JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2027, 28(1), 380–388
https://doi.org/10.12911/22998993/242091
ISSN 2299–8993, License CC-BY 4.0

Received: 2026.09.27
Accepted: 2026.11.16
Published: 2026.12.01

Effects of *Bacillus albus* and *Bacillus wiedmannii* and compost on nitrogen fractions and physicochemical properties of agricultural soil

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ABSTRACT

Excessive use of nitrogen fertilizers can alter soil nitrogen fractions and physicochemical properties. This study aimed to evaluate changes in nitrogen fractions and physicochemical properties of agricultural soil following the application of *Bacillus albus*, *Bacillus wiedmannii*, and a consortium of both species, combined with two compost doses. A completely randomized design with a 3 × 2 factorial arrangement was used, comprising three bacterial treatments and two compost doses (800 and 1200 g), with three replicates per treatment. Total nitrogen, nitrate, nitrite, ammonium, pH, and electrical conductivity were measured at the beginning and after 60 days. Total nitrogen decreased from 1689.24 mg/kg to 485.57–528.61 mg/kg, corresponding to reductions of 68.71–71.26%. The bacterial consortium with 800 g of compost showed the largest numerical reduction (71.26%), although Tukey's test did not detect statistically significant differences among treatment means. In contrast, nitrate increased from 52.63 to 217.50–403.97 mg/kg, with significant effects of bacterial treatment, compost dose, and their interaction ($p < 0.0001$). Soil pH decreased from 7.21 to 5.70–6.38, while electrical conductivity increased from 85 to 237.67–590.33 µS/cm. The results show changes in soil nitrogen fractions and physicochemical properties across the evaluated combinations. However, the absence of uninoculated control treatments and a nitrogen balance prevents determining the specific contribution of the bacteria to the reduction in total nitrogen.

Keywords: bioremediation, *Bacillus*, nitrogen fertilizers, soil contamination, compost.

INTRODUCTION

According to the Food and Agriculture Organization of the United Nations (FAO, 2026), global production of inorganic fertilizers reached 216 million tonnes of nutrients in 2024, of which nitrogen accounted for 57.7%. In the same year, agricultural use of nitrogen fertilizers reached 115 million tonnes of nitrogen. Among nitrogen fertilizers, urea remains one of the most widely used because of its high nitrogen content (46%) and commercial availability (FAO, n.d.).

Intensive use of these fertilizers triggers a cascade of adverse effects on soil. In addition to increasing nitrous oxide (N_2O) emissions and promoting nitrate (NO_3^-) leaching (Hale et al., 2023), it acidifies the substrate and destabilizes microbial communities, including nitrogen-fixing bacteria such as *Rhizobium* and *Azospirillum*. These changes reduce both the functional diversity of the soil ecosystem (Castro-Landin et al., 2023) and the buffering capacity of the cation-exchange complex and the Shannon diversity index (Dong et al., 2026).

Excess nitrogen inputs also contribute to eutrophication and greenhouse-gas emissions, with consequences for water and soil quality (Dissanayake et al., 2026; Nuruzzaman et al., 2025).

Under this scenario, bioremediation has emerged as a sustainable alternative to

conventional chemical treatments, which can be costly and may generate secondary residues. Bioremediation takes advantage of the natural capacity of microorganisms and plants to transform contaminants into less harmful compounds without introducing additional risks to the ecosystem (Alori et al., 2022; Tang et al., 2026), and it has become a viable option for restoring degraded soils (Escobar et al., 2026).

Within this group of microorganisms, the genus Bacillus, composed of Gram-positive rod-shaped bacteria belonging to the phylum Bacillota (Alotaibi et al., 2021), is particularly notable for its ability to sporulate and tolerate extreme environmental conditions. These traits support the diversity of mechanisms by which Bacillus species can degrade or immobilize contaminants (Zambrano-Solórzano et al., 2024).

Gogoi et al. (2021) reported that *Bacillus albus* ASSF01 reduced ammonium concentrations from 3.2 to 0.5 mg/L and nitrite concentrations from 0.30 to 0.01 mg/L during aquaculture effluent treatment. Rashid et al. (2025) identified traits associated with nitrogen fixation, salt tolerance, and plant growth promotion in *Bacillus wiedmannii* RR2. Similarly, Zhang et al. (2022) documented heterotrophic nitrification and aerobic denitrification in strains of the genus *Bacillus*. These findings provide a basis for evaluating both species in agricultural soils, considering that their responses to different nitrogen forms may vary depending on substrate characteristics and experimental conditions.

The responses of these species, applied separately or as a consortium and combined with different compost doses, remain insufficiently documented in soils affected by nitrogen fertilizers. This study evaluated changes in soil nitrogen fractions and physicochemical properties under these experimental combinations.

MATERIALS AND METHODS

Location

The study was conducted in the conventional area of the Environmental Engineering Program at the Escuela Superior Politécnica Agropecuaria de Manabí Manuel Félix López (ESPAM MFL), located at El Limón site, Bolívar canton, Manabí province, Ecuador. The experimental area is located at 0°49′04″ S and 80°00′56″ W, at an altitude of 15 m above sea level. The local climate has an annual average temperature ranging from 21.65 to 30.79 °C and mean annual precipitation of 998 mm. The plot used for the experiment had historically been subjected to continuous application of chemical products.

Materials used

Bacillus albus and *Bacillus wiedmannii* strains were used as bacterial inoculants, both individually and as a microbial consortium. The microorganisms originated from Antarctica and were isolated and preserved in the ESPAM MFL strain bank. The substrate consisted of soil contaminated with nitrogen fertilizers, collected at a depth of 20–30 cm, homogenized, and partially sterilized by autoclaving at 121 °C for 60 min in two cycles. Physicochemical characterization indicated a sandy-loam texture, low organic-matter content, and pH between 6.5 and 7.5.

Study factors

Two study factors were established: bacterial application type (Factor B) and compost dose (Factor C). The levels corresponding to each factor are presented in Table 1.

Experimental design

The experiment used a completely randomized design with a 3 × 2 bifactorial arrangement, combining the three levels of Factor B and the two levels of Factor C. The factorial combination produced six treatments, each with three replicates, for a total of 18 experimental units randomly distributed. Each unit consisted of a plastic container measuring 61.3 cm in height and 44.5 cm in width and filled with 20 kg of contaminated soil. The

Table 1. Study factors and levels evaluated

Factor	Code	Level
Bacteria	B1	*Bacillus wiedmannii*
Bacteria	B2	*Bacillus albus*
Bacteria	B3	Consortium (*B. albus* + *B. wiedmannii*)
Compost	C1	800 g per experimental unit
Compost	C2	1200 g per experimental unit

Note: Compost dose corresponds to the total amount applied to each experimental unit containing 20 kg of soil, not to a proportion per kilogram of soil.

units were transferred to the ESPAM MFL orchid house and kept covered under controlled conditions. The analysis focused on comparing variations in soil physicochemical properties among the six evaluated combinations of bacterial treatments and compost doses.

Description of treatments

The treatments are detailed in Table 2 according to the bacterial inoculation applied. Treatments T1 and T2 corresponded to *Bacillus wiedmannii*, T3 and T4 to *Bacillus albus*, and T5 and T6 to the consortium of both species.

Compost amendment

BIOFERTIL (Eco Alternativas, Ecuador), used as an organic amendment, contained 1.44% total nitrogen, 45.30% organic matter, and 23.00% organic carbon, according to the manufacturer's label, with an estimated C/N ratio of 16:1. The amendment was incorporated once at doses of 800 and 1200 g per 20 kg of soil, corresponding to nominal nitrogen inputs of 11.52 and 17.28 g, respectively.

Bacterial bioaugmentation

The bacterial inoculum was prepared in 20 L containers by combining 10 L of molasses and 6 L of water, leaving an 8 cm headspace to control foam formation and gases generated during fermentation. The containers were subsequently sealed and left to ferment for 10 days. Treatment application began on 19 December 2025 using 2 L manual compression sprayers. For individual bacterial treatments, 2.53 mL of the fermented mixture was diluted in 500 mL of water. For consortium treatments, 1.26 mL of each fermented bacterial mixture was combined and diluted in 500 mL of water.

Considering the 20 kg of soil per experimental unit, the inoculation dose was 0.1265 mL/kg for treatments with a single bacterial species. For the consortium, 0.063 mL/kg of each bacterial preparation was used at a 1:1 volumetric ratio. Applications were performed every 15 days, for a total of four inoculations during the experimental period.

Variables

The evaluated soil physicochemical variables are presented in Table 3. Total nitrogen determination was described using the modified Kjeldahl principle (ISO 11261:1995), whereas nitrate, nitrite, and ammonium determinations were referenced to soil extraction and instrumental analysis procedures (ISO 14256-2:2005). Soil pH and electrical conductivity were assessed using potentiometric and conductometric principles, respectively, as documented in Ecuadorian soil laboratory procedures (MAGAP, 2015). Nitrogen concentrations were expressed in mg/kg and electrical conductivity in µS/cm.

The percentage reduction in total nitrogen was calculated using Equation 1:

$$PR\ (\%) = [(C_0 - C_f) / C_0] \times 100 \qquad (1)$$

where: PR is percentage reduction (%), C_0 is the common initial total nitrogen reference concentration (1689.24 mg/kg; Table 4), and C_f is the final concentration (mg/kg; Table 5). These percentages were interpreted descriptively.

Statistical analysis

The recorded variables were subjected to bifactorial analysis of variance (ANOVA) to evaluate the individual and interactive effects of Factor B (Bacillus strains) and Factor C (compost dose)

Table 2. Treatments evaluated in the assay

Treatment	Nomenclature	Replicates
T1	B1C1	3
T2	B1C2	3
T3	B2C1	3
T4	B2C2	3
T5	B3C1	3
T6	B3C2	3

Table 3. Physicochemical variables evaluated

Variable	Unit
Total nitrogen	mg/kg
Nitrate ($N–NO_3^-$)	mg/kg
Nitrite ($N–NO_2^-$)	mg/kg
Ammonium ($N–NH_4^+$)	mg/kg
pH	—
Electrical conductivity	µS/cm

Note: Variables were determined before bacterial inoculation (initial concentration) and at the end of the inoculation period (final concentration).

on each parameter. When ANOVA indicated statistically significant differences, Tukey's test ($\alpha = 0.05$) was used for mean comparison at a 95% confidence level. Data processing was performed using InfoStat and RStudio.

RESULTS

Initial physicochemical condition of the soil

The initial physicochemical characterization of the soil before bacterial inoculation is presented in Table 4. Total nitrogen was 1689.24 mg/kg, nitrate was 52.63 mg/kg, nitrite was 1.37 mg/kg, and ammonium was 10.00 mg/kg. Soil pH was 7.21, and electrical conductivity was 85 µS/cm (approximately 0.085 dS/m).

Table 4. Initial concentrations of soil physicochemical variables

Variable	Initial concentration	Unit
Total nitrogen	1689.24	mg/kg
Nitrate ($N–NO_3^-$)	52.63	mg/kg
Nitrite ($N–NO_2^-$)	1.37	mg/kg
Ammonium ($N–NH_4^+$)	10.00	mg/kg
pH	7.21	—
Electrical conductivity	85	µS/cm

Physicochemical dynamics after treatment

Table 5 shows that total nitrogen decreased from the initial concentration of 1689.24 mg/kg to final values of 485.57–528.61 mg/kg, while nitrate increased to 217.50–403.97 mg/kg. Final nitrite concentrations ranged from 0.07 to 0.31 mg/kg and ammonium from 4.39 to 7.73 mg/kg. During the trial, electrical conductivity increased from 85 µS/cm to 237.67–590.33 µS/cm, while pH declined from 7.21 to 5.70–6.38.

Analysis of variance

For total nitrogen, the main effects of Factor B ($F_{2,12} = 0.88$; $p = 0.4391$) and Factor C ($F_{1,12} = 0.13$; $p = 0.7199$) were not significant; however, the B × C interaction was significant ($F_{2,12} = 6.20$; $p = 0.0141$), indicating that the bacterial effect depended on the compost dose. Nitrate concentrations showed highly significant effects for Factor B ($F_{2,12} = 564.21$; $p < 0.0001$), Factor C ($F_{1,12} = 139.50$; $p < 0.0001$), and the B × C interaction ($F_{2,12} = 177.87$; $p < 0.0001$), and this variable showed the strongest model fit ($R^2 = 0.99$; CV = 2.80%). Nitrite showed significant effects for Factor C ($F_{1,12} = 31.23$; $p < 0.0001$) and the B × C interaction ($F_{2,12} = 4.52$; $p = 0.0345$), whereas Factor B alone was not significant ($F_{2,12} = 2.22$; $p = 0.1512$). Ammonium showed no significant effects for any evaluated factor (B: $F_{2,12} = 1.51$, $p = 0.2606$; C: $F_{1,12} = 1.35$, $p = 0.2677$; B × C: $F_{2,12} = 0.09$, $p = 0.9152$), which was reflected in the low model fit ($R^2 = 0.27$) and high variability (CV = 32.93%). Soil pH responded significantly only to Factor B ($F_{2,12} = 9.89$; $p = 0.0029$), with no significant interaction ($F_{2,12} = 1.48$; $p = 0.2661$). Electrical conductivity showed a similar pattern and was affected only by Factor B ($F_{2,12} = 10.49$; $p = 0.0023$), with a non-significant interaction ($F_{2,12} = 3.04$; $p = 0.0856$). For variables and factors with significant effects, Tukey's test was subsequently used to identify homogeneous groups and the treatments with the best performance (Table 6).

Tukey mean comparison

The analysis of variance showed a significant interaction between bacterial treatment and compost dose for total nitrogen ($p = 0.0141$). However, Tukey's test did not identify significant

Table 5. Final concentrations of soil physicochemical variables by treatment after the experimental period

Treatment	Total N (mg/kg)	Nitrate (mg/kg)	Nitrite (mg/kg)	Ammonium (mg/kg)	pH	Electrical conductivity (µS/cm)
T1 (B1C1)	522.11 ± 9.90	403.97 ± 5.03	0.16 ± 0.03	6.15 ± 1.23	6.38 ± 0.11	237.67 ± 56.52
T2 (B1C2)	508.45 ± 9.90	391.51 ± 5.03	0.10 ± 0.03	4.39 ± 1.23	5.98 ± 0.11	293.67 ± 56.52
T3 (B2C1)	512.51 ± 9.90	383.67 ± 5.03	0.31 ± 0.03	7.26 ± 1.23	5.73 ± 0.11	590.33 ± 56.52
T4 (B2C2)	492.04 ± 9.90	227.57 ± 5.03	0.07 ± 0.03	6.34 ± 1.23	5.70 ± 0.11	454.67 ± 56.52
T5 (B3C1)	485.57 ± 9.90	217.50 ± 5.03	0.20 ± 0.03	7.73 ± 1.23	5.85 ± 0.11	298.33 ± 56.52
T6 (B3C2)	528.61 ± 9.90	240.56 ± 5.03	0.09 ± 0.03	6.92 ± 1.23	5.74 ± 0.11	433.67 ± 56.52

Note: Values are expressed as mean ± standard error (n = 3).

Table 6. Analysis of variance of soil physicochemical variables

Variable	R^2	Mean	CV (%)	Bacteria p value	Compost dose p value	Interaction p value
Total nitrogen	0.54	508.22	3.37	0.4391	0.7199	0.0141*
Nitrate ($N–NO_3^-$)	0.99	310.80	2.80	<0.0001*	<0.0001*	<0.0001*
Nitrite ($N–NO_2^-$)	0.79	0.155	33.96	0.1512	<0.0001*	0.0345*
Ammonium ($N–NH_4^+$)	0.27	6.47	32.93	0.2606	0.2677	0.9152
pH	0.69	5.90	3.30	0.0029*	0.0674	0.2661
Electrical conductivity	0.69	384.72	25.45	0.0023*	0.6947	0.0856

Note: R^2 = coefficient of determination; CV = coefficient of variation; Bacteria = Factor B; Compost dose = Factor C. * Significant difference.

differences among the means of the six experimental combinations ($p > 0.05$; Figure 1). These results indicate that the total nitrogen response was associated with the combination of both factors, although multiple comparisons did not statistically distinguish the evaluated treatments.

Nitrate showed the strongest model fit (R^2 = 0.99), with highly significant effects for both main factors and their interaction ($p < 0.0001$). Tukey's test separated the treatments into two groups: T1, T2, and T3 formed the upper group (383.67–403.97 mg/kg; letter A), whereas T4, T5, and T6 formed the lower group (217.50–240.56 mg/kg; letter B), as shown in Figure 2. *B. wiedmannii* at both compost doses and *B. albus* at the low compost dose showed the highest final nitrate concentrations, whereas the consortium and *B. albus* at the high compost dose showed the lowest final concentrations.

For nitrite, Tukey's test clearly differentiated T3 (0.31 mg/kg; letter A), while T5 occupied an intermediate position (0.20 mg/kg; letter AB) and the remaining treatments were grouped in the lower range (letter B), as shown in Figure 3. Nitrite responded significantly to compost dose ($F_{1,12} = 31.23$; $p < 0.0001$) and to the B × C interaction ($F_{2,12} = 4.52$; $p = 0.0345$), whereas the bacterial factor alone was not significant ($F_{2,12} = 2.22$; $p = 0.1512$). The highest final nitrite concentration occurred in T3 (B2C1). Both pH and electrical conductivity showed significant effects only for the bacterial factor, with no significant interaction in either case ($F_{2,12} = 9.89$, $p = 0.0029$ and $F_{2,12} = 10.49$, $p = 0.0023$, respectively). For pH, *B. wiedmannii* (B1) maintained the highest mean value (6.18; letter A), whereas *B. albus* and the consortium showed lower values (5.72–5.79; letter B). Electrical conductivity showed the opposite pattern (Figure 4): *B. albus* (B2) produced the highest mean value (522.50 µS/cm; letter A), significantly exceeding *B. wiedmannii* and the consortium (265.67–366.00 µS/cm; letter B).

Percentage reduction in total nitrogen

The percentage reduction in total nitrogen was obtained by comparing the final concentration of each treatment with the common initial reference

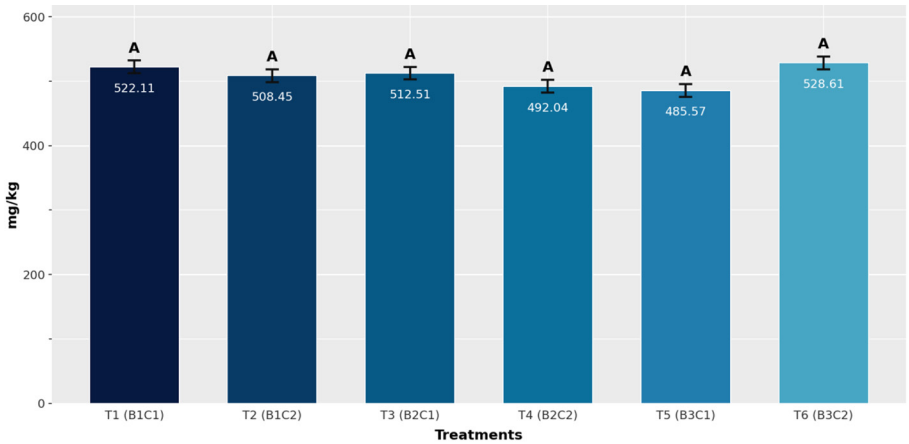

Figure 1. Final total nitrogen concentration by treatment (mean ± SE, n = 3); letters indicate Tukey groups

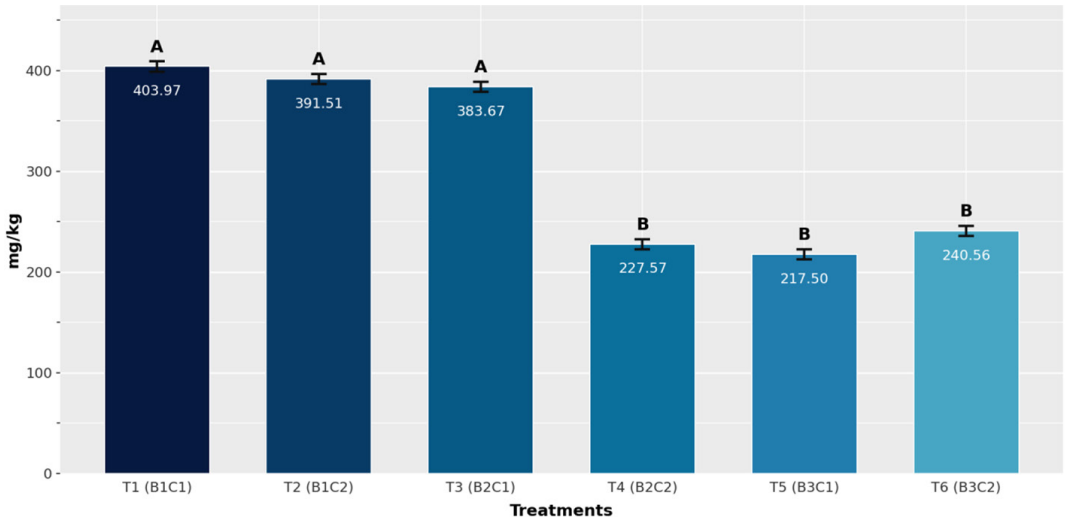

Figure 2. Final nitrate concentration by treatment (mean ± SE, n = 3); letters indicate Tukey groups

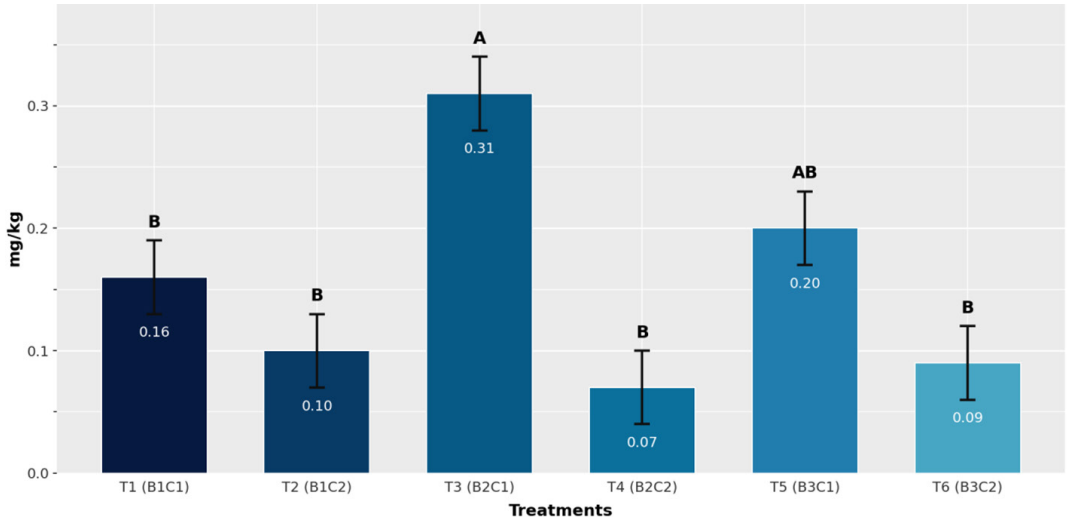

Figure 3. Final nitrite concentration by treatment (mean ± SE, n = 3); letters indicate Tukey groups

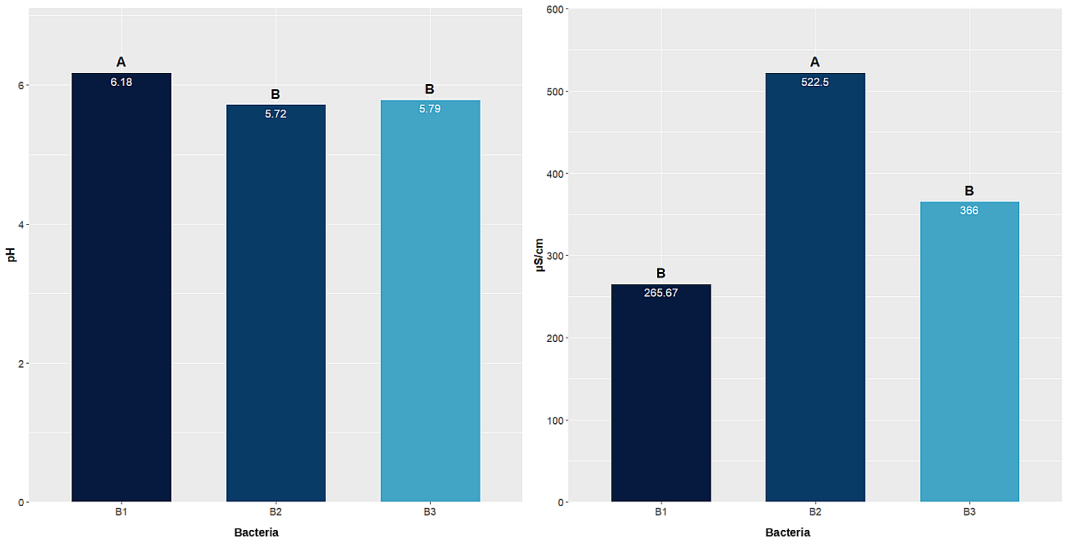

Figure 4. Soil pH and electrical conductivity by bacterial factor, with grouping letters according to Tukey's test

Table 7. Percentage reduction in total nitrogen by treatment

Treatment	Initial total N (mg/kg)	Final total N (mg/kg)	Total N reduction (%)
T1 (B1C1)	1689.24	522.11	69.09
T2 (B1C2)	1689.24	508.45	69.90
T3 (B2C1)	1689.24	512.51	69.66
T4 (B2C2)	1689.24	492.04	70.87
T5 (B3C1)	1689.24	485.57	71.26
T6 (B3C2)	1689.24	528.61	68.71

Note: percentages were calculated using the initial soil reference concentration of 1689.24 mg/kg and Equation 1; values are descriptive.

concentration (Equation 1). The descriptive percentage reduction in total nitrogen ranged from 68.71% (T6) to 71.26% (T5). T5 (B3C1) had the highest numerical reduction (71.26%), followed by T4 (70.87%) and T2 (69.90%). T6 (B3C2) had the lowest numerical reduction (68.71%). These percentages were calculated from a common initial reference concentration and were not statistically compared as separate response variables (Table 7).

DISCUSSION

The initial soil condition confirmed a marked enrichment of nitrogen forms. Total nitrogen (1689.24 mg/kg) exceeded the mean reported for agroecosystems by Podlasek et al. (2021), while nitrate, nitrite, and ammonium were above the values documented by Wolińska et al. (2016) for cultivated soils. In contrast, the initial electrical conductivity remained far below the 2.0 dS/m threshold used by Poma-Chamana et al. (2026) to characterize non-saline conditions. Together, these comparisons support the interpretation that the initial disturbance was dominated by nitrogen enrichment rather than by generalized salinization of the soil matrix.

Total nitrogen decreased from 1689.24 mg/kg to 485.57–528.61 mg/kg during the experimental period, while nitrate concentrations increased. Assuming that nitrate, nitrite, and ammonium were consistently expressed as elemental nitrogen (N), their combined final concentrations accounted for 46.43–78.58% of the reported total nitrogen, without exceeding it in any treatment. This proportional comparison is descriptive and does not constitute a nitrogen mass balance. Zhang et al. (2022) documented heterotrophic nitrification and aerobic denitrification in *Bacillus* strains, whereas Li et al. (2026) reported changes in N_2O emissions following *Bacillus subtilis* application. These findings provide context for interpreting nitrogen transformations, but the present data do not establish the mechanisms or ultimate fate of nitrogen.

Nitrate increased from 52.63 mg/kg to 217.50–403.97 mg/kg after 60 days, with significant effects of bacterial treatment, compost dose, and their interaction ($p < 0.0001$; $R^2 = 0.99$). Final concentrations were higher in T1–T3 than in T4–T6. In contrast, You et al. (2022) reported nitrate removal using *Bacillus megaterium* NCT-2 in secondarily salinized soils. The increase observed in the present study may be related to nitrogen transformations under the experimental conditions, although the processes involved were not determined. Higher nitrate concentrations may increase the potential for leaching to groundwater; however, leaching was not measured.

Final nitrite concentrations ranged from 0.07 to 0.31 mg/kg, with significant differences among some experimental combinations. Gogoi et al. (2021) and Esquén Bayona et al. (2026) reported changes in nitrite concentrations associated with species of the genus *Bacillus* in aquatic systems. Although the experimental conditions differ from those of the present study, these findings suggest the potential involvement of these bacteria in nitrogen transformations, without supporting direct comparisons of the measured concentrations.

Soil pH decreased from 7.21 to 5.70–6.38, while electrical conductivity increased after treatment. The pH decrease may be associated with nitrification or organic compounds derived from fermentation of the bacterial preparation, although their contributions to acidification were not determined. He et al. (2025) reported changes in rhizosphere pH and electrical conductivity following *Bacillus subtilis* co-inoculation in saline-alkaline soil, demonstrating the capacity of

Bacillus activity to modify these properties. In the present experiment, *B. wiedmannii* maintained the highest pH and lower electrical conductivity than *B. albus*, whereas *B. albus* produced the highest electrical conductivity. Rashid et al. (2025) documented salinity tolerance of up to 850 mM NaCl in *B. wiedmannii*; this physiological tolerance is compatible with the comparatively moderate conductivity changes associated with this species, although it does not by itself establish the mechanism responsible for the observed response.

Considering the response of all measured variables, T5 (B3C1) showed the most favorable numerical profile, combining the highest descriptive total-nitrogen reduction (71.26%) with one of the lowest final nitrate concentrations. Nevertheless, Tukey's test did not identify T5 as statistically superior to the other treatments for final total nitrogen. Therefore, its advantage should be interpreted as an overall numerical performance under the tested conditions rather than as definitive statistical superiority. The contrast between T5 and T6 further suggests that increasing the compost dose did not necessarily improve the performance of the bacterial consortium.

CONCLUSIONS

Before bacterial inoculation, the evaluated soil showed substantial nitrogen contamination while remaining within a non-problematic salinity range, indicating that the initial alteration was associated primarily with nitrogen excess rather than with generalized deterioration of the soil matrix.

After 60 days, total soil nitrogen showed descriptive reductions above 68%, accompanied by higher nitrate concentrations, lower pH, and increased electrical conductivity. Because uninoculated controls were not included, these changes cannot be attributed exclusively to bacterial inoculation.

The statistical analysis showed that bacterial treatment, compost dose, and their interaction affected the evaluated physicochemical variables differently. Nitrate showed the most consistent response and the strongest model fit, whereas ammonium did not respond significantly to any bacterial and compost combination. Soil pH and electrical conductivity responded specifically to the bacterial factor.

Treatment T5, consisting of the bacterial consortium and 800 g of compost, showed the highest descriptive percentage reduction in total nitrogen (71.26%) and the lowest final nitrate concentration (217.50 mg/kg). However, Tukey's test did not identify significant differences among treatments for total nitrogen; therefore, these results do not establish the overall superiority of this experimental combination.

Acknowledgements

The authors thank the Escuela Superior Politécnica Agropecuaria de Manabí Manuel Félix López for the institutional support provided during this research and Jonathan Gerardo Chicaiza Intriago for his guidance and dedication in directing the work. Anghelo Álvarez and Wilinton Gracia also acknowledge the support of their families and colleagues throughout the research process.

REFERENCES

1. Alori, E. T., Gabasawa, A. I., Elenwo, C. E., Agbeyegbe, O. O. (2022). Bioremediation techniques as affected by limiting factors in soil environment. *Frontiers in Soil Science, 2*. https://doi.org/10.3389/fsoil.2022.937186
2. Alotaibi, B. S., Khan, M., Shamim, S. (2021). Unraveling the Underlying Heavy Metal Detoxification Mechanisms of Bacillus Species. *Microorganisms, 9*(8), 1628. https://doi.org/10.3390/microorganisms9081628
3. Castro-Landin, A. L., Zapata-Velasco, M. L., Palacios-Lopez, L. A. (2023). El rol de los microorganismos en la fertilidad del suelo agrícola basado en una revisión de estudios recientes. *Innova Science Journal, 1*(1), 26–37. https://doi.org/10.63618/omd/isj/v1/n1/8
4. Dissanayake, W., Najaf Zadeh, H., Abhayawardhana, P. L., Nazmi, A. R. (2026). A review on smart nitrogen fertilizers for sustainable agriculture: Integrating biomaterials and additive manufacturing. *Materials Today Sustainability, 34*, 101374. https://doi.org/10.1016/j.mtsust.2026.101374
5. Dong, X., Yao, Y., Han, B., Rillig, M. C., Zhong, Y., Hu, H., Li, Z. (2026). Anthropogenic soil acidification severely decreases microbial diversity and functionality. *Current Biology, 36*(6), 1444–1453.e3. https://doi.org/10.1016/j.cub.2026.02.020
6. Escobar, J. A. V., Coello, A. C., Villagómez, G. C. M., Toscano, M. A. P. (2026). Efficacy of bioremediation in hydrocarbon-contaminated soils in the Ecuadorian Amazon: a systematic review (in Spanish). *Revista JRG de Estudos Acadêmicos, 9*(20), e093164. https://doi.org/10.55892/jrg.v9i20.3164

7. Esquén Bayona, D. A., Talledo Ancajima, D., Cadena, D. A., Dominguez-Mendoza, L., Leyva, S., Somocurcio Zambrano, M. M., Saldarriaga Yacila, D. E., Rampelotto, P. H., Guzman Escudero, F. L., Diringer, B. M. (2026). Bioaugmentation with native Bacillus strains enhance nitrate and nitrite removal and reshape microbiomes in low-salinity shrimp cultures: Elucidating genetic mechanisms. *PLOS ONE, 21*(1), e0339620. https://doi.org/10.1371/journal.pone.0339620
8. Food and Agriculture Organization of the United Nations. (n.d.). Fertilizer specifications. https://www.fao.org/agriculture/crops/thematic-sitemap/theme/spi/plantnutrition/fertspecs/en/
9. Food and Agriculture Organization of the United Nations. (2026). Inorganic fertilizers: 2015–2024 (FAOSTAT Analytical Brief No. 130). https://doi.org/10.4060/ce0945en
10. Gogoi, M., Bhattacharya, P., Kumar Sen, S., Mukherjee, I., Bhushan, S., Chaudhuri, S. R. (2021). Aquaculture effluent treatment with ammonia remover Bacillus albus (ASSF01). *Journal of Environmental Chemical Engineering, 9*(4), 105697. https://doi.org/10.1016/j.jece.2021.105697
11. Hale, L., Hendratna, A., Scott, N., Gao, S. (2023). Biochar enhancement of nitrification processes varies with soil conditions. *Science of The Total Environment, 887*, 164146. https://doi.org/10.1016/j.scitotenv.2023.164146
12. He, C., Gao, T., Wang, X., Chen, R., Gao, H., Liu, H. (2025). Co-inoculation of Bacillus subtilis and Bradyrhizobium liaoningense increased soybean yield and improved soil bacterial community composition in coastal saline-alkali land. *Frontiers in Plant Science, 16*, 1677763. https://doi.org/10.3389/fpls.2025.1677763
13. International Organization for Standardization. (1995). ISO 11261:1995. Soil quality — Determination of total nitrogen — Modified Kjeldahl method. https://www.iso.org/standard/19239.html
14. International Organization for Standardization. (2005). ISO 14256-2:2005. Soil quality — Determination of nitrate, nitrite and ammonium in field-moist soils by extraction with potassium chloride solution — Part 2: Automated method with segmented flow analysis. https://www.iso.org/standard/32399.html
15. Li, R., Lin, X., Miao, Y., Zhang, C., Li, F., Zhang, G., Sun, Q., Hua, T., Wang, J. (2026). *Bacillus* subtilis biofertilizer mitigates N_2O emissions from saline-alkali farmland. *Life, 16*(4), 635. https://doi.org/10.3390/life16040635
16. Ministerio de Agricultura, Ganadería, Acuacultura y Pesca. (2015). Procedimientos de geopedología: Proyecto SIGTIERRAS, escala 1:25.000. https://fliphtml5.com/wtae/gfqz/basic
17. Nuruzzaman, M., Bahar, M. M., Naidu, R. (2025). Diffuse soil pollution from agriculture: Impacts and remediation. *Science of The Total Environment, 962*, 178398. https://doi.org/10.1016/j.scitotenv.2025.178398
18. Podlasek, A., Koda, E., Vaverková, M. D. (2021). The variability of nitrogen forms in soils due to traditional and precision agriculture: Case studies in Poland. *International Journal of Environmental Research and Public Health, 18*(2), 465. https://doi.org/10.3390/ijerph18020465
19. Poma-Chamana, R., Vilca-Gamarra, C., Linares-Escapa, S., Puma-Huacani, K., Carrillo, A., Villalta Soto, M. J. C., Quispe, K. (2026). Soil quality in olive orchards of southern Peru using a weighted soil quality index (SQIw): constraints by salinity, organic matter and sustainable management approach. *Frontiers in Soil Science, 6*. https://doi.org/10.3389/fsoil.2026.1724235
20. Rashid, R., Iqbal, A., Shahzad, M., Noureen, S., Muqeet, H. A. (2025). Carrier-based application of phyto-benefic and salt-tolerant *Bacillus wiedmannii* and *Bacillus paramobilis* for sustainable wheat production under salinity stress. *Plants, 14*(14), 2096. https://doi.org/10.3390/plants14142096
21. Tang, H., Zhang, J., Hu, K., Tu, J., Hu, X., Luo, L., Men, J., Guo, Y., Han, J., Zhou, B. (2026). Bioremediation of cadmium-contaminated soil: Assessing the potential efficacy of Tetrahymena thermophila. *Journal of Environmental Sciences, 166*, 612–619. https://doi.org/10.1016/j.jes.2025.11.025
22. Wolińska, A., Szafranek-Nakonieczna, A., Banach, A., Błaszczyk, M., Stępniewska, Z. (2016). The impact of agricultural soil usage on activity and abundance of ammonifying bacteria in selected soils from Poland. *SpringerPlus, 5*(1), 565. https://doi.org/10.1186/s40064-016-2264-8
23. You, Y., Chi, Y., Chen, X., Wang, J., Wang, R., Li, R., Chu, S., Yang, X., Zhang, D., Zhou, P. (2022). A sustainable approach for bioremediation of secondary salinized soils: Studying remediation efficiency and soil nitrate transformation by bioaugmentation. *Chemosphere, 300*, 134580. https://doi.org/10.1016/j.chemosphere.2022.134580
24. Zambrano-Solórzano, Á., Guzmán-Cedeño, Á., Pincay, M., Chicaiza, J., Zambrano, D. (2024). Evaluation of Antarctic strains of *Bacillus* sp. as plant growth promoting bacteria. Revista de La Facultad de Agronomía, Universidad Del Zulia, 41(3), e244121. https://doi.org/10.47280/RevFacAgron(LUZ).v41.n3.01
25. Zhang, F., Xie, F., Zhou, K., Zhang, Y., Zhao, Q., Song, Z., Cui, H. (2022). Nitrogen removal performance of novel isolated *Bacillus* sp. capable of simultaneous heterotrophic nitrification and aerobic denitrification. *Applied Biochemistry and Biotechnology, 194*(7), 3196–3211. https://doi.org/10.1007/s12010-022-03877-w