.2	0–0.5
Medium	0.21–0.60	0.3–0.8	5.0–12.0	1.3–5.0	0.6–1.2
High	>0.60	>0.8	>12.0	>5.0	>1.2
			0.2–0.4 m		
Mineral fertilization	0.27	1.62 ▲	17.50	15.62	1.45 ▲
CSS rates (Mg ha^{-1})					
0.0	0.22	1.71 ▲	15.00	15.12	0.55 ▲
15.0	0.24	1.81 ▲	16.50	14.02	1.37 ▲
22.5	0.26	1.66 ▲	15.87	11.66	1.50 ▲
30.0	0.30	1.82 ▲	15.00	12.10	1.66 ▲
37.5	0.29	1.97 •	16.00	12.49	2.70 •
Co inoculation					
With *A. brasilense*	0.24	1.79	16.25	13.55	1.45
Without *A. brasilense*	0.28	1.80	15.10	12.61	1.66
F Test					
CSS rates (R)	1.13 ^{NS}	3.36 *	0.73 ^{NS}	2.86 *	22.82 **
Co inoculation (C)	2.15 ^{NS}	0.01 ^{NS}	2.76 ^{NS}	1.50 ^{NS}	2.23 ^{NS}
R *x* C	0.25 ^{NS}	0.21 ^{NS}	2.21 ^{NS}	1.02 ^{NS}	0.33 ^{NS}
CV (%)	34.30	10.43	13.81	18.20	29.43

*, **, and ^{NS}—indicate significance at $p \leq 0.05$, $p \leq 0.01$, and not significant, respectively. Significant differences ($p \leq 0.05$; Dunnett test) between treatments are indicated by different symbols ▲ and • following the means within the same column. (1) CSS: Composted sewage sludge, wet basis. (2) *Azospirillum brasilense*. (3) [36].

This study provides evidence of CSS's potential to supply various nutrients (Table 1), characterizing it as a multi-element product [7,54]. The crop rotation system enables the maintenance of soil cover and promotes nutrient cycling, thereby increasing the availability of these essential elements to plants. As a result, the residual effect of CSS application rates may have promoted nutrient recycling and gradual release, especially at the higher rates [47,54]. Research has shown that CSS can reduce the need for mineral fertilizers, supplying mainly P, K, Ca, and Mg in the surface layer, while also improving soil physical and chemical properties [12,47,55]. Junio et al. [56] and Sharma et al. [57] reported increased levels of available P and K in soils treated with CSS. Silva et al. [47], in an experiment conducted over three successive maize crops, found high concentrations of available P in the soil (>70 mg kg^{-1}) at sites where higher CSS rates (30 and 40 Mg ha^{-1}, dry basis) were applied.

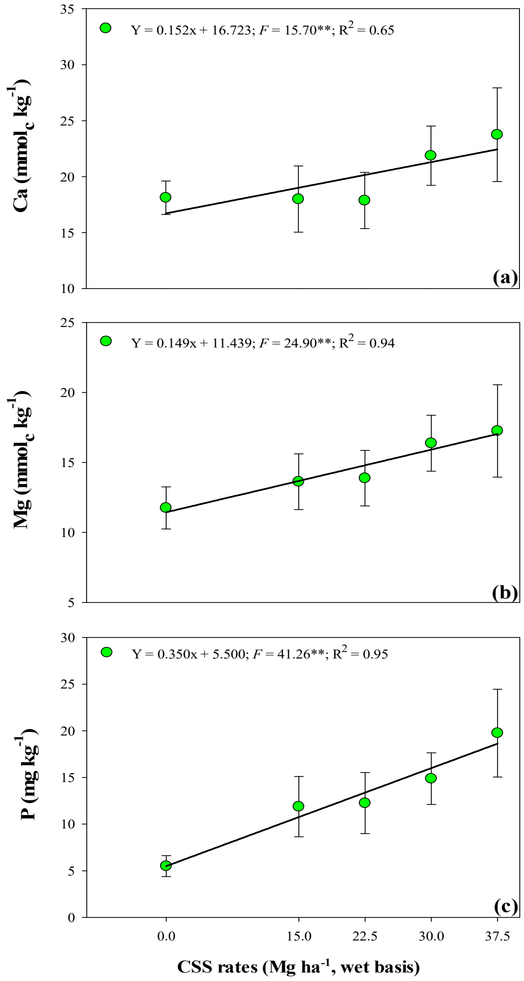

Figure 6. Available soil Ca (**a**), Mg (**b**), and P (**c**) contents in the 0.0–0.2 m layer after soybean cultivation in response to cumulative composted sewage sludge (CSS) rates. **—Significant at the 1% probability level. Error bars stand for the St. Err. of the mean.

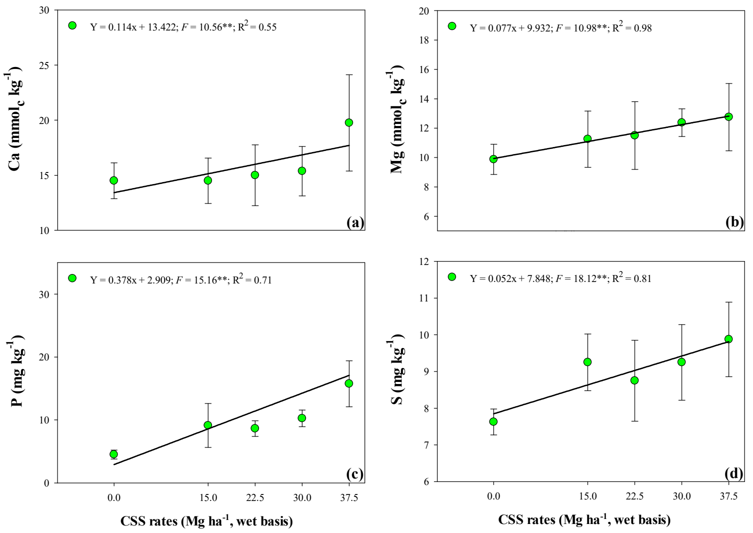

Figure 7. Available soil Ca (**a**), Mg (**b**), P (**c**), and S (**d**) contents in the 0.2–0.4 m layer after soybean cultivation in response to cumulative composted sewage sludge (CSS) rates. **—Significant at the 1% probability level. Error bars stand for the St. Err. of the mean.

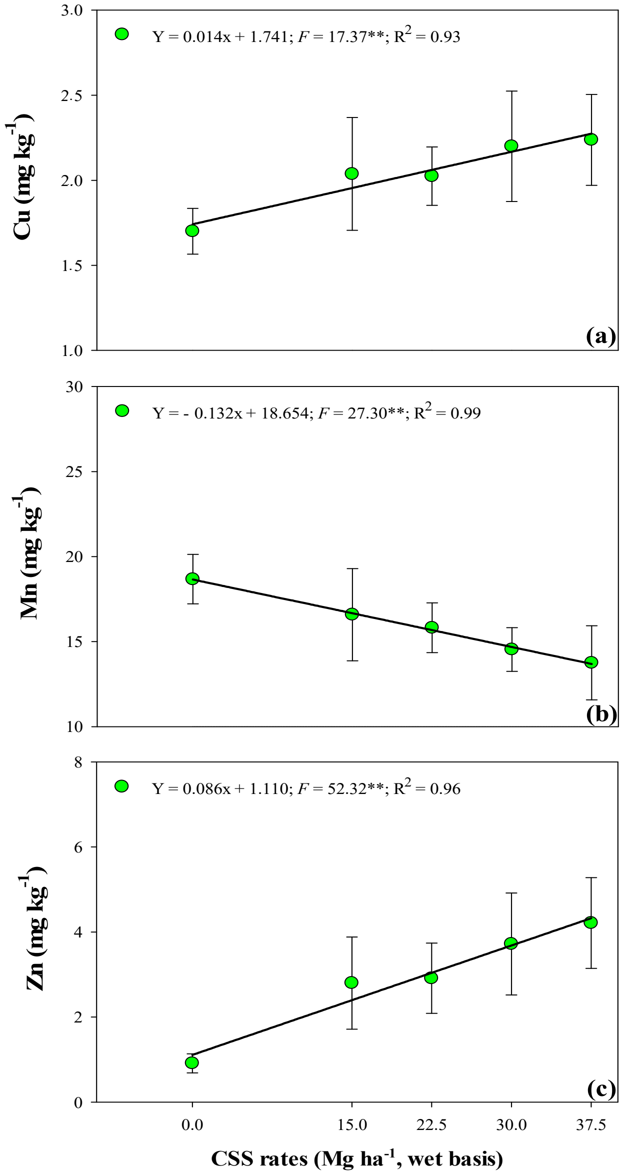

Figure 8. Available soil Cu (**a**), Mn (**b**), and Zn (**c**) contents in the 0.0–0.2 m layer after soybean cultivation in response to cumulative composted sewage sludge (CSS) rates. **—Significant at the 1% probability level. Error bars stand for the St. Err. of the mean.

Soil micronutrient content increased with cumulative CSS rates (Table 5), particularly for cationic micronutrients (Cu, Fe, Mn, and Zn). Crop development depends on adequate nutrient levels, including those less required by plants, especially under adverse conditions such as tropical regions with a high degree of weathering and nutrient losses in various forms [58]. Studies conducted in the Cerrado region have obtained similar results from the application of CSS rates, broadcast as a source of micronutrients, with significant increases in soil B, Cu, Fe, and Zn levels over two consecutive years following soybean cultivation under conventional tillage [10], as well as in maize [11] and common bean [14].

Applying CSS to the soil increased the availability of Fe, Mn, Zn, and Cu, resulting in greater plant accumulation [47]. Moretti et al. [59] and Silva et al. [12] reported results similar to those of the present study regarding micronutrient availability following CSS fertilization. Thus, soil micronutrient availability is directly linked to plant uptake, as any micronutrient deficiency impairs normal plant growth, leading to reduced crop yield [60]. Therefore, CSS is an effective fertilizer for supplying micronutrients, particularly in areas where fertilization with these elements is recommended, such as naturally infertile or degraded lands [47,55].

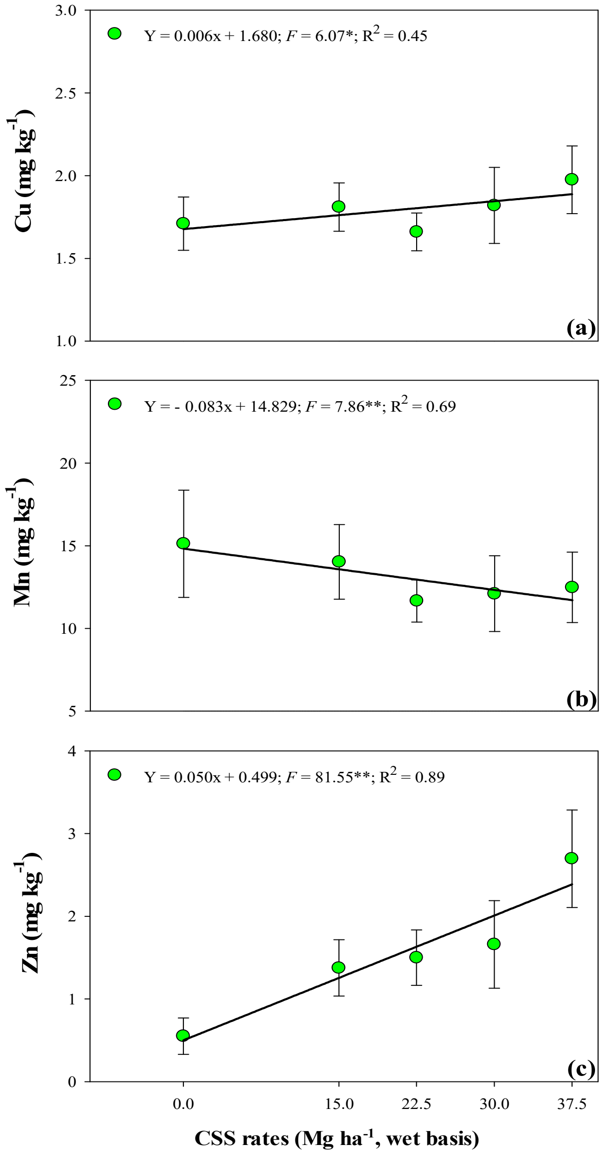

Figure 9. Available soil Cu (**a**), Mn (**b**), and Zn (**c**) contents in the 0.2–0.4 m layer after soybean cultivation in response to cumulative composted sewage sludge (CSS) rates. ** and *—Significant at 1% and 5% probability level, respectively. Error bars stand for the St. Err. of the mean.

Soil nutrient content was not influenced by *Azospirillum brasilense* co-inoculation after soybean cultivation. This contrasts with the findings of Barbosa et al. [15], who concluded, based on a meta-analysis, that co-inoculating soybean with *A. brasilense* and *Bradyrhizobium* spp. can influence nutrient cycling in agroecosystems. Therefore, further studies are needed to thoroughly assess the effects of agronomic practices, edaphoclimatic changes, and PGPB co-inoculation in different agricultural production systems. The combined use of advanced scientific techniques (metabolomics, isotopic and molecular approaches, among others) will be essential to deepen and refine the understanding of the multiple mechanisms and benefits provided by PGPB to the soil–plant–environment microbiome [20].

3.3. Grain Yield

The highest average soybean grain yield (5171 kg ha^{-1}), obtained with the intermediate CSS rate (22.5 Mg ha^{-1}), was statistically similar to the yields at 15.0, 30.0, and 37.5 Mg ha^{-1} CSS, and did not differ from mineral fertilization (5289 kg ha^{-1}).

Soybean grain yield responded quadratically to CSS rates, reaching a maximum yield of 4990 kg ha^{-1} at 24.7 Mg ha^{-1} CSS (Figure 10). In this context, CSS is an alternative fertilizer to conventional mineral fertilizers for soybean cultivation [10,38], particularly in tropical and highly weathered regions. It may also be used in other crops, such as white mustard, lupine [61], and faba bean [62].

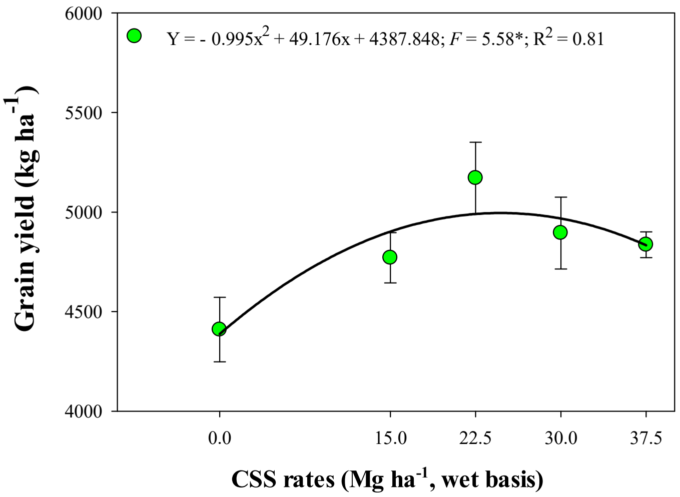

Figure 10. Soybean grain yield in response to cumulative composted sewage sludge (CSS) rates. *—Significant at 5% probability level. Error bars stand for the St. Err. of the mean.

With the CSS application, promising results have been observed in the performance of major crops in the Brazilian Cerrado. In a two-year study, Prates et al. [10] reported increased soybean grain yield following CSS application from the very first season, with results surpassing the national average yield. Similarly, in research conducted with common bean, grain yields above the Brazilian average were recorded for two consecutive years under the residual effect of CSS application rates [14].

Positive responses have also been observed with CSS fertilization in grasses. Silva et al. [47] reported that the application of CSS increased shoot biomass and maize yield. To compare the residual effect of CSS with conventional mineral fertilization in maize, researchers observed significant responses in plant height, thousand-grain weight, and grain yield [11]. Morphological variables of sugarcane were not influenced by CSS application; however, stalk yield per hectare increased [13]. Furthermore, the findings of this study are consistent with other research that reported significant effects on rice yield following CSS application, along with improvements in soil fertility [12,63,64].

Co-inoculation with *Azospirillum brasilense* had no effect in this study of soybeans. Several hypotheses may explain the lack of response, such as the method of co-inoculation, incompatibility between inoculants and crop protection products, or soil chemical conditions [65]. However, other factors may also have contributed, including climate or cultivar. Galindo et al. [66] evaluated two soybean cultivars co-inoculated with *A. brasilense* on the seeds and observed that both cultivars showed a higher number of pods per plant, greater 100-grain weight, and higher grain yield. In contrast, Oliveira et al. [67] concluded that the grain yield of soybean co-inoculated with different PGPB (*A. brasilense* and others) was not superior to that of soybean inoculated with *Bradyrhizobium japonicum*, regardless of the co-inoculation method.

In this regard, contrary to the findings of the present study, there are reports that co-inoculation of *Bradyrhizobium* sp. with *Azospirillum brasilense*, *Bacillus* spp., and *Pseudomonas* spp. can promote crop development and, consequently, grain production [67]. Hungria et al. [68] highlighted that co-inoculation with *A. brasilense* in soybean (*B. japonicum* + *A. brasilense*) and in common bean (*R. tropici* + *A. brasilense*) increased grain yield compared with the control (non-inoculated) treatment and with traditional inoculation using only the symbiotic bacterium. Co-inoculation with *A. brasilense* in soybean promoted a greater number of pods per plant, higher 100-grain weight, and increased grain yield, resulting in an 11.2% yield increase and a 14.4% increase in profitability [69]. A study with cowpea co-inoculated with *Bradyrhizobium* spp. and *A. brasilense* also showed increased grain yield, even when combined with topdressing N application. Moreover, the study found that this PGPB co-inoculation technique offers a greater cost–benefit ratio for cowpea cultivation, making it a recommended technology that eliminates the need for N topdressing fertilization [19].

Although we evaluated the residual effect of CCS application rates after six agricultural years (2017/18–2022/23), we must consider some limitations of the study that need to be taken into account when interpreting the results presented: (i) it is based on data from a single growing season; (ii) it did not include a comprehensive assessment of biological and environmental indicators of the soil, analyzing only chemical and productive parameters; and (iii) was conducted at a specific location, which may limit the extrapolation of the results to other edaphoclimatic conditions.

4. Broader Societal Implications

The integration of CSS and plant growth-promoting bacteria in tropical soybean systems transcends traditional agronomic evaluations, revealing far-reaching consequences for (i) food system resilience, (ii) climate change mitigation, and (iii) evidence-based policy reform [70]. By substituting mineral fertilizers with valorized urban biowastes, this approach not only decreases reliance on finite resources and imported chemical inputs but also fortifies the stability of national and local food supplies amid escalating global disruptions [71].

Through sustained organic amendment, CSS can foster long-term gains in SOC and nutrient cycling, contributing both to improved yield stability and meaningful carbon sequestration; central pillars of climate-smart agriculture [72].

Empirical assessments indicate that compost amendments in subtropical and tropical regions can yield carbon offset rates ranging between 1.1 and 2.8 t CO_2-eq ha^{-1} yr^{-1}, while simultaneously reducing nitrous oxide emissions relative to synthetic fertilization [73].

This evidence underscores the strategic value of circularity in nutrient management: policy frameworks worldwide, including those in Brazil and the European Union, are increasingly recognizing organo-mineral fertilizers derived from urban waste as essential instruments for advancing sustainable intensification and safeguarding food security, provided that quality standards and traceability protocols are rigorously enforced. Ensuring (i) robust farmer incentives, (ii) public communication strategies, and (iii) continuous monitoring will be critical to maximize adoption and optimize both agronomic and societal outcomes [73].

These findings affirm that judicious use of CSS in agriculture can simultaneously address environmental imperatives, elevate food security, and guide future policy directions towards more sustainable agroecosystems [74].

5. Conclusions

Under the edaphoclimatic conditions of this study, no influence was observed from the interaction between CSS rates and co-inoculation with *Bradyrhizobium japonicum* and *Azospirillum brasilense*, nor the isolated effect of this co-inoculation. However, the changes in soil properties and yield in response to the residual effect of three organic fertilizer applications were evident. Overall, the responses obtained under CSS residual treatments were similar to or greater than those observed with conventional mineral fertilization ($N_{30}P_0K_{80}$), regardless of *A. brasilense* co-inoculation. Soil fertility levels were improved, enabling adequate soybean development, with the best soil responses observed at the cumulative rate of 37.5 Mg ha^{-1} CSS. Residual CSS applications promoted increased pH, SB, and CEC, reducing potential acidity ($H^+ + Al^{3+}$). They also increased the contents of Ca, Mg, P, Cu, and Zn in both soil layers analyzed (0.0–0.2 and 0.2–0.4 m) and S content in the subsurface layer after soybean cultivation. Soybean grain yield under CSS residual treatments was similar to that observed with mineral fertilization. Furthermore, the 24.7 Mg ha^{-1} CSS accumulated rate yielded the maximum soybean grain yield (4990 kg ha^{-1}), 30% and 29% higher than the current state and national averages, respectively. Our results confirm that fertilizing with a sewage sludge–based compound organic fertilizer over six growing seasons promotes a residual effect, enhancing soil fertility and increasing grain yield. This represents a viable alternative to reduce and optimize the use of mineral fertilizers in regenerative and sustainable agricultural systems under tropical conditions, fostering a circular economy with environmental benefits (through more appropriate final disposal of municipal sewage sludge) and contributing to global food security. Finally, we emphasize that the results presented refer to a single growing season and, therefore, may not fully reflect the long-term dynamics of the soil–plant system in response to residual effects of CSS application rates. We encourage further studies with more long-term evaluations in different regions and edaphoclimatic conditions to consolidate the evidence obtained in this study.

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