**Soil Reclamation through Microbial Strategies: Evaluating Anion Behavior across Various Salinity Levels**

**Abstract**

A laboratory incubation experiment was conducted to assess the influence of microbial inoculants on bicarbonate (HCO3-), chloride (Cl⁻), and sulphate (SO42-) concentrations in saline soils with electrical conductivity (EC) levels of 4.03, 5.01, and 6.02 dS m-1 under 100% field capacity (FC) for 30, 60 and 90 days. At 90 days after incubation (DAI), the application of halotolerant microbial inoculants exhibited significant reductions in soil anions concentration across varying salinity levels. The treatment with CSR-GROW-SURE at 3 L ha-1 resulted in the percentage reduction of HCO3- (10.20, 7.96 and 11.78 %), Cl⁻ (10.25, 8.05 and 10.59 %), and SO42- (10.22, 8.05 and 6.60 %) over control in soils with EC levels of 4.03, 5.01, and 6.02 dS m-1, respectively. The results were on par with treatment TNAU culture applied at 3 L ha-1, with percentage reduction of (9.91, 7.96 and 11.53 %) for HCO3-, (9.98, 7.87 and 10.33 %) for Cl⁻ and and (10.00, 7.72 and 6.45%) for SO42- in 4.03, 5.01, and 6.03 dS m-1 of saline soils Compared to the treatment control respectively. These findings suggest that prolonged incubation (90 DAI) combined with higher inoculant dosage (3 L ha-1) effectively modulates the accumulation of anions in saline soils. The similar performance of both microbial formulations indicates their potential in reducing anion toxicity and improving soil chemical properties under saline conditions.

**Key Words:** Bacillus spp., Bicarbonate, Chloride, Sulphate, Reclamation, saline soils.

**1. Introduction**

Soil salinization is a major global threat to agricultural productivity, especially in irrigated lands of arid and semi-arid regions (Mwesige *et al*., 2025). Factors such as high evapotranspiration, saline irrigation, and poor drainage contribute to the buildup of soluble salts (Demo *et al*., 2025). Beyond total salinity, the specific anions bicarbonate (HCO₃⁻), chloride (Cl⁻), and sulphate (SO₄²⁻) play a critical role in soil degradation (Datta *et al*., 2025). Increase in HCO₃⁻ content reduces calcium (Ca2+) and magnesium (Mg2+) availability, leading to soil dispersion and reduced permeability (Barrett-Lennard *et al*., 2025). Excess Cl⁻ becomes toxic, disrupting nutrient uptake and reducing yields. Together, these ions alter soil chemistry, hinder plant growth, and impair soil-plant interactions (Silva-Herrera *et al*., 2025).

Similarly, excessive SO₄²⁻ while less toxic than Cl⁻ contributes to the total salinity load and forms insoluble salts with calcium or sodium, influencing soil reaction and plant nutrient balance (Fan *et al*., 2025). Collectively, these ions exert osmotic stress on plants, reduce water use efficiency, and compromise microbial activity, resulting in diminished soil health and agricultural productivity (Patel *et al*., 2025). Traditional remediation approaches, including the application of chemical amendments like gypsum, have been widely employed to manage saline soils (Daba *et al*., 2025). Gypsum acts as a source of soluble calcium, which displaces sodium from exchange sites, thus improving soil structure and facilitating salt leaching (Da Costa *et al*., 2025). However, these methods are often constrained by high input costs, limited long-term efficacy, and potential environmental drawbacks such as nutrient imbalances and groundwater contamination (Li *et al*., 2025). The biological soil management strategies that reduces the functional capacity of soil microorganisms to improve soil health under salinity stress (Luo *et al*., 2025). Microbial inoculants offer an environmentally sustainable and biologically active approach for managing salinity-induced degradation (Yu *et al*., 2025). Certain beneficial microorganisms, especially halotolerant and plant growth-promoting rhizobacteria (PGPR) such as strains of *Bacillus*, have demonstrated remarkable resilience under saline conditions (Zhang *et al*., 2025).

These microbes contribute to soil amelioration through multiple mechanisms, including the secretion of organic acids that solubilize bound carbonates and SO₄²⁻ (Chadha *et al*., 2025), production of exoenzymes (Jamil *et al*., 2025) and carbonic anhydrase that convert HCO₃⁻ into carbon dioxide (CO₂) and water (Liu *et al*., 2025), and synthesis of exopolysaccharides that improve soil aggregation (Peng *et al*., 2025) and enhance salt leaching (Bhardwaj *et al*., 2025). Moreover, their ability to colonize the rhizosphere and modulate pH, improve root architecture, and enhance nutrient bioavailability makes them excellent candidates for integrated salt-affected soil management (Chang *et al*., 2025 and Jin *et al*., 2025). Despite their potential, the specific role of microbial inoculants in regulating the individual behavior of anions particularly HCO₃⁻, Cl⁻, and SO₄²⁻ under saline conditions remains poorly characterized. This knowledge gap limits the optimization of microbial-based interventions tailored to specific soil chemical constraints. A clearer understanding of how microbial consortia affect anion behavior under saline conditions is vital for formulating effective biological approaches to soil restoration.

In the present study two microbial formulations CSR-GROW-SURE and the TNAU microbial culture applied at graded doses on the temporal variation of HCO₃⁻, Cl⁻, and SO₄²⁻ concentrations in saline soils maintained at 100 % field capacity (FC). The study was conducted using soils of three distinct salinity levels (EC 4.03, 5.01, and 6.02 dS m⁻¹) and monitored over a 90-day incubation period. This study evaluates how microbial treatments, salinity levels, and incubation periods influence soil anion dynamics, providing a scientific foundation for their use in reclaiming salt-affected soils sustainably.

**2. Materials and Methods**

**2.1. Site Description and Soil Sample Collection**

Saline soil samples with an electrical conductivity (EC) of 4.03, 5.01 and 6.02 dS m-1 were collected from Adivalli village, located in Udumalpet Taluk of Coimbatore district, Tamil Nadu. The geographic coordinates of the collection points with latitude of 10°41'44" N, 10°41'33" N, and 10°41'29" N, and longitudes 77°09'21" E, 77°09'18" E, and 77°09'04" E, respectively longitude. These locations are representative of dryland saline conditions typical of semi-arid agro ecological zones. After collection, the soil samples were shade-dried, gently crushed using a wooden pestle, and passed through a 2 mm sieve to ensure homogeneity before use in incubation trials.

**2.2. Microbial Inputs for saline Soil Reclamation**

Two microbial inoculants were evaluated for their potential to improve saline soil characteristics. The first was CSR-GROW-SURE, a halotolerant microbial consortium obtained from ICAR–Central Soil Salinity Research Institute (ICAR–CSSRI), Karnal, Haryana. It consisted of three strains: *Lysinibacillus fusiformis* (CSR-A-11), *Lysinibacillus sphaericus* (CSR-A-16), and *Bacillus licheniformis* (CSR-M-16). The second formulation was developed at Tamil Nadu Agricultural University (TNAU), Coimbatore. Initially unidentified, the dominant bacterial strain was later confirmed as *Bacillus subtilis*, a known salt-tolerant species. These two formulations were selected for comparison based on their compatibility with saline environments.

**2.3. Experimental Design and Incubation Setup**

The incubation study was conducted at Tamil Nadu Agricultural University, Coimbatore, to investigate the role of microbial inoculants in modifying the ionic environment of saline soils. A factorial completely randomized design (FCRD) was employed with seven treatments and three replications. For each treatment, 250 g of air-dried saline soil (EC 4.03, 5.01 and 6.02 dS m-1), passed through a 2 mm sieve, maintained with 100 % FC was used. Microbial inoculants were applied at three dose levels 1, 2, and 3 L ha-1 on a soil weight basis. The TNAU Culture (*Bacillus subtilis*) had a viable cell count of 2.8 × 10⁷ CFU mL⁻¹, while CSR-GROW-SURE contained 1.0 × 107 CFU mL-1. Sampling was carried out at 30, 60, and 90 days after incubation (DAI) to analyze soil anions.

**2.4. Details of Experimental Treatments**

The experiment comprised seven treatments designed to assess the efficacy of microbial inoculants under varying salinity conditions. The treatments were as follows: T1 – Control (no inoculant) with three soil salinity levels (4.03, 5.01, and 6.02 dS m-1); T2 - TNAU Culture @ 1 L ha⁻¹; T3 – TNAU Culture @ 2 L ha-1; T4 – TNAU Culture @ 3 L ha-1; T5 – CSR-GROW-SURE @ 1 L ha-1; T6 – CSR-GROW-SURE @ 2 L ha-1; and T7 – CSR-GROW-SURE @ 3 L ha-1. All treatments were subjected to identical incubation conditions and sampling intervals. This setup enabled the comparative evaluation of the two microbial formulations and their dosages in reducing anion concentrations and enhancing soil chemical properties under salinity stress.

**2.4 Study Protocol**

**2.4.1. Soil Analysis**

In soil the EC was analyzed by the 1:2.5 Soil water extract method (Jackson 1973),HCO₃⁻ and Cl⁻ in the soil were estimated using the titration method as described by Richards (1954). Sulphates were determined using the turbidimetric method, following the procedure outlined by Tandon (2005), which involves the measurement of turbidity developed by the reaction of SO42- ions with barium chloride under controlled conditions. The initial soil anionic properties are represented in (Table 1).

**Table 1. Initial soil anionic properties**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **S. No** | **Soil Parameter** | **Soil EC****4.03 dS m-1** | **Soil EC****5.01 dS m-1** | **Soil EC****6.02 dS m-1** |
|  | Bicarbonate (meq kg-1) | 3.34 | 3.67 | 3.91 |
|  | Chloride (meq kg-1  ) | 22.10 | 27.00 | 35.15 |
|  | Sulphate (meq kg-1) | 13.56 | 17.85 | 19.83 |

**2.5. Statistical Analysis**

Data were statistically analyzed using AGRESS 7.01. Treatment means were compared using the Critical Difference (CD) at the 5% significance level (P < 0.05), following Gomez and Gomez (1984). Using R software, heat map was created with the “pheatmap” package by scaling input data and applying cluster analysis, facilitating a clear visual interpretation of multi-parameter treatment responses.

**3. Results and discussion**

**3.1. Effect of Microbial Inoculants on Soil Bicarbonate at various salinity levels**

Soil HCO3- levels under salinity stress can be effectively regulated through microbial inoculation, promoting improved soil chemical balance. The application of microbial inoculants significantly influenced the soil HCO3-concentrations under saline conditions. Among the treatments, CSR-GROW-SURE applied at 3 L ha-1 demonstrated the most effective reduction, with mean HCO₃⁻ levels of 3.16, 3.54, and 3.65 meq kg⁻¹ in soils with EC values of 4.03, 5.01, and 6.02 dS m⁻¹, respectively, under 100% FC. This was statistically comparable to the TNAU microbial culture at the same application rate, which recorded 3.18, 3.55, and 3.67 meq kg-1 across the corresponding salinity gradients. A moderate reduction was also observed with CSR-GROW-SURE at 2 L ha-1, showing values of 3.17, 3.55, and 3.66 meq kg-1. In contrast, the control treatment exhibited the highest HCO3- levels, with values increasing to 3.42, 3.76, and 3.98 meq kg-1, across increasing salinity levels (Figure 1). The observed reduction in soil HCO₃⁻ levels is primarily attributed to microbial respiratory activity, wherein CO₂ is generated and subsequently reacts with soil moisture to form carbonic acid (H₂CO₃). This weak acid plays an essential role in enhancing the solubilization and subsequent leaching or transformation of HCO₃⁻ ions, contributing to their decline in the soil matrix (Rengasamy, 2010).

The highest significant decline in soil HCO3- concentration was recorded at 90 DAI. Under 100% FC conditions with microbial inoculation, the mean HCO3- levels at 30, 60, and 90 DAI were 3.29, 3.20, and 3.14 meq kg-1 for soils with (4.03 dS m-1); 3.65, 3.57, and 3.52 meq kg-1 for (5.01 dS m-1); and 3.83, 3.69, and 3.60 meq kg-1 for (6.02 dS m-1), respectively. The decrease in HCO₃⁻ content is attributed to the activity of *Bacillus* *spp*., which produce organic acids that aid in the breakdown and neutralization of carbonates (Damodaran *et al*., 2014).

A significant interaction effect was observed between microbial cultures and incubation duration on soil HCO3- levels. At 90 DAI a noticeable decline in HCO3- concentration was recorded with CSR-GROW-SURE applied at 3 L ha-1, with percentage reduction of 10.20, 7.96 and 11.78 % in soils maintained at 100 % FC having EC level of 4.03, 5.01, and 6.03 dS m-1 respectively over control treatment. These results statistically on par with those results obtained with the TNAU culture at the same dosage and duration, with HCO3- percentage decrease of 9.91, 7.96 and 11.53 % across the same salinity levels than control treatment. These result highlights the role of prolonged incubation and high-dose microbial treatment in mitigating HCO3- buildup in saline soils. Sharma *et al*., (2013), reported that the decline in HCO3- concentrations in saline soils is primarily driven by microbial secretion of organic acids, which lower the pH of the rhizosphere, thereby promoting the neutralization of HCO3- ions. Additionally, specific microbial taxa will produce the enzyme carbonic anhydrase, which catalyzes the rapid conversion of HCO3- into CO₂ and H₂O, facilitating the volatilization or further transformation of HCO3- from the soil environment.

**3.2. Influence of microbial inoculants on chloride content under various salinity levels**

Microbial inoculation exerted a significant impact on Cl⁻ concentrations in saline soils. The application of microbial cultures at increasing doses resulted in a marked decline in Cl⁻ levels, reduction was positively correlated with the inoculant concentration. The most effective treatment was CSR-GROW-SURE applied at 3 L ha-1, which recorded mean Cl⁻ values of 20.40, 25.40, and 32.50 meq kg-1 in soils with EC levels of 4.03, 5.01, and 6.02 dS m-1, respectively, under conditions of 100 % FC. These reductions were on par with TNAU microbial formulation at an equivalent dose, which resulted Cl⁻ concentrations of 20.47, 25.46, and 32.58 meq kg-1 respectively. A similar trend was observed with CSR-GROW-SURE at 2 L ha-1, which also revealed a notable decline in Cl⁻ content. In contrast, the untreated control exhibited the highest Cl⁻ accumulation, recording 22.12, 27.03 and 35.18 meq kg⁻¹ across the corresponding salinity levels. (Table 2). Plant growth-promoting rhizobacteria (PGPR) stimulate root development and increase Cl⁻ uptake by plants, indirectly reducing Cl⁻ accumulation in the soil (Shrivastava & Kumar, 2015).

At 100% FC, the Cl⁻ content showed a declining form across all incubation intervals. For 4.03 dS m⁻¹ soils, the Cl⁻ values decreased from 21.23 (30 DAI) to 20.29 meq kg⁻¹ (90 DAI). Similarly, soils with EC levels of 5.01 and 6.02 dS m⁻¹ showed reductions from 26.21 to 25.28 meq kg⁻¹ and from 33.93 to 32.14 meq kg⁻¹, respectively, over the same duration. The decline in Cl⁻ concentration is likely attributed to microbial mechanisms, including the production of extracellular polysaccharides, which enhance soil structure and water infiltration, thereby facilitating leaching of Cl⁻ ions (Qadir *et al*., 2007).

The combined influence of microbial inoculant type, application rate, and duration significantly affected Cl⁻ mitigation. CSR-GROW-SURE at 3 L ha-1 proved most effective at 90 DAI, with percentage reduction of Cl⁻ levels to 10.25, 8.05 and 10.59 % than control treatment in increasing salinity conditions. This response was statistically on par with TNAU microbial culture at the same dosage, which showed similar percentage reduction of 9.98, 7.87 and 10.33 % over treatment controlin the corresponding salinity conditions. According to Damodaran *et al*., (2019), *Bacillus* *spp.,* demonstrate the ability to thrive in NaCl concentrations ranging from 5 to 10%, owing to their halophilic characteristics, which enable them to utilize Cl⁻ ions in various cellular processes.

**3.3 Sulphate response microbial inoculants under various salinity levels**

The application of microbial inoculants had a significant impact on soil sulphate (SO42-) concentrations under saline conditions. Increasing the concentration of bacterial cultures led to progressive reductions in SO42- content compared to initial values. Among the treatments, CSR-GROW-SURE at 3 L ha-1 resulted in the lowest SO42- concentrations, with values of 12.53, 16.79, and 18.90 meq kg-1 in soils with EC levels of 4.03, 5.01, and 6.02 dS m-1, respectively, under 100% FC (Table 3). These values were statistically similar to those recorded with the TNAU microbial inoculant at the same rate, which showed 12.56, 16.84, and 18.92 meq kg-1. In the absence of microbial inoculation, the control treatment recorded the highest SO42- concentrations, with mean values of 13.57, 17.86, and 19.84 meq kg-1 in soils having EC levels of 4.03, 5.01, and 6.02 dS m-1, respectively. Under anaerobic conditions, sulfate-reducing bacteria (SRB) significantly contribute to the depletion of SO42- in saline soils by utilizing sulfate as a terminal electron acceptor during their respiratory processes, then converting it into hydrogen sulfide (H₂S) (Muyzer & Stams, 2008).

Throughout the incubation period (30, 60, and 90 DAI) under 100 % FC, a gradual decline in SO42- content was observed. For soils with an EC of 4.03 dS m-1, the average SO42- concentrations were 13.03, 12.69, and 12.45 meq kg-1; for 5.01 dS m-1, values were 17.33, 17.33, and 16.71 meq kg-1; and for 6.02 dS m-1 respectively. This trend indicates a time-dependent reduction in SO4-2 levels under 100 % FC. Plant growth-promoting rhizobacteria (PGPR) enhance root development and stimulate SO₄²⁻ uptake by plants. This increased absorption lowers the concentration of available SO42- in the soil (Etesami *et al*., 2020).

The combined effect of microbial culture type, dosage, and incubation duration significantly influenced soil SO42- concentrations. The maximum reduction was observed with CSR-GROW-SURE at 3 L ha-1 at 90 DAI, with SO42- percentage reduction of 10.22, 8.05 and 6.60 % than control treatment in soils with ECs of 4.03, 5.01, and 6.03 dS m-1, respectively, under 100% FC. These results were statistically on par with TNAU culture at the same dose (3 L ha-1) and CSR-GROW-SURE at 2 L ha-1, which showed percentage decrease of SO42- by 10.00, 7.72 and 6.45 % over treatmentcontrol in the corresponding salinity conditions. The observed decline in SO42- concentrations can be attributed to microbial sulphur oxidation, which promotes the formation of sulphuric acid, thereby reducing SO₄²⁻ levels an effect similar with the findings of Velivelli *et* *al*., (2014) and Samuels *et* *al*., (2020).

**4. Conclusion**

The application of microbial inoculants, particularly CSR-GROW-SURE and TNAU microbial cultures at 3 L ha-1, significantly reduced the concentrations of HCO₃⁻, Cl⁻, and SO42- in saline soils with EC levels of 4.03, 5.01, and 6.03 dS m-1 under 100 % FC. The maximum reduction was consistently observed at 90 DAI, highlighting the time-dependent efficiency of microbial activity. The observed decline in HCO₃⁻ was attributed to microbial respiration and carbonic anhydrase-mediated dissolution, while reductions in Cl⁻ and SO42- levels were driven by organic acid production, ion utilization, and enzymatic transformations. Significant interaction effects between microbial treatments, salinity levels, and incubation durations confirm the efficacy of targeted microbial interventions in saline soil management. These findings underscore the potential of *Bacillus*-based inoculants as an effective and sustainable approach for improving soil chemical properties and supporting reclamation of salt-affected soils.

6. **Acknowledgement**

The authors wish to express their sincere gratitude to the Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore, for providing laboratory support and technical assistance during the course of the investigation. Special thanks are due to Dr. T. Damodaran and the ICAR-Central Soil Salinity Research Institute (ICAR-CSSRI), Karnal, for providing the CSR-GROW-SURE microbial inoculant essential to this study.

**7. Disclaimer (Artificial intelligence)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

**8. Reference**

1. Barrett-Lennard, E. G., Anderson, G. C., Munir, R., Hall, D. J., Riethmuller, G., & Parker, W. (2025). Salinity in Calcarosols occurs through the presence of sodium, chloride, bicarbonate and sulfate ions, is caused by sodicity, and leads to decreased osmotic potential. *Soil Research*, *63*(3).
2. Bhardwaj, S., Badiyal, A., Dhiman, S., Bala, J., & Walia, A. (2025). Exploring Halophiles for Reclamation of Saline Soils: Biotechnological Interventions for Sustainable Agriculture. *Journal of Basic Microbiology*, e70048.
3. Chadha, D., Sharma, V., Kour, S., Arya, V. M., Sharma, D., Chaudhary, D., & Pooniyan, S. (2025). Revitalizing Salt-Affected Soils: Harnessing the Power of Halophilic Microorganisms for Bioremediation. *Communications in Soil Science and Plant Analysis*, *56*(2), 239-250.
4. Chang, D., Lu, X., Sun, Y., Fan, H., & Wang, K. (2025). Responses of rhizosphere microbial communities and resource competition to soil amendment in saline and alkaline soils. *Plant and Soil*, 1-17.
5. Da Costa, M. V., de Medeiros, J. F., da Silva, E. F., da Costa Ferreira, A. K., de Morais Cavalcante Neitzke, P. R., da Paz Rodrigues, K. K. R., ... & de Sousa Antunes, L. F. (2025). Comparative analysis of marine and agricultural gypsum as nutrient sources: feasibility of marine gypsum as a substitute for acid sandy soils and sodic soil recovery. *Environmental Science and Pollution Research*, 1-23.
6. Daba, A. W. (2025). Rehabilitation of soil salinity and sodicity using diverse amendments and plants: a critical review. *Discover Environment*, *3*(1), 53.
7. Damodaran, T., Mishra, V. K., Jha, S. K., Pankaj, U., Gupta, G., & Gopal, R. (2019). Identification of rhizosphere bacterial diversity with promising salt tolerance, PGP traits and their exploitation for seed germination enhancement in sodic soil. Agricultural research, 8, 36-43.
8. Damodaran, T., Rai, R. B., Jha, S. K., Kannan, R., Pandey, B. K., Sah, V., ... & Sharma, D. K. (2014). Rhizosphere and endophytic bacteria for induction of salt tolerance in gladiolus grown in sodic soils. *Journal of plant interactions*, *9*(1), 577-584.
9. Datta, A., Basak, N., Saha, B., & Basak, P. (2025). Enhancing Soil Health by Mitigating Salinity in India. *Soil Health and Sustainability in India*, 352.
10. Demo, A. H., Gemeda, M. K., Abdo, D. R., Guluma, T. N., & Adugna, D. B. (2025). Impact of soil salinity, sodicity, and irrigation water salinity on crop production and coping mechanism in areas of dryland farming. *Agrosystems, Geosciences & Environment*, *8*(1), e70072.
11. Etesami, H., & Adl, S. M. (2020). Plant growth-promoting rhizobacteria (PGPR) and their action mechanisms in availability of nutrients to plants. *Phyto-Microbiome in stress regulation*, 147-203.
12. Fan, Y., Wang, H., Guo, Y., Du, Y., & Zhao, Z. (2025). Soaked Activated Coke Waste Ameliorates Saline-Alkali Soils via Selective Salt Ion Adsorption and Enhances Maize Growth. *Water, Air, & Soil Pollution*, *236*(6), 336.
13. Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research*. John wiley & sons.
14. Jackson, M. L. (1973). Soil chemical analysis, pentice hall of India Pvt. *Ltd., New Delhi, India*, *498*, 151-154.
15. Jamil, H., Ghaffar, A., Afzal, F., Ahmad, H., Abbas, G., Fouad, D., ... & Li, K. (2025). Attenuation of salinity-induced stress and improvement of brackish water aquaculture of Labeo rohita through dietary interventions of multi-species probiotics. *Applied Water Science*, *15*(6), 119.
16. Jin, X., Liu, X., Wang, J., Chang, J., Li, C., & Lu, G. (2025). Rhizosphere growth-promoting bacteria enhance oat growth by improving microbial stability and soil organic matter in the saline soil of the Qaidam Basin. *Plants*, *14*(13), 1926.
17. Li, Z., Kekeli, M. A., Jiang, Y., & Rui, Y. (2025). Progress and prospect of saline-alkaline soil management technology: A review. *Applied Sciences*, *15*(8), 4567.
18. Liu, P., Cao, Y. X., Cheng, Y., & Bai, Y. B. (2025). Experimental study of enhancing the effects of microbial-induced calcite precipitation treated sand using carbonic anhydrase. *Rock and Soil Mechanics*, *45*(9), 2.
19. Luo, S., Yuan, J., Song, Y., Ren, J., Qi, J., Zhu, M., ... & Song, C. (2025). Elevated salinity decreases microbial communities complexity and carbon, nitrogen and phosphorus metabolism in the Songnen Plain wetlands of China. *Water Research*, 123285.
20. Muyzer, G., & Stams, A. J. (2008). The ecology and biotechnology of sulphate-reducing bacteria. *Nature reviews microbiology*, *6*(6), 441-454.
21. Mwesige, F. F. (2025). The extent and distribution of salt-affected soils in sub-Saharan Africa from 1970 to the present: a review of the current state of knowledge. *Frontiers in Soil Science*, *5*, 1571243.
22. Patel, D., Pardhi, D., Rathod, T., Solanki, A., Raval, V. H., Panchal, R. R., ... & Rajput, K. N. (2025). Mechanistic Insights of Plant-Microbe Interactions in Mitigation of Salinity Stress. In *Climate Change and Soil Microorganisms for Environmental Sustainability* (pp. 265-292). Springer, Singapore.
23. Peng, Y., Zhang, H., Li, G., & Zhang, J. (2025). Microbial inoculum improved soil aggregate formation and increased cucumber yield in a greenhouse under secondary salinization conditions. *Journal of Environmental Management*, *376*, 124576.
24. Qadir, M., Oster, J. D., Schubert, S., Noble, A. D., & Sahrawat, K. L. (2007). Phytoremediation of sodic and saline‐sodic soils. *Advances in agronomy*, *96*, 197-247.
25. Rengasamy, P. (2010). Soil processes affecting crop production in salt-affected soils. *Functional Plant Biology*, *37*(7), 613-620.
26. Richards, L. A. (Ed.). (1954). *Diagnosis and improvement of saline and alkali soils* (No. 60). US Government Printing Office.
27. Samuels, Toby, Casey Bryce, Hanna Landenmark, Claire Marie‐Loudon, Natasha Nicholson, Adam H Stevens, and Charles Cockell. 2020. "Microbial weathering of minerals and rocks in natural environments." *Biogeochemical cycles: Ecological drivers and environmental impact*:59-79.
28. Sharma, S. B., Sayyed, R. Z., Trivedi, M. H., & Gobi, T. A. (2013). Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils. *SpringerPlus*, *2*, 1-14.
29. Shrivastava, P., & Kumar, R. (2015). Soil salinity: a serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation*. Saudi J Biol Sci* 22: 123–131.
30. Silva-Herrera, H., Wege, S., Franzisky, B. L., Ahmad, N., Roelfsema, M. R. G., & Geilfus, C. M. (2025). Chloride transport and homeostasis in plants. *Quantitative Plant Biology*, *6*, e20.
31. Tandon, H. L. S. (2005). *Methods of analysis of soils, plants, waters, fertilisers & organic manures* (pp. xi+-203).
32. Velivelli, Siva LS, Angela Sessitsch, and Barbara Doyle Prestwich. 2014. "The role of microbial inoculants in integrated crop management systems." *Potato Research* 57 (3):291-309.
33. Yu, J., Zhang, X., Zhang, Z., Guo, H., Noborio, K., & Han, S. (2025). Effects of bioremediation on soil fertility and microbial communities of degraded grassland soil under dual petroleum contamination and saline-alkali stress. *Journal of Forestry Research*, *36*(1), 1-20.
34. Zhang, G., Zhang, L., Shi, Z., Yang, Y., & Liu, J. (2025). Microbial nutrient limitation and carbon use efficiency in saline-alkali soil amended with biochar: insights from ecoenzymatic C: N: P stoichiometry. *Biochar*, *7*(1), 68.

**Table 2. Impact of halotolerant bacterial inoculants on soil Cl- in different soil salinity levels**

|  |  |  |  |
| --- | --- | --- | --- |
| Treatments | 4.03 dS m-1 | 5.01 dS m-1 | 6.03 dS m-1 |
| 30 DAS | 60 DAS | 90 DAS | Mean | 30 DAS | 60 DAS | 90 DAS | Mean | 30 DAS | 60 DAS | 90 DAS | Mean |
| T1 - Control | 22.10 | 22.10 | 22.15 | 22.12 | 27.00 | 27.00 | 27.07 | 27.03 | 35.15 | 35.15 | 35.23 | 35.18 |
| T2 -TNAU Culture @ 1 L ha-1 | 21.18 | 20.53 | 20.08 | 20.60 | 26.18 | 25.53 | 25.07 | 25.59 | 33.86 | 32.61 | 31.75 | 32.74 |
| T3 - TNAU Culture @ 2 L ha-1 | 21.12 | 20.46 | 20.01 | 20.53 | 26.11 | 25.47 | 25.01 | 25.53 | 33.76 | 32.55 | 31.67 | 32.66 |
| T4 - TNAU Culture @ 3 L ha-1 | 21.06 | 20.41 | 19.94 | 20.47 | 26.05 | 25.40 | 24.94 | 25.46 | 33.69 | 32.45 | 31.59 | 32.58 |
| T5 - CSR-GROW-SURE @ 1 L ha-1 | 21.12 | 20.46 | 20.01 | 20.53 | 26.11 | 25.47 | 25.01 | 25.53 | 33.76 | 32.55 | 31.67 | 32.66 |
| T6 - CSR-GROW-SURE @ 2 L ha-1 | 21.06 | 20.41 | 19.94 | 20.47 | 26.05 | 25.40 | 24.94 | 25.46 | 33.69 | 32.45 | 31.59 | 32.58 |
| T7 - CSR-GROW-SURE @ 3 L ha-1 | 20.99 | 20.34 | 19.88 | 20.40 | 25.99 | 25.34 | 24.89 | 25.40 | 33.59 | 32.40 | 31.50 | 32.50 |
| Mean | 21.23 | 20.67 | 20.29 |   | 26.21 | 25.66 | 25.28 |   | 33.93 | 32.88 | 32.14 |   |
|   | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D |
| SEd |  0.05 |  0.12 |  0.19 |  0.06 |  0.15 |  0.21 |  0.05 |  0.15 |  0.20 |
| CD @ 5 % |  0.09 | 0.25 | 0.34 |  0.10 | 0.30  | 0.40  |  0.10 |  0.30 |  0.40  |

**Table 3. Impact of halotolerant bacterial inoculants on soil SO4 2- in different soil salinity levels**

|  |  |  |  |
| --- | --- | --- | --- |
| Treatments  | 4.03 dS m-1 | 5.01 dS m-1 | 6.02 dS m-1 |
| 30 DAS | 60 DAS  | 90 DAS | Mean | 30 DAS | 60 DAS | 90 DAS | Mean | 30 DAS | 60 DAS |  90 DAS | Mean |
| T1 - Control | 13.56 | 13.56 | 13.60 | 13.57 | 17.85 | 17.85 | 17.880 | 17.86 | 19.83 | 19.83 | 19.86 | 19.84 |
| T2 -TNAU Culture @ 1 L ha-1 | 13.00 | 12.61 | 12.33 | 12.65 | 17.31 | 16.89 | 16.58 | 16.93 | 19.37 | 18.93 | 18.63 | 18.98 |
| T3 - TNAU Culture @ 2 L ha-1 | 12.96 | 12.57 | 12.28 | 12.61 | 17.27 | 16.84 | 16.54 | 16.88 | 19.35 | 18.89 | 18.60 | 18.95 |
| T4 - TNAU Culture @ 3 L ha-1 | 12.92 | 12.53 | 12.24 | 12.56 | 17.22 | 16.79 | 16.50 | 16.84 | 19.32 | 18.87 | 18.58 | 18.92 |
| T5 - CSR-GROW-SURE @ 1 L ha-1 | 12.96 | 12.57 | 12.28 | 12.61 | 17.27 | 16.84 | 16.54 | 16.88 | 19.35 | 18.89 | 18.60 | 18.95 |
| T6 - CSR-GROW-SURE @ 2 L ha-1 | 12.92 | 12.53 | 12.24 | 12.56 | 17.22 | 16.79 | 16.50 | 16.84 | 19.32 | 18.87 | 18.58 | 18.92 |
| T7 - CSR-GROW-SURE @ 3 L ha-1 | 12.89 | 12.49 | 12.21 | 12.53 | 17.18 | 16.75 | 16.44 | 16.79 | 19.30 | 18.84 | 18.55 | 18.90 |
| Mean | 13.03 | 12.69 | 12.45 |   | 17.33 | 16.96 | 16.71 |   | 19.41 | 19.02 | 18.77 |   |
|   | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D |
| SEd |  0.02 |  0.08 |  0.10 |  0.03 |  0.06 |  0.09 |  0.01 |  0.06 |  0.07 |
| CD @ 5 % |  0.04 | 0.15  | 0.19 |  0.06 | 0.11 | 0.16 |  0.03 | 0.12 | 0.15  |



**Figure 1. Heat map of microbial bio inoculant application on soil HCO3- (meq kg⁻¹) in saline soils with varying electrical conductivity. Darker shades showed the high intensity of soil HCO3- and the less intensity has appeared by lighter shades.**