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RESEARCH ARTICLE

Response of soil physicochemical and microbial properties to organic amendment addition in three soil types

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ABSTRACT

Conventional agricultural practices have progressively reduced soil fertility, largely as a consequence of C depletion. So, the application of organic amendments as a fertilization strategy should enhance soil properties and promote long-term sustainability. This study assessed the effects of a composted organic amendment, "bio-stabilized", as improver of the soil properties applied at rates of 1% and 2% (w/w), on the chemical, physical, and microbiological properties of three soils with contrasting textures (sandy loam, silt loam, and clay loam) following a 30 d aerobic incubation. The results showed that bio-stabilized application improved chemical properties across all soils, resulting in agronomically adequate nutrient availability and acceptable electrical conductivity levels (< 0.55 dS m^{-1}). In addition, water retention increased at potentials corresponding to different pore-size classes in two soils (500-1500 kPa in the silt loam soil and 33-1500 kPa in the clay loam soil). Microbiological properties increased quantitatively with bio-stabilized application; however, a significant increase in dissolved organic C was observed only in the clay loam soil (from 98.4 to 283.4 mg kg^{-1}). Overall, the application of bio-stabilized at the evaluated rates improved soil properties, with positive implications for agronomic performance and soil sustainability.

Key words: Bio-stabilized, clay loam, compost, sandy loam, silt loam.

INTRODUCTION

High-intensity conventional agricultural practices have led to substantial losses of soil organic C, adversely affecting crop productivity, soil physicochemical properties, and the activity and diversity of microbial biomass and soil enzymes (Rahman et al., 2016). The incorporation of organic amendments into agricultural systems offers multiple benefits, including enhanced nutrient recycling and improved physical, chemical, and microbiological soil characteristics (Cesaro et al., 2019; Islam et al., 2020; Omokaro et al., 2024). Furthermore, organic amendments can facilitate the bioremediation of heavy metal-contaminated soils, promote the formation of stable soil aggregates that improve nutrient retention and reduce leaching, and contribute to the mitigation of soil erosion (Mahongnao et al., 2023; Wihardjaka et al., 2025).

However, the incorporation of organic amendments may stimulate redox reactions in soil, leading to competition for available oxygen between plant roots and soil microorganisms (Butler et al., 2001; Silva et al., 2016). Moreover, the decomposition of organic amendments can release compounds with potential phytotoxic effects, such as volatile fatty acids, phenolic compounds, ammonium, and certain salts (Huerta et al., 2015). Consequently, it is essential that applied organic amendments possess appropriate organic and chemical characteristics to support biological processes, regulate physicochemical reactions, and promote optimal plant growth (Gutiérrez-González et al., 2024). Numerous studies have reported the advantages of using organic amendments as an alternative fertilization strategy, based on a wide range of biological indicators. These benefits include increased crop yields (Hirzel et al., 2009; Luo et al., 2018; Tao et al., 2024), improvements in soil chemical properties (Scotti et al., 2015), enhancements in soil physical properties (Feng et al., 2014; Tao et al., 2024), and positive effects on soil microbiological properties (Gandolfi et al., 2010; Feng et al., 2014; Tahmasbian et al., 2017).

With respect to soil microbiological properties, microbial biomass is considered an early and sensitive indicator of soil conditions, as it rapidly reflects changes in biological activity following management interventions (Bhaduri et al., 2022). Consequently, it serves as a reliable indicator of soil alterations resulting from the incorporation of C substrates such as organic amendments. In particular, the application of organic amendments increases the availability of labile energy substrates (labile organic C) for soil microorganisms, which is evidenced by enhanced microbial (heterotrophic) respiration, increased microbial biomass, and elevated microbial enzyme activity (Wang et al., 2023; Zhang et al., 2024). To date, there are no studies that analyze the effect of organic fertilizers on physical, chemical, and microbiological properties simultaneously, that also take into account different soil types, and that further evaluate the interrelationships among the soil properties assessed.

This study evaluated the effects of applying a composted organic amendment at different application rates on soil chemical properties, moisture retention, and indicators of microbiological activity in three soils with contrasting textures following an incubation period under controlled laboratory conditions.

MATERIALS AND METHODS

Soils

Soil samples were collected from the 0-30 cm depth at three agricultural fields in Chile cultivated with sweet cherry (*Prunus avium* (L.) L.) The soils corresponded to a Xerorthent sandy loam (36°03′45″ S, 71°41′50″ W), a Haploxeroll silt loam (35°41′48″ S, 71°33′25″ W), and a Durixeralf clay loam (34°22′09″ S, 70°58′96″ W), according to USDA Soil Taxonomy (USDA, 2014). The main physicochemical characteristics of the soils are presented in Table 1. Soil chemical properties were determined following the methodologies described by Sadzawka et al. (2006). Soil texture was analyzed at the beginning of the experiment using the Bouyoucos hydrometer method. Soil pH was measured in a 1:2.5 soil-to-water suspension using a glass electrode. Soil organic matter (OM) content was determined by the Walkley-Black wet oxidation method. Electrical conductivity (EC) was measured using a conductivity cell in a 1:5 soil-to-water extract. Available soil N ($N\text{-}NH_4^+$ and $N\text{-}NO_3^-$) was extracted with 2 mol L^{-1} KCl and quantified by colorimetry using a segmented-flow spectrophotometer (Skalar autoanalyzer; Skalar, York, UK). Available P was extracted with 0.5 M $NaHCO_3$ and determined by the ascorbic acid-molybdate method. Exchangeable Ca, Mg, K, and Na were extracted with 1 M ammonium acetate and measured by flame spectrometry, using atomic absorption for Ca and Mg and emission for K and Na. Exchangeable Al was determined after extraction with 1 M KCl by atomic absorption spectrometry. Available S was extracted with calcium phosphate and determined by turbidimetry. Iron, Mn, Zn, and Cu were extracted with diethylenetriaminepentaacetic acid (DTPA) and quantified by atomic absorption spectrometry (AAS). Available B was determined colorimetrically following hot water extraction. At the end of the experiment, soil moisture retention was determined at matric potentials of 10, 33, 100, 500, and 1500 kPa using a pressure plate apparatus. Soil microbial biomass C (MBC) was determined according to the chloroform fumigation-extraction method described by Vance et al. (1987), with minor modifications. Briefly, 10 g soil from each treatment replicate, previously adjusted to 60% water-filled pore space (WFPS), were used for analysis. Samples were divided into fumigated and non-fumigated subsamples, the latter serving as controls for the extraction procedure.

For fumigation, 0.5 mL ethanol-free chloroform ($CHCl_2$) was added to the samples, which were then incubated in the dark at room temperature for 30 min. Chloroform was subsequently removed by vacuum pump; this process was repeated five times or until complete removal was ensured. Both fumigated and non-fumigated samples were then extracted with 40 mL 0.5 M K_2SO_4 and shaken at 220 rpm for 1 h. The extracts were centrifuged at 10 000 rpm for 10 min and filtered through 0.45 µm syringe filters.

Table 1. Chemical and physical properties of the soils used in the experiment.

Soil property	Sandy loam soil	Silt loam soil	Clay loam soil
Clay, %	7.7	12.6	30.6
Silt, %	30.5	53.2	28.2
Sand, %	61.8	34.2	41.2
$pH_{(soil:water,\ 1:2.5)}$	6.7	6.3	7.5
Organic matter, g kg^{-1}	32.1	58.7	34.9
Available N, mg kg^{-1}	54.1	49.5	62.5
Available P, mg kg^{-1}	69.7	14.3	69.1
Exchangeable Ca, $cmol_+$ kg^{-1}	9.2	6.4	19.9
Exchangeable Mg, $cmol_+$ kg^{-1}	1.2	0.9	3.3
Exchangeable K, $cmol_+$ kg^{-1}	0.84	0.33	0.62
Exchangeable Na, $cmol_+$ kg^{-1}	0.04	0.09	0.19
Exchangeable Al, $cmol_+$ kg^{-1}	0.01	0.01	0.01
Exchangeable cation capacity, $cmol_+$ kg^{-1}	16.1	25.8	32.3
Available Fe, mg kg^{-1}	41.4	26.3	29.0
Available Mn, mg kg^{-1}	4.8	2.4	4.7
Available Zn, mg kg^{-1}	5.9	5.4	13.5
Available Cu, mg kg^{-1}	6.3	8.8	114.2
Available B, mg kg^{-1}	0.59	0.51	1.29
Available S, mg kg^{-1}	1.3	29.0	14.3

For total organic C determination, the filtrates from both fumigated and non-fumigated samples were diluted 1:10 (2 mL extract in 8 mL HPLC-grade water). The total organic C (TOC) concentrations obtained from the analyzer, were expressed in mg L^{-1}. To account for the extraction volume (40 mL 0.5 M K_2SO_4) and the soil solution associated with the 60% WFPS-conditioned soil (6 mL, based on a 10 g soil sample-water solution system), TOC values were first converted to mg per 40 mL extract. These values were then converted to a mass basis (mg kg^{-1} dry soil), considering the total soil mass (10 g) and the dry weight fraction of the soil (DWFS = 0.4 g) corresponding to soils adjusted to 60% WFPS. Basal soil respiration was evaluated using the closed-system incubation method described by Alef and Nannipieri (1995) for each control soil and bead treatment. Briefly, 25 g soil adjusted to 60% WFPS were placed in airtight incubation flasks along with a test tube containing 7.5 mL 0.2 M NaOH to trap evolved CO_2. Control flasks containing only 7.5 mL 0.2 M NaOH were also prepared. The flasks were hermetically sealed and incubated at 22 °C for 48 h. After incubation, 1 mL NaOH solution was withdrawn, and 2 mL 1 M $BaCl_2$ were added to precipitate carbonates. The remaining NaOH was then titrated with 0.1 M HCl to the phenolphthalein endpoint (pH 8.3).

Fluorescein diacetate hydrolase (FDAse) activity was determined following a method adapted from Alef and Nannipieri (1995), based on the colorimetric quantification of fluorescein released by fluorescein diacetate (FDA) hydrolysis. For this analysis, 0.5 g soil adjusted to 60% WFPS was used per assay, with five replicates per soil and bead treatment, including a control treatment. For the FDAse assay, soil samples were placed in 10 mL test tubes containing 4.45 mL sodium phosphate buffer (pH 7.8) and 50 µL FDA. Control tubes contained 5 mL sodium phosphate buffer (pH 7.8) without soil. The tubes were incubated in a thermoshaker bath at 25 °C for 1 h with continuous agitation at 60 rpm. After incubation, the tubes were removed and placed in an ice bath to stop the enzymatic reaction. Subsequently, 5 mL acetone was added to both samples and controls, followed by vigorous shaking. The suspensions were then filtered through Whatman N°40 filter paper.

The filtrates were analyzed by absorbance using a microplate reader at 490 nm (Epoch, Software Gen5, Agilent Technologies, Santa Clara, California, USA). Absorbance values were compared against a reagent blank containing distilled water and acetone (1:1, v/v).

Dissolved organic C (DOC) was quantified using a total organic C analyzer (TOC-L, Shimadzu, Kyoto, Japan). Prior to analysis, soil extracts were filtered through 0.45 µm membrane filters. The analyzer operates on the principle of high-temperature catalytic oxidation (680 °C), converting organic C into CO_2, which is subsequently quantified using a non-dispersive infrared (NDIR) detector. Instrument calibration was performed using potassium hydrogen phthalate standards, and analytical quality was verified using blanks and certified reference solutions (Jones and Willett, 2006).

Organic amendment treatments

Three organic amendment treatments were evaluated for each soil: (1) An unamended control, (2) bio-stabilized applied at a rate of 1% (w/w), and (3) bio-stabilized applied at a rate of 2% (w/w). The bio-stabilized used in this study –pig manure and biosolids derivate of the pig industry mixed and composted during 3 to 4 mo– was obtained from Agrosuper, located in south-central Chile, and was chemically and physically characterized at the Instituto de Investigaciones Agropecuarias (INIA) Laboratory following standard procedures (Methods of Soil Analysis, 1996). The main chemical and physical properties of the organic amendment are presented in Table 2.

Table 2. Chemical characteristics of the organic amendment (Bio-stabilized) used in the experiment and supply of nutrients per pot with both rates of application. *Each pot was 100 g dry soil.

		Supply of nutrients (mg pot^{-1})*	
Parameter	Bio-stabilized (Bio)	Treatment 1 (1% w/w of Bio)	Treatment 1 (2% w/w of Bio)
Water content, %	33.70	-	-
Dry matter, %	66.30	-	-
pH$_{(soil:water,\ 1:2.5)}$	8.64	-	-
Electrical conductivity, dS m^{-1}	11.29	-	-
Organic matter, %	69.90	699.00	1398.00
Organic C, %	38.80	388.00	776.00
Total N, %	2.34	234.00	468.00
C:N ratio	16.58	-	-
N-NH_4^+, mg kg^{-1}	1640.30	16.40	32.80
N-NO_3, mg kg^{-1}	1.02	0.01	0.02
NH_4^+:NO_3^- ratio	1601.60	-	-
Total P, %	2.45	245.00	490.00
Total K, %	1.68	168.00	336.00
Total Ca, %	3.00	300.00	600.00
Total Mg, %	1.05	105.00	210.00
Total Na, %	0.51	51.00	102.00
Total Zn, mg kg^{-1}	2632.00	26.32	52.64
Total Cu, mg kg^{-1}	1103.00	11.03	22.06
Total Fe, mg kg^{-1}	4036.00	40.36	80.72
Total Mn, mg kg^{-1}	463.00	4.63	9.26
Total B, mg kg^{-1}	75.00	0.75	1.50

Soil incubation

The bio-stabilized amendment was finely ground using a mortar and pestle to pass through a < 60-mesh sieve, a procedure intended to enhance nutrient availability under controlled experimental conditions over the short incubation period. Homogenized soil samples (100 g) were placed individually into 0.25 L plastic incubation jars. The application rates for the control, bio-stabilized 1%, and bio-stabilized 2% treatments were 0, 1, and 2 g jar^{-1}, respectively. The organic amendment was thoroughly mixed with the soil, and the samples were moistened to 80% of their water-holding capacity. Soils were then incubated aerobically at 25 ± 2 °C in a refrigerated incubator (FOC 225E, Velp Scientifica, Usmate, Italy) for 30 d. The jars were left uncovered for 1 h to ensure adequate aeration, and soil moisture was adjusted gravimetrically on a weekly basis throughout the incubation period (Hirzel et al., 2009). For each soil type, treatments were arranged with four replicates.

Statistical analysis

Due to inherent differences in the physical and chemical properties of the three soils, a block experimental design was adopted, with each soil considered as a separate block. Data were analyzed using one-way and two-way ANOVA, and mean comparisons were performed using Tukey's honestly significant difference (HSD) test at a 5% significance level. All statistical analyses were conducted using SAS software version 8.0 (SAS Institute, Cary, North Carolina, USA). In addition, Pearson's correlation analysis was performed using pooled data from the three soils, resulting in a total of 36 replicates per parameter.

RESULTS

The soils used in the experiment exhibited chemical characteristics suitable for most cultivated species (Havlin et al., 2016) and showed no major limitations for biological activity, except in the clay loam soil, where Cu concentrations were high (Table 1). The chemical characteristics of the bio-stabilized amendment used in the experiment were within the typical range for composted organic amendments derived from swine production, with the exception of the ammonium-to-nitrate ratio and the concentrations of Zn and Cu, which exceeded the values recommended by the Chilean Compost Standard (NCh 2880; INN, 2004). Nutrient inputs associated with bio-stabilized applications at rates of 1% and 2% (w/w) were high, exceeding 100 mg kg^{-1} for macronutrients and 10 mg kg^{-1} for three of the five evaluated micronutrients (Table 2).

Sandy loam soil

The application of bio-stabilized at both rates affected most of the evaluated soil properties (Table 3). Notably, slight decreases were observed in soil pH, Al saturation, and available Fe ($p < 0.05$), while increases were detected in electrical conductivity (EC), cation exchange capacity (CEC), available N, P, S, Zn, Cu, Mn, and B, as well as nitrate concentrations and exchangeable Ca, Mg, K, and Na relative to the control ($p < 0.05$). Ammonium concentrations increased only at the higher bio-stabilized application rate ($p < 0.05$).

Table 3. Chemical, physical and microbiological properties of the sandy loam soil at finish of incubation time. Letters different in the same row indicate significant differences in according to Tukey test ($p < 0.05$). EC: Electrical conductivity; CEC: cation exchange capacity; FDA: fluorescein diacetate.

Parameter evaluated	Control	Bio-stabilized at rate of 1%	Bio-stabilized at rate of 2%	Significance value
$pH_{(soil:water,\ 1:2.5)}$	6.71^{a}	6.48^{b}	6.41^{c}	0.0001
EC, dS m^{-1}	0.13^{c}	0.36^{b}	0.54^{a}	0.0001
N, mg kg^{-1}	52.10^{c}	147.10^{b}	229.80^{a}	0.0001
P, mg kg^{-1}	63.30^{c}	115.80^{b}	179.90^{a}	0.0001
Ca, $cmol_+$ kg^{-1}	9.09^{ab}	9.49^{a}	8.78^{b}	0.04
Mg, $cmol_+$ kg^{-1}	1.24^{c}	2.26^{b}	3.52^{a}	0.0001
K, $cmol_+$ kg^{-1}	0.84^{c}	1.33^{b}	1.83^{a}	0.0001
Na, $cmol_+$ kg^{-1}	0.05^{c}	0.21^{b}	0.40^{a}	0.0001
Al, $cmol_+$ kg^{-1}	0.01^{a}	0.01^{a}	0.01^{a}	0.87
Al saturation, %	0.09^{a}	0.08^{b}	0.07^{b}	0.0004
CEC, $cmol_+$ kg^{-1}	16.80^{b}	18.10^{ab}	22.40^{a}	0.002
Zn, mg kg^{-1}	5.90^{c}	19.40^{b}	29.70^{a}	0.0001
Fe, mg kg^{-1}	42.10^{a}	38.60^{ab}	35.00^{b}	0.04
Cu, mg kg^{-1}	6.10^{c}	7.60^{b}	8.90^{a}	0.0001
Mn, mg kg^{-1}	4.50^{b}	5.10^{ab}	5.90^{a}	0.02
B, mg kg^{-1}	0.60^{c}	0.78^{b}	0.99^{a}	0.0001
S, mg kg^{-1}	1.30^{c}	37.30^{b}	63.00^{a}	0.0001
$N\text{-}NH_4^+$, mg kg^{-1}	4.20^{b}	8.40^{b}	24.80^{a}	0.0002
$N\text{-}NO_3^-$, mg kg^{-1}	47.90^{c}	138.70^{b}	204.90^{a}	0.0001
FDA activity, µg FDA gr^{-1}	11.90^{a}	17.00^{a}	22.70^{a}	0.11
Basal respiration, µg CO_2 g^{-1} h^{-1}	0.13^{a}	0.12^{a}	0.12^{a}	0.87
Biomass microbial C, mg kg^{-1}	40.70^{a}	62.80^{a}	68.10^{a}	0.67
Dissolved organic C, mg kg^{-1}	193.20^{a}	306.90^{a}	312.50^{a}	0.11
Humidity content at 10 kPa	32.19^{a}	32.57^{a}	32.37^{a}	0.84
Humidity content at 33 kPa	19.16^{a}	19.54^{a}	18.87^{a}	0.47
Humidity content at 100 kPa	15.21^{a}	15.96^{a}	15.35^{a}	0.08
Humidity content at 500 kPa	10.18^{a}	10.43^{a}	10.12^{a}	0.41
Humidity content at 1500 kPa	9.70^{a}	9.94^{a}	9.61^{a}	0.49
Humidity retention, %	9.46^{a}	9.60^{a}	9.27^{a}	0.23

Overall soil enzymatic activity, assessed through FDA hydrolysis, showed nonsignificant differences among treatments at the end of the incubation period ($p = 0.11$). Values ranged from 11.9 to 22.7 µg FDA g^{-1} soil, with a nonsignificant trend toward higher activity in the 2% bio-stabilized treatment. Similarly, basal soil respiration was not affected by bio-stabilized application, with comparable values between the control and amended treatments ($p = 0.87$), averaging approximately 0.12-0.13 µg CO_2 g^{-1} h^{-1}.

Microbial biomass C (MBC) also showed nonsignificant differences among treatments ($p = 0.67$). Nevertheless, a numerical increase in MBC was observed in soils amended with bio-stabilized (62.8 and 68.1 mg kg^{-1} for 1% and 2% rates, respectively) compared with the control (40.7 mg kg^{-1}). Consistently, dissolved organic C (DOC) concentrations did not differ significantly among treatments at the end of the incubation period ($p = 0.11$), although amended soils exhibited numerically higher values (306.9-312.5 mg kg^{-1}) than the control (193.2 mg kg^{-1}). Soil moisture contents determined at different matric potentials were not affected by the treatments ($p > 0.05$) (Table 3). When comparing the concentrations of nutrients that increased significantly following bio-stabilized application, using the average values of both application rates (Tables 2 and 3), the estimated nutrient retention was 60.7% for N, 54.8% for P, 0% for K, 0% for Mg, 24.5% for Na, 51.8% for Zn, 86.9% for Cu, 86.0% for Mn, and 77.0% for B.

Silt loam soil

In this soil, bio-stabilized application also affected most of the evaluated soil properties (Table 4). An erratic response in soil pH was observed, along with a slight decrease in Al saturation ($p < 0.05$) and increases in EC, CEC, available N, P, S, Zn, Fe, Cu, Mn, and B, as well as nitrate concentrations and exchangeable Ca, Mg, K, and Na compared with the control ($p < 0.05$). Ammonium concentrations increased only at the higher bio-stabilized application rate. In the silt loam soil, overall soil enzymatic activity, measured as FDA hydrolysis, did not differ significantly between the control and bio-stabilized-amended treatments at the end of the incubation period ($p = 0.76$), with values ranging from 25.3 to 30.1 µg FDA g^{-1} soil. Similarly, basal soil respiration was not significantly affected by bio-stabilized application ($p = 0.34$), although numerically higher values were observed in amended treatments (0.27-0.28 µg CO_2 g^{-1} h^{-1}) compared with the control (0.18 µg CO_2 g^{-1} h^{-1}). Microbial biomass C also showed nonsignificant differences among treatments ($p = 0.15$); however, a progressive increase in mean MBC values was observed with increasing bio-stabilized application rate, reaching 67.6 mg kg^{-1} in the 2% treatment compared with 15.1 mg kg^{-1} in the control. Dissolved organic C did not differ significantly among treatments ($p = 0.08$); however, soils amended with bio-stabilized exhibited numerically higher DOC values (291.9-342.1 mg kg^{-1}) compared with the control (203.3 mg kg^{-1}). An increase in soil water content at matric potentials of 500 and 1500 kPa was also observed, accompanied by a decrease in overall moisture retention ($p < 0.05$) (Table 4). When comparing the concentrations of nutrients that increased significantly following bio-stabilized application, using the average values of both application rates (Tables 2 and 4), the estimated nutrient retention was 68.2% for N, 89.1% for P, 4.8% for K, 83.6% for Ca, 0% for Mg, 6.8% for Na, 58.6% for Zn, 92.7% for Fe, 84.9% for Cu, 72.7% for Mn, and 86.7% for B.

Clay loam soil

The application of bio-stabilized at both rates also affected most of the evaluated soil properties (Table 5). Notably, soil pH decreased, and a slight reduction in Al saturation was observed only at the higher bio-stabilized rate, while increases were detected in EC, CEC, available N, P, S, Zn, Cu, Mn, and B, as well as ammonium and nitrate concentrations and exchangeable Ca, Mg, K, and Na relative to the control ($p < 0.05$). In the clay loam soil, overall soil enzymatic activity, assessed by FDA hydrolysis, did not differ significantly between the control and bio-stabilized-amended treatments at the end of the incubation period ($p = 0.39$), with values ranging from 11.8 to 16.0 µg FDA g^{-1} soil. Similarly, basal soil respiration was not significantly affected by bio-stabilized application ($p = 0.18$), with comparable rates across treatments (0.10-0.19 µg CO_2 g^{-1} h^{-1}). Microbial biomass C also showed nonsignificant differences among treatments ($p = 0.31$); however, numerically higher MBC values were observed in amended soils (55.1-73.7 mg kg^{-1}) compared with the control (27.9 mg kg^{-1}). Dissolved organic C showed a significant response to bio-stabilized application ($p = 0.005$), with a progressive increase associated with increasing application rate, reaching the highest value in the 2% treatment (283.4 mg kg^{-1}), which was significantly higher than that of the control (98.4 mg kg^{-1}). Soil moisture content also increased at matric potentials of 33, 500, and 1500 kPa with both bio-stabilized rates; however, a reduction in overall water retention was observed at the higher application rate ($p < 0.05$) (Table 4). When comparing the concentrations of nutrients that increased significantly following bio-stabilized application, using the average values of both application rates (Tables 2 and 5), the estimated nutrient retention was 67.0% for N, 79.4% for P, 69.8% for K, 4.6% for Ca, 0% for Mg, 9.8% for Na, 24.3% for Zn, 0% for Cu, 74.8% for Mn, and 41.6% for B.

Table 4. Chemical, physical and microbiological properties of the silt loam soil at finish of incubation time. Letters different in the same row indicate significant differences in according to Tukey test ($p < 0.05$). EC: Electrical conductivity; CEC: cation exchange capacity; FDA: fluorescein diacetate.

Parameter evaluated	Control	Bio-stabilized at rate of 1%	Bio-stabilized at rate of 2%	Significance value
pH (soil:water, 1:2.5)	6.37[a]	6.23[b]	6.34[a]	0.0005
EC, dS m^{-1}	0.11[c]	0.31[b]	0.45[a]	0.0001
N, mg kg^{-1}	48.00[c]	131.30[b]	188.40[a]	0.0001
P, mg kg^{-1}	14.80[c]	43.70[b]	65.80[a]	0.0001
Ca, $cmol_+$ kg^{-1}	6.31[b]	6.71[a]	6.65[a]	0.007
Mg, $cmol_+$ kg^{-1}	0.97[c]	2.03[b]	2.96[a]	0.0001
K, $cmol_+$ kg^{-1}	0.32[c]	0.74[b]	1.13[a]	0.0001
Na, $cmol_+$ kg^{-1}	0.08[c]	0.29[b]	0.49[a]	0.0001
Al, $cmol_+$ kg^{-1}	0.01[a]	0.01[a]	0.01[a]	0.92
Al saturation, %	0.13[a]	0.10[b]	0.09[c]	0.0001
CEC, $cmol_+$ kg^{-1}	26.40[b]	29.50[a]	29.90[a]	0.0001
Zn, mg kg^{-1}	5.60[c]	17.10[b]	26.80[a]	0.0001
Fe, mg kg^{-1}	25.90[b]	26.60[ab]	28.60[a]	0.02
Cu, mg kg^{-1}	8.80[c]	10.50[b]	12.10[a]	0.0001
Mn, mg kg^{-1}	2.50[c]	3.80[b]	5.00[a]	0.0001
B, mg kg^{-1}	0.53[c]	0.64[b]	0.72[a]	0.0002
S, mg kg^{-1}	28.60[c]	54.90[b]	93.30[a]	0.0001
N-NH_4^+, mg kg^{-1}	5.60[b]	10.60[b]	34.90[a]	0.0001
N-NO_3^-, mg kg^{-1}	42.40[c]	120.70[b]	153.50[a]	0.0001
FDA activity, µg FDA g^{-1}	30.10[a]	25.30[a]	26.90[a]	0.76
Basal respiration, µg CO_2 g^{-1} h^{-1}	0.18[a]	0.28[a]	0.27[a]	0.34
Biomass microbial C, mg kg^{-1}	15.10[a]	31.00[a]	67.60[a]	0.15
Dissolved organic C, mg kg^{-1}	203.30[a]	342.10[a]	291.90[a]	0.08
Humidity content at 10 kPa	41.88[a]	41.82[a]	42.92[a]	41.88
Humidity content at 33 kPa	25.72[a]	25.83[a]	25.78[a]	25.72
Humidity content at 100 kPa	20.24[a]	20.61[a]	20.45[a]	20.24
Humidity content at 500 kPa	13.19[b]	13.92[a]	14.46[a]	13.19
Humidity content at 1500 kPa	13.07[c]	13.59[b]	14.00[a]	13.07
Humidity retention, %	12.64[a]	12.24[ab]	11.79[b]	12.64

Table 5. Chemical, physical and microbiological properties of the clay loam soil at finish of incubation time. Letters different in the same row indicate significant differences in according to Tukey test ($p < 0.05$). EC: Electrical conductivity; CEC: cation exchange capacity; FDA: fluorescein diacetate.

Parameter evaluated	Control	Bio-stabilized at rate of 1%	Bio-stabilized at rate of 2%	Significance value
pH(soil:water, 1:2.5)	7.55^a	7.23^b	7.07^c	0.0001
EC, dS m^{-1}	0.14^c	0.36^b	0.54^a	0.0001
N, mg kg^{-1}	57.60^c	146.90^b	199.90^a	0.0001
P, mg kg^{-1}	71.10^c	122.90^b	170.90^a	0.0001
Ca, $cmol_+$ kg^{-1}	20.39^b	22.29^a	22.83^a	0.005
Mg, $cmol_+$ kg^{-1}	3.31^c	4.51^b	5.20^a	0.0001
K, $cmol_+$ kg^{-1}	0.61^c	0.78^b	1.00^a	0.0001
Na, $cmol_+$ kg^{-1}	0.19^c	0.39^b	0.59^a	0.0001
Al, $cmol_+$ kg^{-1}	0.01^a	0.01^a	0.01^a	0.77
Al saturation, %	0.04^a	0.04^a	0.03^b	0.007
CEC, $cmol_+$ kg^{-1}	30.19^a	32.09^a	32.74^a	0.11
Zn, mg kg^{-1}	13.50^c	36.80^b	50.00^a	0.0001
Fe, mg kg^{-1}	28.20^a	27.90^a	27.40^a	0.39
Cu, mg kg^{-1}	111.80^c	123.80^b	145.70^a	0.0002
Mn, mg kg^{-1}	4.80^c	5.70^b	7.40^a	0.0001
B, mg kg^{-1}	1.40^c	1.86^b	2.26^a	0.001
S, mg kg^{-1}	14.50^c	34.20^b	64.80^a	0.0001
N-NH_4^+, mg kg^{-1}	6.30^b	7.40^a	8.50^a	0.003
N-NO_3^-, mg kg^{-1}	51.30^c	139.40^b	191.40^a	0.0001
FDA activity, µg FDA g^{-1}	11.80^a	15.10^a	16.00^a	0.39
Basal respiration, µg CO_2 g^{-1} h^{-1}	0.17^a	0.19^a	0.10^a	0.18
Biomass microbial C, mg kg^{-1}	27.90^a	73.70^a	55.10^a	0.31
Dissolved organic C, mg kg^{-1}	98.40^b	188.90^{ab}	283.40^a	0.005
Humidity content at 10 kPa	30.62^a	30.63^a	30.36^a	0.89
Humidity content at 33 kPa	21.44^c	23.04^b	23.36^a	0.0001
Humidity content at 100 kPa	16.56^b	17.42^{ab}	18.10^a	0.008
Humidity content at 500 kPa	12.93^c	15.28^b	16.59^a	0.0001
Humidity content at 1500 kPa	11.92^c	14.03^b	15.48^a	0.0001
Humidity retention, %	9.52^a	9.01^a	7.87^b	0.004

Pearson correlation analysis

Correlation analysis revealed several well-established relationships among soil chemical properties, such as the significant positive correlations between soil pH and the cations Ca and Mg, as well as the negative correlations between pH and both exchangeable Al and Al saturation (Table 6). Therefore, emphasis is placed here on the relationships involving microbiological properties and soil moisture retention. The FDA hydrolytic activity showed significant negative correlations with soil pH and with the concentrations of the metallic cations Cu and Zn, as well as with B concentration ($p < 0.05$). In contrast, FDA activity was positively correlated with exchangeable Al, Al saturation, available S, and ammonium, indicating a close association with variables related to soil acidity and mineral N availability (Table 6). Basal soil respiration exhibited significant negative correlations with available P and Fe concentrations ($p < 0.05$), suggesting a limited respiratory response to increases in these nutrients under the evaluated incubation conditions.

The MBC was positively correlated with total N, available P, exchangeable K, Zn, Mn, EC, and nitrate concentrations ($p < 0.05$), reflecting a direct relationship between microbial biomass size and soil nutritional status. The DOC showed significant negative correlations with soil pH and with Ca and Cu concentrations ($p < 0.05$). In contrast, DOC was positively correlated with the concentrations of N, K, S, ammonium, nitrate, EC, and FDA activity ($p < 0.05$), highlighting its role as a labile C fraction closely associated with nutrient availability and microbial C processing (Table 6). Soil moisture contents measured at matric potentials of 10, 33, 100, 500, and

1500 kPa exhibited different correlation patterns with soil chemical properties (Table 6). However, a consistent effect was observed for soil moisture at 10, 33, and 100 kPa (associated with macropore space), which showed negative correlations with available P and Mn concentrations (p < 0.05) and positive correlations with FDA activity and basal respiration (p < 0.05).

Table 6. Pearson's correlation for the parameters evaluated in the three soils. SatAl: Al saturation; EC: electrical conductivity; CEC: cation exchangeable capacity: NO_3^-: nitrate; NH_4^+: ammonia; FDA: fluorescein diacetate hydrolase (FDAse) activity; BR: basal respiration; MBC: microbial biomass C: DOC: dissolved organic C; soil humidity at 10, 33, 100, 500, and 1500 kPa; HR: humidity retention.

	pH	N	P	K	Ca	Mg	Na	Al	Sat Al	Zn	Fe	Cu	Mn	B	S	EC	CEC	NO_3	NH_4	FDA	BR	MBC	DOC	10 kPa	33 kPa	100 kPa	500 kPa	1500 kPa	HR
pH		0.91	-0.22	-0.22	0.91	0.97	0.98	-0.22	-0.21	0.36	-0.15	0.27	0.44	0.34	-0.42	0.97	0.98	0.99	-0.42	-0.27	-0.31	0.48	0.33	-0.72	-0.12	-0.01	0.22	0.13	-0.12
N	0.21		0.75	0.76	0.78	0.64	0.68	-0.35	-0.35	0.75	-0.86	0.05	0.88	0.34	0.58	0.97	0.71	0.99	0.95	0.16	-0.39	0.45	0.67	-0.57	-0.36	-0.01	0.28	0.07	-0.29
P	0.12	0.0001		0.15	0.45	0.74	0.64	-0.71	-0.71	0.76	0.15	0.41	0.88	0.34	0.32	0.76	0.02	0.81	0.15	-0.17	-0.29	0.38	0.42	-0.57	-0.52	-0.24	0.02	-0.08	-0.29
K	0.21	0.0001	0.0001		0.63	0.33	0.44	-0.21	-0.21	0.41	0.61	-0.25	0.55	0.66	0.45	0.75	-0.35	0.77	0.57	-0.18	-0.21	0.41	0.47	-0.27	-0.35	-0.48	-0.41	-0.45	-0.39
Ca	0.0001	0.63	0.63	0.33		0.8	0.33	-0.33	-0.91	0.61	-0.33	0.85	0.82	0.86	-0.17	0.15	0.54	0.15	-0.36	-0.48	-0.21	0.30	-0.26	-0.72	-0.11	-0.13	0.53	0.41	0.73
Mg	0.0001	0.0001	0.0001	0.53	0.0001		0.85	-0.85	-0.86	0.22	-0.32	0.21	0.85	0.21	0.41	0.25	0.55	0.85	0.18	-0.25	-0.11	0.32	0.38	0.53	-0.34	-0.12	0.57	0.56	-0.67
Na	0.55	0.0001	0.0001	0.007	0.63	0.0001		-0.35	-0.91	0.92	-0.77	0.47	0.74	0.62	0.82	0.99	0.61	0.15	0.53	0.53	0.27	0.92	0.35	-0.03	0.13	0.12	0.52	0.58	-0.33
Al	0.0001	0.55	0.0001	0.09	0.0001	0.0001	0.0001		0.55	-0.85	0.64	-0.45	-0.81	-0.85	0.001	-0.41	-0.33	-0.41	0.12	0.52	0.25	-0.24	0.01	0.05	0.02	0.07	0.11	0.38	0.39
Sat Al	0.0001	0.59	0.0001	0.12	0.0001	0.0001	0.0001	0.0001		-0.85	0.64	-0.85	-0.81	-0.81	0.001	-0.41	-0.35	-0.41	0.13	0.53	0.23	-0.24	0.21	0.01	0.24	0.15	-0.33	-0.33	0.55
Zn	0.11	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001		-0.27	0.62	0.86	0.81	0.55	0.55	0.52	0.35	0.27	-0.11	-0.32	0.15	0.39	-0.25	0.06	0.11	0.53	0.53	-0.39
Fe	0.11	0.11	0.33	0.006	0.11	0.86	0.05	0.79	0.79	0.11		-0.42	0.14	-0.31	-0.59	-0.24	-0.55	-0.05	-0.07	-0.31	-0.35	0.12	0.36	-0.39	-0.78	-0.72	-0.77	-0.79	-0.39
Cu	0.0001	0.22	0.11	0.18	0.0001	0.0001	0.074	0.0001	0.0001	0.0001	0.11		0.86	0.86	-0.26	0.18	0.67	0.15	-0.31	-0.41	-0.12	0.28	-0.34	-0.38	0.06	-0.38	0.57	0.56	-0.52
Mn	0.01	0.0001	0.0001	0.0004	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.41	0.0001		0.76	0.66	0.76	0.11	0.72	0.15	-0.34	-0.31	0.32	0.14	-0.64	-0.64	-0.33	0.17	0.17	-0.32
B	0.0001	0.04	0.0001	0.88	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.054	0.0001	0.0001		0.14	0.48	0.55	0.41	-0.12	-0.32	-0.34	0.07	-0.55	-0.44	-0.43	-0.18	0.43	0.51	-0.73
S	0.11	0.0001	0.08	0.208	0.35	0.355	0.0001	0.99	0.99	0.0001	0.05	0.72	0.72	0.75		0.83	0.41	0.76	0.81	0.42	0.22	0.35	0.55	0.42	0.45	0.49	0.51	0.44	0.56
EC	0.37	0.0001	0.0001	0.0001	0.35	0.0001	0.0001	0.025	0.125	0.0001	0.75	0.72	0.728	0.729	0.0001		0.23	0.27	0.82	0.88	-0.11	0.33	0.33	-0.14	-0.45	-0.39	0.55	0.22	-0.37
CEC	0.02	0.22	0.31	0.06	0.0001	0.0001	0.0001	0.02	0.06	0.0001	0.0001	0.0001	0.22	0.0001	0.0001	0.15		0.21	0.12	0.12	0.31	0.01	-0.07	0.14	0.59	0.59	0.59	0.39	0.29
NO_3	0.54	0.0001	0.0001	0.0001	0.97	0.0001	0.0001	0.39	0.01	0.0001	0.75	0.34	0.0001	0.0001	0.0001	0.0001	0.11		0.54	0.11	-0.05	0.24	0.55	-0.15	-0.09	-0.05	0.21	0.23	-0.29
NH_4	0.01	0.0001	0.25	0.0003	0.29	0.29	0.0008	0.47	0.47	0.12	0.56	0.76	0.28	0.28	0.0001	0.0001	0.48	0.0007		0.54	0.24	0.26	0.54	0.55	0.18	0.22	0.22	0.25	0.21
FDA	0.0001	0.95	0.12	0.5	0.955	0.15	0.79	0.0008	0.0008	0.56	0.07	0.02	0.06	0.02	0.01	0.31	0.48	0.54	0.02		0.11	-0.01	0.41	0.56	0.48	0.52	0.59	0.17	0.41
BR	0.32	0.95	0.02	0.21	0.19	0.19	0.98	0.55	0.56	0.46	0.04	0.36	0.07	0.18	0.18	0.38	0.07	0.75	0.15	0.15		0.06	0.36	0.33	0.47	0.31	0.22	0.56	0.46
MBC	0.85	0.309	0.01	0.01	0.35	0.16	0.04	0.15	0.15	0.04	0.47	0.65	0.65	0.22	0.18	0.02	0.85	0.095	0.12	0.15	0.74		0.31	-0.15	-0.15	-0.13	0.02	-0.07	-0.18
DOC	0.0001	0.0001	0.02	0.004	0.06	0.35	0.55	0.25	0.22	0.39	0.72	0.64	0.42	0.25	0.0005	0.001	0.71	0.0005	0.007	0.02	0.39	0.07		0.32	0.13	0.21	-0.002	0.07	0.34
10 kPa	0.0001	0.58	0.0001	0.11	0.0001	0.0005	0.65	0.55	0.0001	0.06	0.02	0.0001	0.0001	0.0001	0.0001	0.41	0.42	0.32	0.02	0.0001	0.001	0.39	0.36		0.74	0.83	0.24	0.27	0.92
33 kPa	0.82	0.76	0.006	0.0008	0.22	0.82	0.14	0.47	0.06	0.71	0.0001	0.71	0.74	0.25	0.098	0.79	0.0001	0.64	0.34	0.053	0.204	0.31	0.44	0.0001		0.57	0.74	0.32	0.56
100 kPa	0.06	0.55	0.0007	0.003	0.13	0.44	0.15	0.06	0.006	0.96	0.0001	0.62	0.02	0.56	0.096	0.92	0.0001	0.76	0.17	0.021	0.001	0.21	0.21	0.0001	0.0001		0.63	0.74	0.72
500 kPa	0.88	0.07	0.55	0.05	0.0003	0.0003	0.0001	0.25	0.25	0.0001	0.0001	0.0001	0.11	0.0001	0.02	0.14	0.0001	0.31	0.35	0.31	0.21	0.61	0.55	0.41	0.0001	0.0001		0.53	-0.003
1500 kPa	0.35	0.33	0.33	0.006	0.02	0.065	0.0001	0.54	0.25	0.001	0.0001	0.0001	0.22	0.041	0.007	0.19	0.0001	0.31	0.75	0.31	0.71	0.71	0.69	0.11	0.0001	0.0001	0.0001		0.11
HR	0.0001	0.38	0.0001	0.02	0.0001	0.0001	0.04	0.25	0.0001	0.0001	0.259	0.0401	0.0499	0.0001	0.15	0.02	0.25	0.20	0.21	0.0001	0.204	0.15	0.41	0.0001	0.0001	0.0001	0.29	0.22	

Available S was positively correlated with soil moisture across all matric potentials, whereas available Fe showed a negative correlation (p < 0.05) and also negatively affected overall water retention (Table 6). Potassium concentration negatively affected soil moisture at matric potentials ranging from 33 to 1500 kPa and was also negatively correlated with overall water retention (p < 0.05). In contrast, Ca and Mg concentrations were positively correlated with soil moisture at 500 and 1500 kPa (associated with micropore space) but negatively correlated with overall water retention (p < 0.05). The CEC was positively correlated with soil moisture at matric potentials between 33 and 1500 kPa (p < 0.05). Regarding correlations among soil moisture values at different matric potentials, as expected, positive correlations were observed among moisture contents at 10-100 kPa (associated with macropore space). In addition, soil moisture at 33 kPa was positively correlated with moisture contents at 100-1500 kPa and with overall water retention (p < 0.05) (Table 6). Soil moisture at 100 kPa was also positively correlated with moisture contents at 500 and 1500 kPa (p < 0.05). Finally, as expected, a positive correlation was observed between soil moisture at 500 and 1500 kPa, reflecting the behavior of water retained in micropore spaces.

DISCUSSION

The beneficial effects of organic amendment application on soil chemical properties have been broadly reported in the literature (Luo et al., 2018; Omokaro et al., 2024) and are primarily associated with nutrient inputs provided by the amendment, as well as with the effects of added C and nutrients on soil biological and biochemical properties. These inputs stimulate oxidative processes that enhance nutrient mineralization and availability and contribute stable organic compounds that increase cation exchange capacity (CEC). Consequently, the increase in nutrient availability directly influences electrical conductivity (EC), and the observed rise in EC values with increasing bio-stabilized application rates was therefore expected. The increase in EC was more pronounced in the sandy loam soil, which can be attributed to its lower CEC and lower clay and organic matter (OM) contents (Fageria and Nascente, 2014; Havlin et al., 2016). Nevertheless, EC values resulting from bio-stabilized application at both rates remained within agronomically acceptable ranges for cultivated plants (Havlin et al., 2016). Similarly, the greatest increases in available N, P, and K were observed in the sandy loam soil, due to its lower capacity for N stabilization (associated with lower OM content and basal respiration) and reduced capacity for P fixation (clay-Al-humic complexes) and K retention (clay minerals) (Fageria and Nascente, 2014; Havlin et al., 2016). As expected, the highest K fixation occurred in the clay loam soil, reflecting its higher CEC and clay content (Fageria and Nascente, 2014; Havlin et al., 2016). Across all three soils, nitrate predominated over ammonium, which is typical of soil incubation under aerobic conditions that favor nitrification of mineralized N (ammonium) (Bhaduri et al., 2022). The decrease in Al saturation observed in all soils following bio-stabilized application was also expected and is associated with increased concentrations of K, Mg, and Na resulting from amendment application, as well as increased Ca concentrations in the silt loam and clay loam soils (Fageria and Nascente, 2014).

In the three evaluated soils, no Mg fixation was observed following bio-stabilized application, likely due to the continuous release of H^+ ions associated with redox processes (Fageria and Nascente, 2014; Omokaro et al., 2024). These processes promote soil acidification and cation exchange, thereby enhancing Mg availability.

In contrast, Ca fixation was observed primarily in the silt loam soil, where K fixation was very low. Conversely, Ca fixation was limited in the clay loam soil, where K fixation was high. This behavior can be attributed to the clay content and mineralogy of the clay loam soil, dominated by 1:1 clay minerals, which favor K fixation and enhance the availability of other cations (Fageria and Nascente, 2014; Havlin et al., 2016).

Sodium exhibited generally low fixation across all three soils, which is consistent with its large hydrated ionic radius under moist conditions and its weak retention in soil exchange sites (Havlin et al., 2016). Zinc showed moderate fixation in the sandy loam and silt loam soils but low fixation in the clay loam soil. Although higher Zn fixation would be expected in soils with greater clay content, the elevated Cu concentration in the clay loam soil likely reduced Zn fixation due to competitive interactions at sorption sites (Xia et al., 2007; Cheng et al., 2018; Gong et al., 2020).

With respect to Mn, a high level of fixation was observed in all three soils, being quantitatively greater in the sandy loam soil, likely associated with the higher activity of the applied OM amendment in this soil (lower CEC and OM content), which facilitates the formation of organo-mineral ligands with soil metals (Omokaro et al., 2024). Iron (Fe) exhibited fixation only in the silt loam soil, probably due to the high concentration of this element in the sandy loam soil (lower fixation capacity) and the elevated Cu concentration in the clay loam soil, which generates competition for the fixation of metallic micronutrients (Havlin et al., 2016; Cheng et al., 2018; Feng et al., 2022). Regarding Cu, a high degree of fixation was observed in the sandy loam and silt loam soils, exceeding that observed for the other cationic micronutrients. In this regard, Cheng et al. (2018) report that Cu fixation in soils is greater than that of Zn. Although greater Cu fixation would have been expected in the clay loam soil, the high concentration observed in this soil may indicate saturation of Cu fixation sites, resulting in increases in Cu concentration directly proportional to the applied dose (Havlin et al., 2016). Furthermore, increasing soil pH, as observed in the clay loam soil condition, enhances the fixation of Fe, Zn, and Mn, whereas it has little effect on Cu fixation (Penney, 2002; Havlin et al., 2016; Reyes et al., 2020). Regarding B, high fixation was observed in the sandy loam and silt loam soils, while an intermediate value was recorded in the clay loam soil. This is likely associated with the greater decrease in pH in the clay loam soil following the application of the organic amendment, which induced acidification and promoted greater solubilization from Fe oxides, Mg hydroxide, clay minerals, and Ca carbonate (Goldberg, 1997; Havlin et al., 2016). The correlations obtained among the analyzed chemical properties were largely as expected, given the well-documented directly proportional relationship between pH and the cations Ca and Mg (increased relative concentration of OH^- and decreased concentration of H^+), as well as the inverse relationship between pH and exchangeable Al, Al saturation, and available S (Fageria and Nascente, 2014; Havlin et al., 2016). Likewise, the strong correlations observed between available N and its ammoniacal and nitrate fractions were also anticipated; however, the highest correlation was found between available N and nitrate N, which is typical in soils amended with OM and incubated under aerobic conditions, as these conditions favor nitrification processes (Butterly et al., 2013; Havlin et al., 2016; Bhaduri et al., 2022).

Those elements present in the applied OM generally exhibited positive correlations, since the mineralization of carbonaceous compounds and the solubilization of chemical constituents contained in the organic amendment led to an increase in the concentration of most nutrients (Scotti et al., 2015; Omokaro et al., 2024). The negative correlation observed between S and Fe may be explained by the formation of stable chemical compounds such as pyrite (FeS_2) (Fageria and Nascente, 2014). In turn, the cationic micronutrients, with the exception of Fe, showed positive correlations among themselves, which is associated with the nutrient input from the organic amendment and the pH decrease generated by redox reactions and OM mineralization (Butler et al., 2001; Silva et al., 2016; Omokaro et al., 2024). In the case of Fe, a negative correlation with Cu was observed, which may be attributed to fixation processes in different chemical or organic compounds in the soil as the availability of either cation increases (Havlin et al., 2016; Cheng et al., 2018; Feng et al., 2022). The negative correlation between Fe and B may be explained by B fixation on Fe oxides (Goldberg, 1997; Havlin et al., 2016). The EC was only affected by Al concentration, which can be explained by the fact that Al promotes precipitation or chemical reactions that reduce the availability of certain nutrients (Fageria and Nascente, 2014; Havlin et al., 2016). Conversely, CEC generally showed a positive correlation with most nutrients, associated with their greater availability and the increase in active negative charge resulting from the application of organic compounds.

The negative correlation between CEC and K can be explained by the greater intensity of fixation of divalent cations such as Ca and Mg on cation exchange sites, which may lead to the retrogradation of available K (Fageria and Nascente, 2014; Havlin et al., 2016). Exchangeable Al and available Fe showed a negative correlation with CEC, associated with the formation of stable organo-chemical compounds between organic molecules and Al or Fe, which reduce the generation of exchangeable charge (Fageria and Nascente, 2014; Havlin et al., 2016). The positive correlation observed between nitrate and most nutrients is associated with their supply through the organic amendment, as well as with their increased availability under aerobic conditions. In contrast, the negative correlation between nitrate and Al may be related to reducing conditions or increased acidity, both of which negatively affect nitrification (Havlin et al., 2016; Bhaduri et al., 2022). Ammonium also exhibited a positive correlation with most of the evaluated nutrients, which was expected based on the previously discussed evidence; however, a negative correlation with soil pH was observed, since soil acidity negatively affects N mineralization and, consequently, ammonium formation (Havlin et al., 2016; Bhaduri et al., 2022).

The results obtained show that the application of the bio-stabilized material produced clear improvements in soil chemical properties (nutrients and EC) across the three evaluated textures; however, the responses of microbiological indicators were more moderate. This aligns with recent studies that caution that biological responses may be slower or more context-dependent compared to the more immediate chemical responses following amendment application. In particular, enzymatic activity measured by fluorescein diacetate (FDA) hydrolysis and basal soil respiration did not show significant differences among treatments in any of the soils, suggesting that these integrated processes of the microbial community may be less sensitive to rapid changes in nutrient availability or soil chemistry under short-term incubation conditions. This pattern has been reported in other studies in which microbiological activity responds more slowly than chemical indicators to changes in organic amendment application (Semenov et al., 2025).

The numerical increase in microbial biomass C (MBC) following bio-stabilized amendment application, although nonsignificant in all cases, is consistent with evidence that MBC reflects the mass of active microorganisms and is closely linked to the availability of organic substrates and soil nutrients (Zhang et al., 2024). Furthermore, the patterns observed in dissolved organic C, particularly the significant increase in the fine-textured soil, are in line with the notion that labile fractions of organic C respond positively to the addition of organic amendments and may be modulated by soil texture and the retention capacity of these soils (Kalbitz et al., 2005).

Overall, these results underscore the importance of considering multiple microbiological and chemical indicators when assessing soil quality, as some parameters, such as dissolved organic C (DOC), may respond more rapidly than others (e.g., enzymatic activities or basal respiration) to changes induced by organic amendments. This integrated approach is essential for a more comprehensive evaluation of soil health, as proposed in recent reviews on soil bioindicators (Semenov et al., 2025).

The changes reported in soil moisture retention following the application of the bio-stabilized amendment demonstrate that the effect of organic amendments on water dynamics is highly dependent on soil texture and pre-existing physical constraints. In the sandy loam soil, dominated by macropores, nonsignificant changes in water content were detected across the entire range of evaluated tensions, suggesting that, under the conditions of this experiment, amendment incorporation was insufficient to substantially modify pore size distribution. Previous studies (Hudson, 1994; Rawls et al., 2003) have highlighted that in coarse-textured soils, moderate increases in OM do not always translate into measurable improvements in water-holding capacity due to inherent structural limitations.

In contrast, in the silt loam and clay loam soils, the application of the bio-stabilized amendment significantly increased the water content retained at high tensions (500 and 1500 kPa), which are primarily associated with the dominance of micropores. This effect was more pronounced in the clay loam soil, where both amendment rates increased water retention from 33 kPa onwards, reflecting a greater capacity to store strongly retained water. In this regard, Rawls et al. (2003) and Lal (2020) emphasize that OM promotes the formation and stabilization of micropores, thereby enhancing the total water storage capacity of soils.

However, the increase in water retention at high tensions in fine-textured soils was accompanied by a reduction in water retained at lower tensions, particularly at the highest rate of bio-stabilized amendment. This result suggests a relative shift of the fraction of water readily available to plants from intermediate pores toward micropores, thereby reducing this readily available fraction. This type of non-linear response has been widely documented and is attributed to changes in soil structural organization induced by OM incorporation, whereby improvements in water storage may occur at the expense of physical quality related to the soil water-air balance (Dexter, 2004; Bronick and Lal, 2005).

From the perspective of precision irrigation, these findings are particularly relevant. In irrigation systems that wet a limited volume of soil, such as drip or microsprinkler irrigation, most root activity is concentrated within the wetted bulb; therefore, pore size distribution governs both water availability and oxygen diffusion to roots (Hillel, 1998). In fine-textured soils, where water retention at high tensions is naturally elevated, the main constraint under localized irrigation is often not water availability but rather inadequate aeration of the root system, particularly when high irrigation frequencies are used. This aspect is especially critical in crops sensitive to root hypoxia, for which poor soil aeration has been shown to reduce root growth and functionality, as well as physiological processes associated with water and nutrient uptake, even under apparently adequate soil moisture conditions, particularly in intensive systems under localized irrigation (Ruperti et al., 2019; Pérez-Jiménez and Pérez-Tornero, 2021).

In this context, in clay or clay loam soils under precision irrigation, the use of organic amendments should primarily aim to improve soil structure and aeration, promoting post-irrigation drainage and oxygen diffusion, rather than increasing water storage capacity. The reduction in moisture retention observed with the highest rate of the bio-stabilized amendment may be interpreted as a potentially favorable effect in terms of soil aeration, provided that it does not severely compromise water availability for the crop. Conversely, in coarse-textured soils, where the main limitation under precision irrigation is low water-holding capacity and rapid percolation, the focus is on increasing water storage within the wetted bulb and reducing irrigation frequency. In such cases, although nonsignificant changes in moisture retention were detected in the present study, repeated applications of organic amendments over time have been associated with gradual improvements in water-holding capacity and in the stability of water supply, thereby contributing to greater flexibility in irrigation scheduling (Hudson, 1994; Lal, 2020).

CONCLUSIONS

The application of the organic amendment bio-stabilized at rates of 1% and 2% w/w improved chemical properties in the three evaluated soils, achieving agronomically adequate levels of nutrient availability and electrical conductivity. At the same time, in two of these soils it enhanced water retention at tensions corresponding to different pore spaces. The microbiological properties assessed were quantitatively improved with the application of bio-stabilized; however, a significant effect on dissolved organic C was observed in only one of the soils. Therefore, the use of this organic amendment at the evaluated rates enables the improvement of soil properties, which has positive agronomic implications and may contribute to enhancing the productivity of different crops, while also representing a viable alternative to conventional fertilizers.

Author contributions

Conceptualization: J.H., J.D. Methodology: J.H., J.D. Software: J.H. Validation: J.H. Formal analysis: J.H. Investigation: J.H., J.D. Resources: J.H., J.D. Data curation: J.H. Writing-original draft: J.H. Writing-review & editing: J.H. Visualization: J.H. Supervision: J.H. Project administration: J.H., J.D. Funding acquisition: J.D. All co-authors reviewed the final version and approved the manuscript before submission.

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