**Influence of Microbial Inoculants on Anion Behavior in Saline Soils under Moisture-Stressed Conditions**

**Abstract**

Soil salinity is a major constraint affecting agricultural productivity by disrupting nutrient balance and increasing toxic ion accumulation. Microbial inoculants offer a sustainable approach to ameliorate saline soils through biochemical transformations and anionic regulation. To evaluate the potential of salt-tolerant microbial inoculants for the biological reclamation of dry land saline soils with electrical conductivities (EC) of 4.03, 5.01, and 6.03 dS m-1 in alaboratory incubation experiment with 75 % field capacity (FC) moisture level at Tamil Nadu Agricultural University, Coimbatore, during 2021-2022 with incubation periods of 30, 60, and 90 days. The study evaluated two microbial inoculants: CSR-GROW-SURE Bacillus licheniformis, Lysinibacillus fusiformis, and Lysinibacillus sphaericus (from CSSRI, Karnal), and TNAU Culture containing Bacillus subtilis (from TNAU, Coimbatore). Both microbial inoculants CSR-GROW-SURE and TNAU Culture significantly reduced bicarbonate (HCO3-) chloride (Cl⁻), and sulphate (SO42-) concentrations across all salinity levels (4.03, 5.01, and 6.03 dS m⁻¹), with the greatest reductions observed at 90 days after incubation (DAI) and at the 3 L ha-1 dose. CSR-GROW-SURE @ 3 L ha-1 recorded the lowest values for HCO₃⁻ (3.09, 3.47, and 3.53 meq kg-1), Cl⁻ (19.94, 24.94, and 31.59 meq kg-1), and SO4-1 (12.24, 16.50, and 18.58 meq kg-1) in 4.03, 5.01, and 6.03 dS m-1 soils, respectively. Similarly, TNAU Culture @ 3 L ha-1 showed on par with values of 3.10, 3.48, and 3.54 meq kg-1, HCO3-; 20.01, 25.01, and 31.67 meq kg-1 of Cl⁻; and 12.28, 16.54, and 18.60 meq kg-1 of SO42- respectively in 4.03, 5.01, and 6.03 dS m-1 respectively. Compared to the control, both treatments attained 8–11 % reduction in Cl⁻ and decreases in HCO3- and SO42-, emphasizing the role of halotolerant microbes in improving soil health under dryland saline conditions.

**Key Words:** Bicarbonate, Chloride, Sulphate, Bacillus subtilis, CSR-GROW-SURE, Saline soils, Dry land condition

**1. Introduction**

Soil salinity is one of the major limiting factor to sustainable agricultural productivity (Wani et al., 2020), particularly in arid and semi-arid regions (Naorem *et al*., 2023 and Navarro-Torre *et al*., 2023). ease in global food security (Aadiwal *et al*., 2025 and Toshtemirovna *et al*., 2025). Food and Agriculture Organization of the United Nations (FAO), more than 833 million hectares, representing approximately 8.7 % of the Earth’s total land area are at risk of salinization (FAO 2021) Saline soils are characterized by electrical conductivity (EC) > 4 dS m⁻¹ (Datta *et al*., 2019 and Ismayilov *et al*., 2021) pH between 6-8, ESP < 15%, SAR < 13 (Gunarathne et al., 2020), indicating high soluble salts but low sodium hazard., with excessive concentrations of soluble anions salts such as bicarbonate (HCO3-), chloride (Cl⁻), and sulphate (SO₄²⁻) (Rai *et al*., 2021) and cations such sodium (Na⁺), calcium (Ca²⁺), and magnesium (Mg²⁺) (Datta *et al*., 2025). which adversely affect microbial activity (Zhang *et al*., 2024), nutrient availability (Zhu *et al*., 2021), soil structure (Tang *et al*., 2020) and water uptake (Chen *et al*., 2019).

In dryland ecosystems, where water availability is limited, and during evaporation of water the salts present the soil will come upward and accumulate in the top layer of the soil which causes the soil salinity (Wale *et al*., 2013, Hailu *et al*., 2021 and Stavi *et al*., 2021). Conventional reclamation practices such as gypsum application, leaching and mechanical drainage, though effective, are often unsustainable in low-input systems due to high water and resource demands (Skousen *et al*., 2019 and Chhabra *et al*., 2021). Hence, there is an increasing emphasis on biological approaches that offer eco-friendly, cost-effective, and sustainable solutions to soil salinity problems (Altynbay *et al*., 2024 and santhosh *et al*., 2025). Among biological strategies, the use of halotolerant plant growth-promoting rhizobacteria (PGPR) developed as a favorable approach (Abbas *et al*., 2019).

These microbes modulate soil chemistry by producing organic acids, exopolysaccharides (EPS), and enzymes that can neutralize or transform toxic salts, improve nutrient cycling, and enhance soil aggregation and permeability (Otlewska *et al*., 2020 and Ali *et al*., 2024). In particular, *Bacillus* *spp*. and *Lysinibacillus* *spp*. have shown strong potential for remediation of salt-affected soils through mechanisms such as microbial respiration, carbonic anhydrase activity, and cation–anion balance regulation (Muyzer & Stams, 2008, Damodaran *et al*., 2014 and Deka *et al*., 2018). In this regard, an incubation study was conducted to evaluate the effect of microbial cultures on anion dynamics in saline soils with an EC of 4.03, 5.01 and 6.03 dS m⁻¹, maintained under dryland conditions at 75% FC which was depicted in this paper.

**2. Materials and Methods**

**2.1. Collection of soil samples and Microbial inoculants**

Soil samples with an EC of 4.03, 5.01 and 6.03 dS m-1 were collected from Adivalli village in Udumalpet Taluk of Coimbatore district. The sampling locations were situated at latitudes 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. In this incubation experiment, microbial inoculants comprising halotolerant bacterial strains were employed to evaluate their efficiency under saline soil conditions. The CSR-GROW-SURE bio-stimulant, obtained from the Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana, contained halotolerant strains including *Lysinibacillus fusiformis* (CSR-A-11), *Lysinibacillus sphaericus* (CSR-A-16), and *Bacillus* *licheniformis* (CSR-M-16). Additionally, another microbial consortium sourced from Tamil Nadu Agricultural University (TNAU), Coimbatore, consisted of a salinity-resistant, initially unidentified bacterial strain that was later characterized and confirmed as *Bacillus subtilis*. This strain was used to compare its performance with CSR-GROW-SURE in improving saline soil conditions.

**2.2. Details of Incubation Experiment**

For the incubation study, 250 g of air-dried saline soil (EC 4.03, 5.01 and 6.03 dS m-1), sieved through a 2 mm mesh, was utilized. Microbial inoculants were applied at three doses 1, 2, and 3 L ha-1 (weight basis) in a factorial completely randomized design (CRD) with three replications. The experimental setup included three separate sets to facilitate destructive sampling. Two microbial formulations were used: the TNAU Culture (Bacillus subtilis) with a concentration of 2.8 × 107 CFU mL-1 and the CSR-GROW-SURE bio-stimulant containing 1.0 × 107 CFU mL-1. Incubation was conducted for 90 days under controlled moisture conditions 75 % FC. To maintain consistent moisture throughout the incubation period, distilled water was added every two days based on weight loss. Sampling was carried out at 30, 60, and 90 days after incubation (DAI) to analyze soil anions. Moisture correction factors were calculated and applied to report the analytical results on an oven-dry weight basis.

**2.3. Experiment details**

An incubation study was carried out to evaluate the effectiveness of microbial inoculants in reclaiming dryland saline soils and to determine the optimal dose of their application. An incubation study was conducted to evaluate the effect of microbial cultures on saline soils under controlled conditions. The experiment consisted of seven treatments: T1 – Control with soil EC levels of 4.03, 5.01, and 6.03 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. The soils were maintained at 75% FC to mimic dryland moisture conditions. The incubation periods were set at 30, 60, and 90 days, and each treatment was replicated three times to ensure statistical validity.

**2.4 Methodology**

**2.4.1. Soil Analysis**

In soil the EC was analysed 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). Sulphate was determined using the turbid metric 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. Initial anionic properties of soil 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**  **6.03 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**

The experimental data were analyzed statistically using AGRESS software version 7.01. When the “F” test indicated significance at the 5% level (P < 0.05), the Critical Difference (CD) was computed to compare treatment means Gomez and Gomez (1984). Heat map was developed using the “pheatmap” package in R to depict spatial variations among treatments, following data normalization and hierarchical clustering to enhance pattern recognition across variables.

**3. Results and discussion**

**3.1. Changes of bicarbonate content by microbial inoculants in dry land saline soil**

Under 75% FC dry land condition, the application of CSR-GROW-SURE with 3 L ha-1 was most effective in reducing soil HCO3- content, with mean levels of 3.17, 3.55, and 3.66 meq kg-1 in soils with EC 4.03, 5.01, and 6.03 dS m-1, respectively. This treatment was statistically similar to the TNAU culture applied at the same rate, with values of 3.18, 3.55, and 3.67 meq kg-1 across the same salinity levels. A moderate reduction was also attained with CSR-GROW-SURE at 2 L ha-1, having identical values to the TNAU culture with 3 L ha-1. In contrast, untreated control plots showed the highest HCO3- accumulation, with corresponding mean values of 3.43, 3.76, and 3.98 meq kg-1 with increasing EC levels (Table 2). The HCO3- content was decreased by *Bacillus* spp. by producing organic acids which leads to dilution of the carbonates reported by (Damodaran *et al.,* 2014).

Maximum decline of HCO₃⁻ was shown at incubation period of 90 days. And the mean values of 30, 60 and 90 DAI were 3.29, 3.21, 3.15; 3.66, 3.58, 3.53; 3.84, 3.70 and 3.61 meq kg-1 respectively in the soils with EC 4.03, 5.01 and 6.03 dS m-1 amended with microbial inoculum at 75 % FC. Bicarbonates (HCO3-) in saline soils are lowered primarily through the activity of soil microbes that excrete organic acids, which acidify the rhizosphere and neutralize HCO3- ions (Sharma *et al.,* 2013).

A significant interaction effect was observed between microbial cultures and incubation duration on soil HCO3- levels. After 90 DAI at 75 % FC, a noticeable decline in HCO3- concentration was recorded with CSR-GROW-SURE applied at 3 L ha-1, with values of 3.09, 3.47, and 3.53 meq kg-1 in soils with EC of 4.03, 5.01, and 6.03 dS m-1, respectively. These results closely matched those obtained with the TNAU culture at the same dosage and duration, which resulted in slightly higher but statistically equivalent with HCO₃⁻ values of 3.10, 3.48, and 3.54 meq kg-1 across the same salinity levels. This result highlights the role of prolonged incubation and high-dose microbial treatment in mitigating HCO3- buildup in saline soils. Microbial respiration releases carbon dioxide, which reacts with water to produce carbonic acid, facilitating the dissolution of HCO3- (Rengasamy, 2010). Furthermore, microbes secrete the enzyme carbonic anhydrase, which enhances the conversion of HCO3- into carbon dioxide and water, thereby increasing the reduction of HCO3- in the soil (Sharma *et al*., 2013).

**3.2. Influence of microbial inoculants on chloride content in dryland saline soils**

The influence of microbial inoculants on Cl⁻ changes in saline soils was assessed across varying application rates and salinity levels. A consistent reduction in Cl⁻ concentration was observed with increasing inoculant rates, shows it as a dose-dependent effect. Among the treatments, CSR-GROW-SURE applied at 3 L ha-1 recorded the lowest Cl⁻ levels, with mean values of 20.47, 25.46, and 32.58 meq kg-1 in soils of EC 4.03, 5.01, and 6.03 dS m-1, respectively, at 75 % FC. The TNAU culture at the same rate exhibited comparable reductions with Cl⁻ values of 20.53, 25.53, and 32.66 meq kg-1. Moderate declines were also noted with both formulations at 2 L ha⁻¹. In contrast, the untreated control constantly showed the highest Cl⁻ accumulation, with values of 22.13, 27.05, and 35.20 meq kg-1. Treatments at 3 L ha-1 from both microbial sources achieved a Cl⁻ reduction ranging between 6 and 8%. These findings are detailed in (Table 3), which presents Cl⁻ concentrations after microbial inoculation**.** Microbial production of extracellular polysaccharides improves soil aggregation and water movement, thereby promoting the leaching of Cl⁻ ions (Qadir *et al*., 2007).

At 75% FC, the Cl⁻ content showed a gradual decline over time, with mean values of 21.29, 20.73, and 20.35 meq kg-1 at 30, 60, and 90 DAI in soils with 4.03 dS m-1 salinity; 26.27, 25.72, and 25.33 meq kg-1 in soils with 5.02 dS m-1; and 34.00, 32.96, and 32.21 meq kg-1 in soils with 6.03 dS m-1. Damodaran *et al*., (2019) reported that the *Bacillus* *spp*. have the tolerance to survive in sodium chloride solution from 5 to 10 %, this is due to the halophilic nature of the *Bacillus* *spp*. as these utilize the chlorine for their cellular functions.

The interaction between cultures with various rates and incubation periods on soil Cl⁻ were significant. Among the treatments, significantly greater reduction in Cl⁻ was verified in CSR-GROW-SURE @ 3 L ha-1 at 90 DAI with the Cl⁻ of 19.94, 24.94 and 31.59 meq kg-1 in 4.03, 5.01 and 6.03 soils at 75 % FC moisture levels respectively. And it was at par with TNAU culture @ 3 L ha-1 at 90 DAI with the Cl⁻ of 20.01, 25.01 and 31.67 meq kg-1 in 4.03, 5.01 and 6.03 dS m-1 soils at 75 % FC moisture level. In both treatments the percent of Cl⁻ reduction is 8 to 11 %. The plant growth-promoting rhizobacteria (PGPR) enhance plant root development and Cl⁻ uptake, indirectly lowering Cl⁻ concentration in the soil (Shrivastava & Kumar, 2015).

**3.3 Sulphate response in dryland saline soil to microbial inoculants**

A decline in soil SO42- concentrations was observed following the application of microbial cultures, with the extent of reduction increasing alongside higher application rates. The treatment with CSR-GROW-SURE at 3 L ha-1 resulted in the most pronounced reduction across all salinity levels, recording mean values of 12.56, 16.84, and 18.92 meq kg-1 in soils with EC 4.03, 5.01, and 6.03 dS m-1, respectively, at 75 % FC. This was statistically comparable to the TNAU culture at the same dosage, which recorded mean SO42- levels of 12.61, 16.88, and 18.95 meq kg-1 (Table 4). In contrast, the control treatment, where no microbial inoculants were applied, showed the highest SO42- concentrations with values of 13.59, 17.87, and 19.85 meq kg-1 under similar salinity and moisture conditions Microbes assimilate SO42- into their biomass by incorporating it into sulphur-containing amino acids like cysteine and methionine. This process temporarily reduces the availability of SO42- in the soil solution. (Saha *et al*., 2018 and Chaudhary *et al*., 2023)

A consistent decline in SO42- concentration was observed over the incubation period across all levels of soil salinity. In soils with an EC of 4.03 dS m-1, the mean SO42- content decreased from 13.06 meq kg-1 at 30 DAI to 12.73 meq kg-1 at 60 DAI, and further to 12.49 meq kg-1 at 90 DAI. A similar trend was noted in soils with 5.01 dS m-1 EC, where SO42- levels declined from 17.37 to 17.01 and 16.75 meq kg-1 over the same time intervals. In the most saline condition (EC 6.03 dS m-1), the SO42- concentration reduced from 19.43 meq kg-1 at 30 DAI to 19.05 meq kg-1 at 60 DAI and finally to 18.79 meq kg-1 at 90 DAI. These results indicate a time-dependent decrease in SO₄²⁻ levels, with greater reductions observed in soils with higher salinity, due to enhanced microbial-mediated transformations at 75 % FC. The reduction in SO42- content due to Sulphur oxidation by product of bacteria that is sulphuric acid reported by (Velivelli *et al*., 2014 and Samuels *et al*., 2020).

The interaction between microbial inoculant types, their application rates, and incubation durations had a significant impact on soil SO42- concentrations. Among the treatments, the most notable reduction in SO42- was observed with CSR-GROW-SURE applied at 3 L ha-1 after 90 DAI, with recorded values of 12.24, 16.50, and 18.58 meq kg-1 in soils with EC levels of 4.03, 5.01, and 6.03 dS m-1, respectively, under 75% FC. This was on par with TNAU culture at the same dosage and incubation period, which resulted SO42- concentrations of 12.28, 16.54, and 18.60 meq kg-1 across the same salinity levels. Slightly higher SO₄²⁻ levels were observed with the application of CSR-GROW-SURE and TNAU cultures at 2 L ha-1, which resulted in SO42- values of 12.28, 16.54, and 16.58 meq kg-1, respectively, at 90 DAI. Sulphate (SO42-) are reduced through microbial respiration under anaerobic conditions by sulfate-reducing bacteria, which convert SO42- into hydrogen sulfide (Muyzer & Stams, 2008). 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).

**4. Conclusion**

The incubation study conducted under dryland conditions 75% FC revealed that halotolerant microbial inoculants CSR-GROW-SURE and TNAU Culture significantly reduced the anions of HCO3-, Cl⁻, and SO42- concentrations in saline soils with EC levels of 4.03, 5.01, and 6.03 dS m-1. Among the treatments, CSR-GROW-SURE @ 3 L ha-1 was the most effective, with HCO₃⁻ levels of 3.09, 3.47, and 3.53 meq kg-1 after 90 DAI, which was on par with TNAU Culture @ 3 L ha⁻¹ (3.10, 3.48, and 3.54 meq kg-1) with the respective EC levels. The control treatment showed significantly higher values of HCO3- levels from 3.43, 3.77 and 3.98 meq kg-1. Chloride (Cl⁻) content was also reduced with application of CSR-GROW-SURE @ 3 L ha⁻¹ (19.94, 24.94 and 31.59 meq kg-1) and TNAU Culture @ 3 L ha-1 (20.01, 25.01 and 31.67 meq kg-1), representing an 8–11% decrease over the control (22.15, 27.07 and 35.23 meq kg-1). Similarly, maximum reduction in sulphate is observed in treatment CSR-GROW-SURE @ 3 L ha-1 with values of 12.24, 16.50 and 18.58 meq kg-1 and it was on par with TNAU Culture @ 3 L ha-1. Decrease of anions in soil is due to microbial mechanisms such as organic acid production, carbonic anhydrase activity, and exopolysaccharide secretion. The findings confirm that microbial inoculants, particularly at higher doses (3 L ha-1), are effective in improving saline soil quality by reducing harmful anions. Thus, the study representing sustainable strategy for the biological reclamation of saline soils under moisture-stressed, dryland environments.

**Reference**

1. Aadiwal, V., Meher, K., Kalidhas, A. M., & Mishra, A. K. (2025). Spatial Modeling of Soil Salinity and Its Impact on Nutrient Availability and Agricultural Productivity. *Natural and Engineering Sciences*, *10*(1), 312-324.
2. Abbas, R., Rasul, S., Aslam, K., Baber, M., Shahid, M., Mubeen, F., & Naqqash, T. (2019). Halotolerant PGPR: A hope for cultivation of saline soils. *Journal of King Saud University-Science*, *31*(4), 1195-1201.
3. Ali, N., Abbas, S. A. A. A., Sharif, L., Shafiq, M., Kamran, Z., Haseeb, M., & Shahid, M. A. (2024). Microbial extracellular polymeric substance and impacts on soil aggregation. In *Bacterial secondary metabolites* (pp. 221-237). Elsevier.
4. Altynbay, N., Tastambek, K., Akimbekov, N., Digel, I., Tagayev, K., Kamenov, B., & Liu, X. (2024). A comprehensive review on enhancing saline soil reclamation efficiency through bacterial solubilization of low-rank coal. *Engineered Science*, *30*, 1147.
5. Chaudhary, S., Sindhu, S. S., Dhanker, R., & Kumari, A. (2023). Microbes-mediated sulphur cycling in soil: Impact on soil fertility, crop production and environmental sustainability. *Microbiological Research*, *271*, 127340.
6. Chen, L., Li, C., Feng, Q., Wei, Y., Zhao, Y., Zhu, M., & Deo, R. C. (2019). Direct and indirect impacts of ionic components of saline water on irrigated soil chemical and microbial processes. *Catena*, *172*, 581-589.
7. Chhabra, R., & Chhabra, R. (2021). Management and Reclamation of Saline Soils. *Salt-Affected Soils and Marginal Waters: Global Perspectives and Sustainable Management*, 101-160.
8. 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.
9. 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.
10. Datta, A., Basak, N., Saha, B., & Basak, P. (2025). Enhancing Soil Health by Mitigating Salinity in India. *Soil Health and Sustainability in India*, 352.
11. Datta, A., Mandal, A. K., & Yadav, R. K. (2019). Proper measurement of electrical conductivity and other parameters influence profile salinity and sodicity under different land uses. *Ecological Indicators*, *101*, 1004-1006.
12. Deka, P. (2018). *A study on the role of exopolysaccharide in conferring acid tolerance in Bacillus sp* (Doctoral dissertation, Assam Agricultural University JORHAT).
13. Dhami, N. K., Reddy, M. S., & Mukherjee, A. (2013). Bacillus megaterium mediated mineralization of calcium carbonate as biogenic surface treatment of green building materials. *World Journal of Microbiology and Biotechnology*, *29*, 2397-2406.
14. Doneen, L.D., 1964. Notes on water quality in agriculture published as a water science and engineering paper 4001. Department of Water Science and Engineering, University of California, Davis, Oakland, CA, USA.
15. 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.
16. FAO (2021) Global Map of Salt Affected Soils Version 1.0 <https://www.fao.org/soilsportal/data-hub/soil-maps-and-databases/global-map-of-salt-affected-soils>.
17. Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research*. John wiley & sons.
18. Gunarathne, V., Senadheera, J. A. I., Gunarathne, U., Almaroai, Y. A., & Vithanage, M. (2020). Reclamation of salt-affected soils. In *Soil and Groundwater Remediation Technologies* (pp. 183-199). CRC Press.
19. Hailu, B., & Mehari, H. (2021). Impacts of soil salinity/sodicity on soil-water relations and plant growth in dry land areas: A review. *J. Nat. Sci. Res*, *12*(3), 1-10.
20. Hataf, N., & Baharifard, A. (2020). Reducing soil permeability using microbial induced carbonate precipitation (MICP) method: a case study of shiraz landfill soil. *Geomicrobiology Journal*, *37*(2), 147-158.
21. Ismayilov, A. I., Mamedov, A. I., Fujimaki, H., Tsunekawa, A., & Levy, G. J. (2021). Soil salinity type effects on the relationship between the electrical conductivity and salt content for 1: 5 soil-to-water extract. *Sustainability*, *13*(6), 3395.
22. Jackson, M. L. (1973). Soil chemical analysis, pentice hall of India Pvt. *Ltd., New Delhi, India*, *498*, 151-154.
23. Muyzer, G., & Stams, A. J. (2008). The ecology and biotechnology of sulphate-reducing bacteria. *Nature reviews microbiology*, *6*(6), 441-454.
24. Naorem, A., Jayaraman, S., Dang, Y. P., Dalal, R. C., Sinha, N. K., Rao, C. S., & Patra, A. K. (2023). Soil constraints in an arid environment—challenges, prospects, and implications. *Agronomy*, *13*(1), 220.
25. Navarro-Torre, S., Garcia-Caparrós, P., Nogales, A., Abreu, M. M., Santos, E., Cortinhas, A. L., & Caperta, A. D. (2023). Sustainable agricultural management of saline soils in arid and semi-arid Mediterranean regions through halophytes, microbial and soil-based technologies. *Environmental and Experimental Botany*, *212*, 105397.
26. Niknam Safari Kouchi, E., Nikooee, E., Habibagahi, G., Niazi, A., & Nagel, T. (2025). The Swelling Characteristics of an Unsaturated Bio-cemented Sand-Bentonite Mixture: Analyzing the Effect of Bacterial Concentration and Suction. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 1-21.
27. Osman, H. S., Rady, A. M., Awadalla, A., Omara, A. E. D., & Hafez, E. M. (2022). Improving the antioxidants system, growth, and sugar beet quality subjected to long-term osmotic stress by phosphate solubilizing bacteria and compost tea. *International Journal of Plant Production*, *16*(1), 119-135.
28. Otlewska, A., Migliore, M., Dybka-Stępień, K., Manfredini, A., Struszczyk-Świta, K., Napoli, R., ... & Pinzari, F. (2020). When salt meddles between plant, soil, and microorganisms. *Frontiers in plant science*, *11*, 553087.
29. 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.
30. Rai, A. K., Basak, N., & Sundha, P. (2021). Chemistry of salt-affected soils. Managing salt-affected soils for sustainable agriculture, 128-148.
31. Rengasamy, P. (2010). Soil processes affecting crop production in salt-affected soils. *Functional Plant Biology*, *37*(7), 613-620.
32. Richards, L. A. (Ed.). (1954). *Diagnosis and improvement of saline and alkali soils* (No. 60). US Government Printing Office.
33. Saha, B., Saha, S., Roy, P. D., Padhan, D., Pati, S., & Hazra, G. C. (2018). Microbial transformation of sulphur: an approach to combat the sulphur deficiencies in agricultural soils. *Role of rhizospheric microbes in soil: Volume 2: nutrient management and crop improvement*, 77-97.
34. Salma Santhosh, S., Meena, S., Baskar, M., Karthikeyan, S., Vanniarajan, C., & Ramesh, T. (2025). Transformative strategies for saline soil restoration: Harnessing halotolerant microorganisms and advanced technologies. *World Journal of Microbiology and Biotechnology*, *41*(5), 1-41.
35. 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.
36. 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.
37. 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*.
38. Skousen, J., Zipper, C. E., McDonald, L. M., Hubbart, J. A., & Ziemkiewicz, P. F. (2019). Sustainable reclamation and water management practices. In *Advances in productive, safe, and responsible coal mining* (pp. 271-302). Woodhead Publishing.
39. Stavi, I., Thevs, N., & Priori, S. (2021). Soil salinity and sodicity in drylands: A review of causes, effects, monitoring, and restoration measures. *Frontiers in Environmental Science*, *9*, 712831.
40. Tandon, H. L. S. (2005). *Methods of analysis of soils, plants, waters, fertilisers & organic manures* (pp. xi+-203).
41. Tang, S., She, D., & Wang, H. (2020). Effect of salinity on soil structure and soil hydraulic characteristics. *Canadian Journal of Soil Science*, *101*(1), 62-73.
42. Tarolli, Paolo & Luo, Jian & Park, Edward & Barcaccia, Gianni & Masin, Roberta. (2024). Soil salinization in agriculture: Mitigation and adaptation strategies combining nature-based solutions and bioengineering. iScience. 27. 108830. 10.1016/j.isci.2024.108830.
43. Toshtemirovna, N. U., & Raufovna, K. G. (2025). The effect of salinity on the growth and development of soybean varieties. *Modern American Journal of Biological and Environmental Sciences*, *1*(2), 78-87.
44. 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.
45. Wale, H. A., & Dejenie, T. (2013). Dryland ecosystems: Their features, constraints, potentials and managements. *Research Journal of Agricultural and Environmental Management*, *2*(10), 277-288.
46. Wani, S. H., Kumar, V., Khare, T., Guddimalli, R., Parveda, M., Solymosi, K., ... & Kavi Kishor, P. B. (2020). Engineering salinity tolerance in plants: progress and prospects. *Planta*, *251*(4), 76.
47. Zhang, G., Bai, J., Zhai, Y., Jia, J., Zhao, Q., Wang, W., & Hu, X. (2024). Microbial diversity and functions in saline soils: A review from a biogeochemical perspective. *Journal of advanced research*, *59*, 129-140.
48. Zhu, Y., Guo, B., Liu, C., Lin, Y., Fu, Q., Li, N., & Li, H. (2021). Soil fertility, enzyme activity, and microbial community structure diversity among different soil textures under different land use types in coastal saline soil. *Journal of Soils and Sediments*, *21*, 2240-2252.

**Table 2. Effect of microbial inoculant on HCO3⁻ concentration (meq kg-1) under varying soil salinity levels**

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Treatments | **4.03 dS m-1** | | | | **5.01 dS m-1** | | | | **6.03 dS m-1** | | | |
| **30 DAI** | **60 DAI** | **90 DAI** | **Mean** | **30 DAI** | **60 DAI** | **90 DAI** | **Mean** | **30 DAI** | **60 DAI** | **90 DAI** | **Mean** |
| T1 - Control | 3.42 | 3.43 | 3.43 | 3.43 | 3.75 | 3.77 | 3.77 | 3.76 | 3.98 | 3.99 | 3.99 | 3.98 |
| T2 -TNAU Culture @ 1 L ha-1 | 3.29 | 3.19 | 3.12 | 3.20 | 3.65 | 3.56 | 3.50 | 3.57 | 3.83 | 3.67 | 3.56 | 3.69 |
| T3 - TNAU Culture @ 2 L ha-1 | 3.28 | 3.18 | 3.11 | 3.19 | 3.64 | 3.55 | 3.49 | 3.56 | 3.82 | 3.66 | 3.55 | 3.68 |
| T4 - TNAU Culture @ 3 L ha-1 | 3.27 | 3.17 | 3.10 | 3.18 | 3.63 | 3.54 | 3.48 | 3.55 | 3.81 | 3.65 | 3.54 | 3.67 |
| T5 - CSR-GROW-SURE @ 1 L ha-1 | 3.28 | 3.18 | 3.11 | 3.19 | 3.64 | 3.55 | 3.49 | 3.56 | 3.82 | 3.66 | 3.55 | 3.68 |
| T6 - CSR-GROW-SURE @ 2 L ha-1 | 3.27 | 3.17 | 3.10 | 3.18 | 3.63 | 3.54 | 3.48 | 3.55 | 3.81 | 3.65 | 3.54 | 3.67 |
| T7 - CSR-GROW-SURE @ 3 L ha-1 | 3.26 | 3.16 | 3.09 | 3.17 | 3.63 | 3.54 | 3.47 | 3.55 | 3.80 | 3.64 | 3.53 | 3.66 |
| Mean | 3.29 | 3.21 | 3.15 |  | 3.66 | 3.58 | 3.53 |  | 3.84 | 3.70 | 3.61 |  |
|  | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D |
| SEd | 0.01 | 0.02 | 0.03 | 0.01 | 0.02 | 0.03 | 0.01 | 0.04 | 0.05 |
| CD @ 5 % | 0.02 | 0.04 | 0.06 | 0.02 | 0.03 | 0.05 | 0.03 | 0.07 | 0.10 |

**Table 3. Effect of microbial cultures on Cl-1 (meq kg-1) under varying 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 | 22.15 | 22.15 | 22.13 | 27.00 | 27.07 | 27.07 | 27.05 | 35.15 | 35.23 | 35.23 | 35.20 |
| T2 -TNAU Culture @ 1 L ha-1 | 21.25 | 20.60 | 20.14 | 20.66 | 26.24 | 25.60 | 25.13 | 25.66 | 33.93 | 32.69 | 31.82 | 32.81 |
| T3 - TNAU Culture @ 2 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 |
| T4 - TNAU Culture @ 3 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 |
| T5 - CSR-GROW-SURE @ 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 |
| T6 - CSR-GROW-SURE @ 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 |
| T7 - CSR-GROW-SURE @ 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 |
| Mean | 21.29 | 20.73 | 20.35 |  | 26.27 | 25.72 | 25.33 |  | 34.00 | 32.96 | 32.21 |  |
|  | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D |
| SEd | 0.04 | 0.15 | 0.19 | 0.05 | 0.17 | 0.21 | 0.05 | 0.25 | 0.30 |
| CD @ 5 % | 0.08 | 0.31 | 0.39 | 0.10 | 0.34 | 0.42 | 0.10 | 0.51 | 0.61 |

**Table 4. Influence of microbial inoculants on SO42- under varying 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 | 13.56 | 13.60 | 13.60 | 13.59 | 17.85 | 17.880 | 17.880 | 17.87 | 19.83 | 19.86 | 19.86 | 19.85 |
| T2 -TNAU Culture @ 1 L ha-1 | 13.04 | 12.64 | 12.36 | 12.68 | 17.35 | 16.93 | 16.62 | 16.97 | 19.40 | 18.96 | 18.66 | 19.01 |
| T3 - TNAU Culture @ 2 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 |
| T4 - TNAU Culture @ 3 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 |
| T5 - CSR-GROW-SURE @ 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 |
| T6 - CSR-GROW-SURE @ 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 |
| T7 - CSR-GROW-SURE @ 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 |
| Mean | 13.06 | 12.73 | 12.49 |  | 17.37 | 17.01 | 16.75 |  | 19.43 | 19.05 | 18.79 |  |
|  | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D |
| SEd | 0.03 | 0.09 | 0.12 | 0.04 | 0.11 | 0.14 | 0.02 | 0.10 | 0.12 |
| CD @ 5 % | 0.06 | 0.18 | 0.24 | 0.07 | 0.22 | 0.28 | 0.04 | 0.20 | 0.24 |