**Reclamation of Saline Soils through Microbial-Induced Exchangeable Cationic Shifts**

**Abstract**

A laboratory incubation study was carried out at TNAU, Coimbatore (2021–2022), to assess the impact of salt-tolerant microbial inoculants CSR-GROW-SURE (containing *Lysinibacillus fusiformis* (CSR-A-11), *Lysinibacillus sphaericus* (CSR-A-16), and *Bacillus licheniformis* (CSR-M-16) and TNAU culture (consisting *Bacillus subtilis*) applied at 1, 2, and 3 L ha⁻¹ on saline soils with EC levels of 4.03, 5.01, and 6.03 dS m-1. The study evaluated changes in exchangeable calcium (Ca2+), magnesium (Mg2+), sodium (Na+), and exchangeable potassium (K+) at 30, 60, and 90 days after incubation (DAI) under 100 % field capacity (FC). At 90 DAI, the application of CSR-GROW-SURE at 3 L ha-1 significantly reduced the concentrations of exchangeable cations Ca²⁺ (9.50, 12.09, 13.75 meq kg-1), Mg2+ (5.04, 6.68, 8.09 meq kg-1), and Na⁺ (11.18, 14.13, 17.63 meq kg-1) with increasing soil salinity levels (EC 4.03, 5.01, and 6.03 dS m⁻¹). In contrast, a significant increase in exchangeable K+ was observed, with values of 9.44, 11.90, and 14.11 meq kg-1, representing improved soil nutrient balance. A similar response was recorded with TNAU *Bacillus* *subtilis* culture at 3 L ha⁻¹, where Ca2+, Mg2+, and Na+ were reduced to 9.52, 12.12, 13.76; 5.05, 6.70, 8.10; and 11.32, 14.23, 17.78 meq kg-1, respectively, across the same salinity levels, while K+ increased to 9.39, 11.86, and 14.06 meq kg-1. These trends suggest that microbial inoculation modifies ionic dynamics by decreasing exchangeable sodicity and enhancing potassium availability under saline stress. These results confirm that both microbial inoculants at higher application rates were effective in improving the chemical properties of saline soils by reducing exchangeable cations (Na+, Ca2+, & Mg2+) and increasing exchangeable K+, with the most significant changes observed at 90 DAI.

**Key Words:** *Bacillus* *spp*., CSR-GROW-SURE, Exchangeable calcium, Exchangeable Magnesium, Exchangeable potassium, Exchangeable sodium, Saline soils

**1. Introduction**

Soil salinity is one of the most significant challenges limiting sustainable agricultural productivity, especially in arid and semi-arid regions where evapotranspiration exceeds precipitation (Naorem *et al.,* 2023, Afrooz et al., 2025 and Gelu et al., 2025). As salts accumulate in the soil profile, they hinder plant water and nutrient uptake, ultimately reducing crop yields (Abd El Baki *et al*.*,* 2025 and Demo *et al*., 2025). Globally, more than 833 million hectares, accounting for approximately 8.7% of the Earth’s land surface, are reported to be affected by salt stress (FAO, 2021; Aadiwal *et al*., 2025). In India, dryland agriculture constitutes around 51% of total cultivated land, Dryland ecosystems are characterized by limited moisture availability, where evaporation consistently exceeds rainfall, causes prolonged aridity. These regions include approximately 5.36 million km² around 41% of the Earth’s total land are and are inhabited by nearly one-third of the world’s population (Kundu *et al*., 2025). Soils in such environments frequently exhibits alkaline properties and tend to accumulate higher concentrations of soluble salts such as sodium (Na+), exchangeable (K⁺), and calcium (Ca2+). The build-up of these ions can induce toxicity, disrupt nutrient dynamics, and hinder both plant development and microbial activity in the soil (Saleem *et al*., 2025 and Verma *et al*., 2025)

Saline soils are characterized by an electrical conductivity (EC) > 4 dS m⁻¹, sodium absorption ratio (SAR) < 13, exchangeable sodium percentage (ESP) < 15%, and a near-neutral pH (Gunarathne *et al.,* 2020; Datta *et al.,* 2019; Ismayilov *et al.,* 2021). These soils are often rich in soluble salts, such as chloride (Cl⁻), bicarbonate (HCO3-), and sulphate (SO42-), along with cations like Na+, Ca2+, Mg+, and K+ (Rai *et al.,* 2021, Datta *et al.,* 2025 and Singh *et al.,* 2025). Though some saline soils have good aggregation due to flocculation, repeated leaching can cause clay dispersion, thereby reducing permeability and water movement (Abrol *et al.,* 1988; Saleem *et al.,* 2025). Additionally, salt accumulation suppresses microbial activity (Zhang *et al.,* 2024), slows down organic matter decomposition, and restricts nutrient cycling (Zhu *et al.,* 2021; Tripathi *et al.,* 2006; Sahoo *et al.,* 2025).

Conventional management practices, including gypsum application, leaching, and subsurface drainage, though effective, are not always feasible in resource-limited systems due to high water and input demands (Ammu *et al*., 2025, Guo *et al.,* 2025 and Liu *et al.,* 2025). Hence, there is increasing interest in alternative biological approaches that are cost-effective, eco-friendly, and adaptable to field-level variability (Bhardwaj *et al*., 2025; Shelke *et al*., 2025). Among these, halotolerant plant growth-promoting rhizobacteria (PGPR) have emerged as potential bio-tools for ameliorating salt stress (Salma *et al*., 2025). These microbes secrete phytohormones, organic acids, exopolysaccharides (EPS), siderophores, and enzymes like ACC deaminase, which not only enhance nutrient availability but also improve microbial colonization and soil structure (Upadhyay *et al*., 2009; Shanware *et al*., 2014 and Egamberdieva *et al*., 2019).

Species such as *Bacillus*, *Pseudomonas*, and *Arthrobacter* have been extensively reported for their role in improving salinity tolerance in plants by supporting root architecture, maintaining ion balance, and conserving soil nutrients (Jha and Subramanian, 2014; Bhise *et al.,* 2017 and Sarkar *et al*., 2018). Particularly, *Bacillus* spp. are considered highly effective due to their resilience in extreme environments, production of carbonic anhydrase, and facilitation of cation–anion balance under saline stress (Muyzer and Stams, 2008; Abd-Allah *et al*., 2018 and Deka *et al*., 2018). In addition, they bind excess Na+ (Chen *et al*., 2007), solubilize phosphorus and micronutrients, and enhance plant tolerance to abiotic stress (Dey *et al*., 2021). In this study, halophilic microbial consortia were evaluated as a promising approach for the reclamation of salt-affected dryland soils. The effectiveness of two microbial formulations was assessed under salinity levels of 4.03, 5.01, and 6.03 dS m⁻¹, with soils maintained at 100% field capacity (FC). The impact of microbial application on soil cation dynamics was monitored at intervals of 30, 60, and 90 days.

**2. Materials and Methods**

**2.1. Soil sampling and microbial formulations selection for salinity mitigation**

Soil samples were collected from salt-affected fields in Adivalli village, located in Udumalpet taluk of Coimbatore district. The selected sampling sites exhibited varying salinity levels, with EC values of 4.03, 5.01, and 6.03 dS m⁻¹. The geographical coordinates of the sampling locations 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. The collected samples were air-dried, sieved through a 2 mm mesh, and stored for further analysis and incubation studies. Two microbial formulations were used in the study. Two microbial formulations such as CSR-GROW-SURE, collected from the ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana, consisting halotolerant bacterial strains such as *Lysinibacillus fusiformis* (CSR-A-11), *Lysinibacillus sphaericus* (CSR-A-16), and *Bacillus licheniformis* (CSR-M-16), with a cell concentration of 1.0 × 10⁷ CFU mL-1 and another formulation, obtained from Tamil Nadu Agricultural University (TNAU), Coimbatore, contained a salinity-tolerant strain later identified as *Bacillus subtilis*, with a population density of 2.8 × 10⁷ CFU mL-1. These formulations were used for evaluating microbial efficacy in ameliorating saline soil conditions under controlled incubation experiments

**2.2. Details of Incubation Experiment**

The experiment was designed to assess the efficacy of microbial inoculants in saline soils with EC levels of 4.03, 5.01, and 6.03 dS m⁻¹, maintained at 100 % FC. A total of 250 g of air-dried, 2 mm-sieved soil was used for each treatment. The study followed a factorial completely randomized design (FCRD) with three replications and was conducted over a 90-day incubation period. Treatments included a Control (T1), TNAU Culture at 1 L ha-1 (T2), 2 L ha-1 (T3), and 3 L ha-1 (T4), and CSR-GROW-SURE at 1 L ha-1 (T5), 2 L ha-1 (T6), and 3 L ha-1 (T7). The microbial formulations were applied at concentrations of 2.8 × 10⁷ CFU mL-1 for the TNAU strain and 1.0 × 10⁷ CFU mL-1 for the CSR-GROW-SURE consortium.

Soils were incubated under controlled moisture conditions, with distilled water added every two days to maintain the target moisture content. Destructive sampling was carried out at 30, 60, and 90 DAI to monitor temporal changes in soil cations. Three parallel sets of each treatment were maintained for destructive sampling. All analytical results were standardized and reported on an oven-dry weight basis, applying appropriate moisture correction factors to ensure accuracy and comparability across treatments.

**2.3 Methodology**

**2.3.1. Soil Analysis**

In soil the EC was analyzed by the 1:2.5 Soil water extract method (Jackson 1973)Exchangeable cations like Ca2+ and Mg2+ were determined using the Versenate method, which uses EDTA-based complex metric titration to calculate divalent cations. Exchangeable Na+ and exchangeable K⁺ was analyzed using a flame photometer following the procedure outlined by Richards (1968). Three saline soil samples with EC levels of 4.03, 5.01, and 6.02 dS m-1 were collected and analyzed for selected exchangeable cations. The concentrations of exchangeable cations in the soil increased proportionally with rising salinity levels. In soils with EC values of 4.03, 5.01, and 6.02 dS m⁻¹, the exchangeable Ca2+ contents were 10.34, 12.64, and 14.58 meq kg⁻¹, respectively. Exchangeable Mg2+ levels were observed at 5.48, 6.98, and 8.58 meq kg-1 across the same salinity gradients. Similarly, exchangeable Na⁺ concentrations rose from 15.27 to 19.10, and 23.76 meq kg-1. exchangeable K⁺ also exhibited an increasing trend with values of 7.99, 9.89, and 12.04 meq kg-1 in the respective saline soils.

**2.3.2. Statistical Analysis**

The data obtained from the experiment were analyzed statistically using AGRES software version 7.01. When the F-test showed significance at the 5% probability level (P < 0.05), the Critical Difference (CD) was calculated to determine significant differences among treatment means, as outlined by Gomez and Gomez (1984). The “pheatmap” package in R was used to construct heat map that explain treatment-related variability, with data normalized and grouped through hierarchical clustering to enhance interpretability.

**3. Results and discussion**

**3.1. Impact of microbial inoculants on soil exchangeable calcium**

 Irrespective of the soil EC levels (4.03, 5.01, and 6.03 dS m-1), a consistent decrease in exchangeable Ca2+ was observed following the application of CSR-GROW-SURE at 3 L ha-1, with average values recorded at 9.72, 12.23, and 13.98 meq kg-1 under 100 % FC. These results were statistically on par with those of the TNAU culture applied at the same rate, which yielded comparable mean values of 9.74, 12.26, and 14.00 meq kg-1. In contrast, the control treatment exhibited the highest levels of exchangeable Ca²⁺, with average values of 10.35, 12.65, and 14.58 meq kg-1 corresponding to the respective EC levels (Table 1). A general trend of decreasing exchangeable Ca2+ was observed across all treatments and salinity levels as the incubation period progressed, showing decline from 10.03 to 9.66 meq kg-1 at 4.03 dS m-1, from 12.46 to 12.20 meq kg-1 at 5.01 dS m⁻¹, and from 14.31 to 13.89 meq kg⁻¹ at 6.03 dS m-1. Chen *et* *al*., (2000) similarly observed that the organic acids generated by *Bacillus* *spp*. aid in breaking down calcareous minerals, which in turn significantly impacts the distribution and availability of exchangeable Ca2+ in the soil.

 The interaction between microbial inoculants and incubation duration revealed that the most significant reduction in exchangeable Ca2+ was observed with CSR-GROW-SURE applied at 3 L ha-1 at 90 DAI, with values of 9.52, 12.12, and 13.76 meq kg-1 at EC levels of 4.03, 5.01, and 6.03 dS m⁻¹, respectively. A similar trend was noted with the TNAU culture at the same application rate, which was on par with values of 9.57, 12.14, and 13.78 meq kg-1 under identical conditions. The decline in exchangeable Ca2+ levels is likely due to the release of organic acids, especially carbonic acid, by *Bacillus* *spp.* which promotes the solubilization and mobilization of Ca2+ ions within the soil matrix (Macias-Benitez *et* *al*., 2020). Similarly, Neina (2019) noted that the release of organic acids caused changes in soil pH, which in turn led to a decrease in soil exchangeable Ca2+ levels.

**3.2. Impact of microbial inoculants on soil exchangeable magnesium**

In terms of exchangeable Mg2+ dynamics, the application of CSR-GROW-SURE at 3 L ha-1 resulted in a marked reduction in exchangeable Mg2+ concentrations, with mean values of 5.16, 6.76, and 8.22 meq kg-1 under soil EC levels of 4.03, 5.01, and 6.03 dS m-1, respectively (Figure1). These values were statistically on par with TNAU microbial inoculant applied at an equivalent rate, which recorded mean exchangeable Mg2+ contents of 5.17, 6.77, and 8.23 meq kg-1 under the respective salinity conditions (Figure 1). In contrast, the untreated control exhibited significantly higher Mg²⁺ levels, with concentrations of 5.49, 6.99, and 8.58 meq kg-1 under 100 % FC at the corresponding EC levels.

The greatest decline in exchangeable Mg2+ was recorded at 90 DAI, with average values reducing from 5.32 to 5.12 meq kg-1 (4.03 dS m-1), from 6.88 to 6.74 meq kg-1 (5.01 dS m-1), and from 8.41 to 8.17 meq kg-1 (6.03 dS m-1). This reduction is mainly attributed to microbial-induced soil acidification, particularly through the secretion of organic acids, which modify the soil pH and promote the depletion of exchangeable Mg²⁺ (Stamford *et al*., 2007).

The interaction effect between microbial inoculants and incubation duration indicated that the most significant decrease in exchangeable Mg2+ was observed with the application of CSR-GROW-SURE at 3 L ha-1 at 90 DAI, with values of 5.04, 6.68, and 8.09 meq kg-1 at EC levels of 4.03, 5.01, and 6.03 dS m⁻¹ respectively. These values were statistically comparable to those obtained with the TNAU culture at the same dosage, with exchangeable Mg2+ concentrations of 5.05, 6.70, and 8.10 meq kg-1 under similar conditions. These observations are identical with the findings of Thomas *et* *al*., (2014), who reported that the ability of *Bacillus* *spp*. to bind cations contributes to the reduction of exchangeable Mg2+ in soils.

**3.3. Impact of microbial inoculants on soil exchangeable sodium**

The exchangeable Na⁺ levels consistently decreased with the application of microbial inoculants at different dosages, prolonged incubation enhanced microbial activity, causes greater reduction. The use of CSR-GROW-SURE at a rate of 3 L ha⁻¹ led to average exchangeable Na⁺ concentrations of 12.20, 15.35, and 19.33 meq kg-1 in soils with EC levels of 4.03, 5.01, and 6.03 dS m-1, respectively (Table 2). Similar results were obtained with the TNAU culture at the same application rate, recorded exchangeable Na+ values of 12.34, 15.35, and 19.33 meq kg-1 under the corresponding salinity conditions. In contrast, the control treatment registered the highest levels of exchangeable Na+, with mean values of 15.31, 19.15, and 23.81 meq kg⁻¹ at the respective EC levels. Arora *et* *al*., (2016), reported that the effectiveness of microbial inoculants in reducing soil exchangeable Na+ levels and enhancing soil chemical properties under saline conditions.

A constant decline in exchangeable Na⁺ content was recorded over the 90-day incubation period, with levels decreasing from 13.82 to 12.67 meq kg⁻¹ (4.03 dS m-1), from 17.25 to 15.03 meq kg⁻¹ (5.01 dS m-1), and from 21.78 to 18.70 meq kg⁻¹ (6.03 dS m-1) under 100 % FC. This reduction is likely attributed to the displacement of Na+ ions by organic acids such as sulfuric acid produced by Bacillus *spp*. during microbial activity (Stamford *et* *al*., 2007). Similar findings have been reported in earlier studies (Sarathambal & Ilamurugu, 2013). The combined effect of microbial inoculant type, application rate, and incubation duration had a significant impact on exchangeable Na⁺ levels. At 90 DAI, the most substantial decreases were observed in soils treated with CSR-GROW-SURE at 3 L ha-1, with exchangeable Na+ concentrations reduces to 11.18, 14.13, and 17.63 meq kg-1 under EC conditions of 4.03, 5.01 and 6.03 dS m-1 respectively. These reductions were statistically comparable to those achieved with the TNAU culture at the same dosage, which resulted in Na⁺ values of 11.32, 14.23, and 17.78 meq kg-1 under the corresponding salinity levels. Supporting these findings, Damodaran *et* *al*., (2013) reported that Bacillus subtilis and Bacillus pumilus effectively reduced soil Na⁺ through active uptake mechanisms, achieving concentrations of 1.271 and 1.122 meq L-1, respectively, under 1 M NaCl stress.

**3.4. Impact of microbial inoculants on soil exchangeable potassium**

Soils treated with the bio-inoculant CSR-GROW-SURE at 3 L ha-1 showed an increase in exchangeable K+ content, with average values of 9.01, 11.39, and 13.51 meq kg-1 under EC levels of 4.03, 5.01, and 6.03 dS m-1, respectively. These results were statistically similar to those recorded with the TNAU culture at the same rate of application, which yielded mean exchangeable K+ concentrations of 8.96, 11.33, and 13.46 meq kg-1 across the corresponding salinity levels. In comparison, the control plots exhibited the lowest exchangeable K+ levels, with mean values of 7.97, 9.87, and 12.02 meq kg-1 under the respective EC conditions at 100 % FC (Table 3). The enhanced exchangeable K+ availability is likely attributed to the release of organic acids such as lactic, pyruvic, and butyric acids by Bacillus *spp*, which promote the solubilization of non-exchangeable forms of soil K⁺ (Styriakova *et* *al*., 2003).

 The exchangeable K+ content showed a steady increase with prolonged incubation, rising from 8.38 to 9.16 meq kg-1 (4.03 dS m-1), 10.60 to 11.54 meq kg-1 (5.01 dS m-1), and 12.66 to 13.75 meq kg-1 (6.03 dS m-1). This enhancement in K⁺ levels is attributed to the solubilization of native soil K+. Similar findings have been reported by Parmar *et* *al*., (2016), confirming the effectiveness of this process.

The interaction between the type of microbial inoculant and incubation period significantly influenced the exchangeable K⁺ content, showing noticeable improvements over the control. The highest exchangeable K⁺ levels were observed in soils treated with CSR-GROW-SURE at 3 L ha-1 at 90 DAI, with concentrations of 9.44, 11.90, and 14.11 meq kg-1 under EC conditions of 4.03, 5.01, and 6.03 dS m-1, respectively. These results were statistically equivalent to those obtained with the TNAU culture at the same application rate, which also recorded K⁺ levels of 9.44, 11.90, and 14.11 meq kg-1. The increased availability of exchangeable K⁺ is likely due to microbial-mediated solubilization of native soil K+, facilitated by the production of organic acids such as citric and gluconic acids (Velivelli *et* *al*., 2014).

**4. Conclusion**

The results of the incubation study indicated a consistent decline in cation concentration (exchangeable Ca2+, Mg2+, and Na+) following the application of both microbial inoculants, regardless of dosage or duration, in saline soils with EC levels of 4.03, 5.01, and 6.03 dS m-1 maintained at 100 % FC. The magnitude of reduction in these cations increased proportionally with higher application rates and longer incubation periods. Among the cations, Na+ exhibited the highest reduction. In contrast, both microbial treatments led to a more increase in exchangeable K+, which also intensified with higher application rates and extended incubation durations.Among the treatments, CSR-GROW-SURE with 3 L ha-1 consistently resulted in the greatest reduction in exchangeable Ca2+, Mg2+, and Na+ across all salinity levels, and its performance was statistically comparable to TNAUculture with 3 L ha⁻¹ at 90 DAI. Furthermore, CSR-GROW-SURE also significantly enhanced the concentration of exchangeable K⁺, which was again on par with the TNAU culture at 3 L ha-1 across all EC levels under the same moisture condition. These findings underscore the efficacy of halotolerant microbial inoculants in ameliorating saline soils and enhancing soil cationic balance, thereby supporting the restoration of soil health and sustainable agricultural productivity under salt-affected conditions.

**5. 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. Abd El Baki, H. M., Fujimaki, H., Toderich, K., Nana, J. B., & Qureshi, A. S. (2025). Impact of saline water irrigation on soil salinity, growth, and productivity of triticale in sandy soil. Soil Systems, 9(2), 28.
3. Abd\_Allah, E. F., Alqarawi, A. A., Hashem, A., Radhakrishnan, R., Al-Huqail, A. A., Al-Otibi, F. O. N., ... & Egamberdieva, D. (2018). Endophytic bacterium *Bacillus subtilis* (BERA 71) improves salt tolerance in chickpea plants by regulating the plant defense mechanisms. *Journal of Plant Interactions*, *13*(1), 37-44.
4. Abrol, I. P., Yadav, J. S. P., & Massoud, F. I. (1988). *Salt-affected soils and their management* (Vol. 39). Food & Agriculture Org..
5. Afrooz, S. C., Shabani, A., Azizian, A., & Sepaskhah, A. R. (2025). Assessing AquaCrop Accuracy in Simulating Corn Yield and Growth Under the Combined Effects of Salinity, Drought and Nitrogen Stress in Semi‐Arid Regions. *Irrigation and Drainage*.
6. Ammu, K. P., Malathi, P., Sellamuthu, K. M., Jayashree, R., & Senthil Kumar, G. (2025). Phytoremediation of salt-affected soils: mechanistic insights and criteria for plant selection. *Arid Land Research and Management*, 1-21.
7. Arora, S., Singh, Y. P., Vanza, M., & Sahni, D. (2016). Bio-remediation of saline and sodic soils through halophilic bacteria to enhance agricultural production. *Journal of Soil and Water Conservation*, *15*(4), 302-305.
8. 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.
9. Bhise, K. K., Bhagwat, P. K., & Dandge, P. B. (2017). Synergistic effect of Chryseobacterium gleum sp. SUK with ACC deaminase activity in alleviation of salt stress and plant growth promotion in Triticum aestivum L. *3 Biotech*, *7*, 1-13.
10. Chen, J., Blume, H. P., & Beyer, L. (2000). Weathering of rocks induced by lichen colonization—a review. *Catena*, *39*(2), 121-146.
11. Chen, M., Wei, H., Cao, J., Liu, R., Wang, Y., & Zheng, C. (2007). Expression of *Bacillus* *subtilis* proBA genes and reduction of feedback inhibition of proline synthesis increases proline production and confers osmotolerance in transgenic Arabidopsis. *BMB Reports* 40 (3):396-403.
12. Damodaran, T., Sah, V., Rai, R. B., Sharma, D. K., Mishra, V. K., Jha, S. K., & Kannan, R. (2013). Isolation of salt tolerant endophytic and rhizospheric bacteria by natural selection and screening for promising plant growth-promoting rhizobacteria (PGPR) and growth vigour in tomato under sodic environment. *Afr. J. Microbiol. Res*, *7*(44), 5082-5089.
13. Datta, A., Basak, N., Saha, B., & Basak, P. (2025). Enhancing Soil Health by Mitigating Salinity in India. *Soil Health and Sustainability in India*, 352.
14. 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.
15. Deka, P. (2018). *A study on the role of exopolysaccharide in conferring acid tolerance in Bacillus sp* (Doctoral dissertation, Assam Agricultural University JORHAT).
16. 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.
17. Dey, G., Banerjee, P., Sharma, R. K., Maity, J. P., Etesami, H., Shaw, A. K., ... & Chen, C. Y. (2021). Management of phosphorus in salinity-stressed agriculture for sustainable crop production by salt-tolerant phosphate-solubilizing bacteria—A review. Agronomy, 11(8), 1552.
18. Egamberdieva, D., Wirth, S., Bellingrath-Kimura, S. D., Mishra, J., & Arora, N. K. (2019). Salt-tolerant plant growth promoting rhizobacteria for enhancing crop productivity of saline soils. *Frontiers in microbiology*, *10*, 2791.
19. Etesami, Hassan, Somayeh Emami, and Hossein Ali Alikhani. 2017. "Potassium solubilizing bacteria (KSB):: Mechanisms, promotion of plant growth, and future prospects A review." *Journal of soil science and plant nutrition* 17 (4):897-911.
20. 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>
21. Gelu, G., Komai, K., Dane, C., Ayza, A., & Ayele, T. (2025). Investigating the salinity distribution using field measurements in the semi-arid region of southern Ethiopia. *Environmental Monitoring and Assessment*, *197*(2), 1-20.
22. Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research*. John wiley & sons.
23. 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.
24. Guo, H., Wang, G., Song, Z., Xu, P., Li, X., & Ma, L. (2025). Optimization of Subsurface Drainage Parameters in Saline–Alkali Soils to Improve Salt Leaching Efficiency in Farmland in Southern Xinjiang. *Agronomy*, *15*(5), 1222.
25. 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.
26. Jha, Y., & Subramanian, R. B. (2014). PGPR regulate caspase-like activity, programmed cell death, and antioxidant enzyme activity in paddy under salinity. *Physiology and Molecular Biology of Plants*, *20*, 201-207.
27. Kundu, S., Srinivasarao, C., Singh, V. K., & Naveen, J. (2025). Arid Eco-Region and Dryland Soil Health. *Soil Health and Sustainability in India*, 70.
28. Liu, Y., Tan, W., Zeng, W., Ao, C., & Jiang, D. (2025). Optimizing subsurface pipe layout by considering leaching efficiency of major salt ions to improve crop coverage using HYDRUS-2D. *Agricultural Water Management*, *312*, 109392.
29. Muyzer, G., & Stams, A. J. (2008). The ecology and biotechnology of sulphate-reducing bacteria. *Nature reviews microbiology*, *6*(6), 441-454.
30. 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.
31. Neina, D. (2019). The role of soil pH in plant nutrition and soil remediation. *Applied and environmental soil science*, *2019*(1), 5794869.
32. Parmar, KB, BP Mehta, and MD Kunt. 2016. "Isolation, characterization and identification of potassium solubilizing bacteria from rhizosphere soil of maize (Zea mays)." *Int J Sci Environ Technol* 5 (5):3030-3037.
33. Rai, A. K., Basak, N., & Sundha, P. (2021). Chemistry of salt-affected soils. Managing salt-affected soils for sustainable agriculture, 128-148.
34. Sahoo, C., Saini, A., Vandana Devi, V. S., Saha, A., & Fayezizadeh, M. R. (2025). Revitalizing Dryland Soils: Strategies for Sustainable Management. In Ecologically Mediated Development: Promoting Biodiversity Conservation and Food Security (pp. 399-418). Singapore: Springer Nature Singapore.
35. Saleem, M. A., Khan, A., Tu, J., Huang, W., Liu, Y., Feng, N., ... & Xue, Y. (2025). Salinity Stress in Rice: Multilayered Approaches for Sustainable Tolerance. *International Journal of Molecular Sciences*, *26*(13), 6025.
36. 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.
37. Sarathambal, C., & Ilamurugu, K. (2013). Saline tolerant plant growth promoting diazotrophs from rhizosphere of Bermuda grass and their effect on rice. *Indian Journal of Weed Science* 45 (2):80-85.
38. Sarkar, A., Ghosh, P. K., Pramanik, K., Mitra, S., Soren, T., Pandey, S., ... & Maiti, T. K. (2018). A halotolerant Enterobacter sp. displaying ACC deaminase activity promotes rice seedling growth under salt stress. *Research in microbiology*, *169*(1), 20-32.
39. Shanware, A. S., Kalkar, S. A., & Trivedi, M. M. (2014). Potassium solublisers: occurrence, mechanism and their role as competent biofertilizers. *Int J Curr Microbiol App Sci*, *3*(9), 622-629.
40. Shelke, D. B., Chambhare, M. R., Sonawane, H. B., Islam, N. F., Patowary, R., Das, M. R., ... & Sarma, H. (2025). Synergistic approaches in halophyte-microbe interactions: mitigating soil salinity and industrial contaminants for sustainable agriculture. *Discover Life*, *55*(1), 11.
41. Singh, P., Dheri, G. S., & Nazir, G. (2025). Management of Saline and Sodic Soils for Carbon Sequestration. *Communications in Soil Science and Plant Analysis*, 1-22.
42. Stamford, N. P., Ribeiro, M. R., Cunha, K. P. V., Freitas, A. D. S., Santos, C. E. R. S., & Dias, S. H. L. (2007). Effectiveness of sulfur with *Acidithiobacillus* and gypsum in chemical attributes of a Brazilian sodic soil. *World Journal of Microbiology and Biotechnology*, *23*, 1433-1439.
43. Styriakova, I., Styriak, I., Galko, I. G. O. R., Hradil, D. A. V. I. D., & Bezdicka, P. (2003). The release of iron-bearing minerals and dissolution of feldspars by heterotrophic bacteria of *Bacillus* species. *Ceramics Silikaty*, *47*(1), 20-26.
44. Thomas, K. J., & Rice, C. V. (2014). Revised model of calcium and magnesium binding to the bacterial cell wall. *Biometals*, *27*, 1361-1370.
45. Tripathi, S., Kumari, S., Chakraborty, A., Gupta, A., Chakrabarti, K., & Bandyapadhyay, B. K. (2006). Microbial biomass and its activities in salt-affected coastal soils. *Biology and fertility of soils*, *42*, 273-277.
46. Upadhyay, S. K., Singh, D. P., & Saikia, R. (2009). Genetic diversity of plant growth promoting rhizobacteria isolated from rhizospheric soil of wheat under saline condition. *Current microbiology*, *59*, 489-496.
47. Velivelli, S. L., Sessitsch, A., & Prestwich, B. D. (2014). The role of microbial inoculants in integrated crop management systems. *Potato Research*, *57*, 291-309.
48. Verma, P., Ghosh Bag, A., Verma, S., & PA, A. (2025). Amelioration of Salt Affected Soil with Potassium Fertilization: A Review. *Communications in Soil Science and Plant Analysis*, *56*(3), 396-418.
49. 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.
50. Zhu, F., Qu, L., Hong, X., & Sun, X. (2011). Isolation and characterization of a phosphate‐solubilizing halophilic bacterium Kushneria sp. YCWA18 from Daqiao Saltern on the coast of Yellow Sea of China. *Evidence‐based Complementary and Alternative Medicine*, *2011*(1), 615032.
51. 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 1. Interaction effect of soil salinity and microbial inoculant dose on soil exchangeable Ca2+ concentration (meq kg-1)**

|  |  |  |  |
| --- | --- | --- | --- |
| 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 | 10.34 | 10.34 | 10.36 | 10.35 | 12.64 | 12.64 | 12.66 | 12.65 | 14.58 | 14.58 | 14.59 | 14.58 |
| T2 -TNAU Culture @ 1 L ha-1 | 10.02 | 9.77 | 9.61 | 9.80 | 12.45 | 12.27 | 12.15 | 12.29 | 14.31 | 14.01 | 13.81 | 14.04 |
| T3 - TNAU Culture @ 2 L ha-1 | 9.99 | 9.75 | 9.57 | 9.77 | 12.44 | 12.26 | 12.14 | 12.28 | 14.27 | 13.99 | 13.78 | 14.01 |
| T4 - TNAU Culture @ 3 L ha-1 | 9.97 | 9.73 | 9.52 | 9.74 | 12.42 | 12.23 | 12.12 | 12.26 | 14.25 | 13.98 | 13.76 | 14.00 |
| T5 - CSR-GROW-SURE @ 1 L ha-1 | 9.99 | 9.75 | 9.57 | 9.77 | 12.44 | 12.26 | 12.14 | 12.28 | 14.27 | 13.99 | 13.78 | 14.01 |
| T6 - CSR-GROW-SURE @ 2 L ha-1 | 9.97 | 9.73 | 9.52 | 9.74 | 12.42 | 12.23 | 12.12 | 12.26 | 14.25 | 13.98 | 13.76 | 14.00 |
| T7 - CSR-GROW-SURE @ 3 L ha-1 | 9.95 | 9.71 | 9.50 | 9.72 | 12.40 | 12.22 | 12.09 | 12.23 | 14.23 | 13.97 | 13.75 | 13.98 |
| Mean | 10.03 | 9.83 | 9.66 |   | 12.46 | 12.30 | 12.20 |   | 14.31 | 14.07 | 13.89 |   |
|   | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D |
| SEd |  0.01 |  0.04 | 0.05  |  0.02 |  0.04 | 0.06  | 0.02 |  0.03 |  0.04 |
| CD @ 5 % |  0.03 | 0.08 | 0.11  |  0.04 | 0.07  |  0.11 | 0.03  | 0.05  | 0.08  |

**Table 2. Interaction effect of soil salinity and microbial inoculant dose on soil exchangeable Na+ concentration (meq kg-1)**

|  |  |  |  |
| --- | --- | --- | --- |
| 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 | 15.27 | 15.27 | 15.39 | 15.31 | 19.10 | 19.10 | 19.24 | 19.15 | 23.76 | 23.76 | 23.91 | 23.81 |
| T2 -TNAU Culture @ 1 L ha-1 | 13.76 | 12.43 | 11.52 | 12.57 | 17.18 | 15.70 | 14.55 | 15.81 | 21.64 | 19.51 | 18.03 | 19.73 |
| T3 - TNAU Culture @ 2 L ha-1 | 13.64 | 12.31 | 11.42 | 12.46 | 17.01 | 15.53 | 14.40 | 15.65 | 21.52 | 19.38 | 17.90 | 19.60 |
| T4 - TNAU Culture @ 3 L ha-1 | 13.53 | 12.17 | 11.32 | 12.34 | 16.86 | 15.36 | 14.23 | 15.48 | 21.40 | 19.23 | 17.78 | 19.47 |
| T5 - CSR-GROW-SURE @ 1 L ha-1 | 13.64 | 12.31 | 11.42 | 12.46 | 17.01 | 15.53 | 14.40 | 15.65 | 21.52 | 19.38 | 17.90 | 19.60 |
| T6 - CSR-GROW-SURE @ 2 L ha-1 | 13.53 | 12.17 | 11.32 | 12.34 | 16.86 | 15.36 | 14.23 | 15.48 | 21.40 | 19.23 | 17.78 | 19.47 |
| T7 - CSR-GROW-SURE @ 3 L ha-1 | 13.39 | 12.04 | 11.18  | 12.20 | 16.72 | 15.20 | 14.13 | 15.35 | 21.23 | 19.12 | 17.63 | 19.33 |
| Mean | 13.82 | 12.67 | 11.94 |   | 17.25 | 15.97 | 15.03 |   | 21.78 | 19.94 | 18.70 |   |
|   | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D |
| SEd |  0.08 |  0.21 |  0.29 |  0.09 |  0.32 |  0.39 |  0.08 |  0.20 |  0.28 |
| CD @ 5 % |  0.17 |  0.41  |  0.58 |  0.18 | 0.64  | 0.79  |  0.16 | 0.40 | 0.56 |

**Table 3. Effect of different microbial cultures on soil exchangeable** K⁺ **(meq kg-1) under various 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 | 7.99 | 7.99 | 7.94 | 7.97 | 9.89 | 9.89 | 9.84 | 9.87 | 12.04 | 12.04 | 11.99 | 12.02 |
| T2 -TNAU Culture @ 1 L ha-1 | 8.37 | 8.93 | 9.29 | 8.86 | 10.62 | 11.23 | 11.72 | 11.19 | 12.69 | 13.44 | 13.97 | 13.37 |
| T3 - TNAU Culture @ 2 L ha-1 | 8.42 | 8.97 | 9.34 | 8.91 | 10.69 | 11.29 | 11.79 | 11.26 | 12.74 | 13.49 | 14.02 | 13.42 |
| T4 - TNAU Culture @ 3 L ha-1 | 8.46 | 9.02 | 9.39 | 8.96 | 10.75 | 11.38 | 11.86 | 11.33 | 12.78 | 13.53 | 14.06 | 13.46 |
| T5 - CSR-GROW-SURE @ 1 L ha-1 | 8.42 | 8.97 | 9.34 | 8.91 | 10.69 | 11.29 | 11.79 | 11.26 | 12.74 | 13.49 | 14.02 | 13.42 |
| T6 - CSR-GROW-SURE @ 2 L ha-1 | 8.46 | 9.02 | 9.39 | 8.96 | 10.75 | 11.38 | 11.86 | 11.33 | 12.78 | 13.53 | 14.06 | 13.46 |
| T7 - CSR-GROW-SURE @ 3 L ha-1 | 8.51 | 9.07 | 9.44 | 9.01 | 10.81 | 11.45 | 11.90 | 11.39 | 12.85 | 13.57 | 14.11 | 13.51 |
| Mean | 8.38 | 8.85 | 9.16 |   | 10.60 | 11.13 | 11.54 |   | 12.66 | 13.30 | 13.75 |   |
|   | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D | Cultures(C) | Duration(D) | C × D |
| SEd |  0.04 |  0.07 |  0.11 |  0.03 |  0.06 |  0.09 |  0.04 |  0.08 |  0.12 |
| CD @ 5 % |  0.06 | 0.15  | 0.19 |  0.05 | 0.11 | 0.15  |  0.07 | 0.16 | 0.23  |

****

**Figure 1. Heat map of microbial bio inoculant application on exchangeable Mg2+ (meq kg⁻¹) under various salinity levels. Darker shades showed the high intensity of exchangeable Mg2+ and the less intensity has appeared by lighter shades.**